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FINAL REPORT

SIMULATION AND CONTROL ENGINEERING STUDIES OF THE NASA-AMES 40' x 80'/80' x 120' WIND TUNNELS

(NASA-CR-152145) SIMULATION AND CONTROL ENGINEERING STUDIES OF NASA-AMES 40 FOOT BY 80 FOOT/80 FOOT BY 120 FOOT WIND TUNNELS Final Report, Aug. 1977 - Mar. 1978 (Systems Control, Inc., Palo Alto, Calif.) 316 p
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20. ABSTRACT (Continue on reverse side if necessary and identify by block number)

IN THIS REPORT ARE DISCUSSED THE DEVELOPMENT AND USE OF A DIGITAL COMPUTER SIMULATION OF THE PROPOSED 40'x80'/80'x120' WIND TUNNEL FACILITY AT NASA/AMES RESEARCH CENTER, THE FEASIBILITY OF AUTOMATIC CONTROL OF WIND TUNNEL AIRSPEED AND OTHER PARAMETERS, AND SPECIFICATIONS AND IMPLEMENTATION RECOMMENDATIONS FOR A COMPUTER - BASED AUTOMATIC CONTROL AND MONITORING SYSTEM.

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FORWORD

This report was prepared for NASA Ames Research Center under Contract No. NAS2-9665. Mr. Kenneth Mort was the technical monitor for this work. Mr. Charles Hermach is the manager of the wind tunnel modification project for which this work was performed.

The program manager at Systems Control, Inc. (Vt) was Dr. W.E. Hall, Jr. The project manager was Mr. J.G. Bohn. Computer simulation development was performed by Mr. J.E. Jones, assisted by Dr. R. DeHoff, and computer control system specifications were prepared by Mr. B. Kendall. Computer system implementation studies were assisted by Mr. B. Reed and Mr. Jones. Electrical machine analysis was assisted by Mr. C.H.M. Saylor and Mr. S. Virmani. Report preparation and artwork were performed under the direction of Ms. C. Walker.

NOMENCLATURE

Note: Computer math model nomenclature is given separately in Appendix B.

Symbol	Definition
A	Tunnel cross-section area, ft.^{2}
a	Speed of sound, fps
C_Q	Fan aerodynamic torque coefficient; torque/$\rho\Omega^2R^5\pi$
D	Drag, model in test section, lbs.
E_e	Electrical supply voltage, per unit
E_q'	Transformed synchronous motor excitation voltage, per unit
e	Voltage
f	Frequency, hz
G	Compressibility factor, $G = (1+\gamma M^2)/(1+(\gamma-1)M^2/2)^{\gamma/(\gamma-1)}$
H	Frequency response transfer function
h	Tail strut height
I	Electrical current, ac or dc, amps or per unit, rms
i	Electrical current, amps
J	Moment of inertia, slug-ft^2
K	(1)ω/60; (2) controller feedback gain
K_{T_V}	Theoretical fan head rise coefficient, $\Delta p^o/\frac{1}{2}\rho V^2$
K^*	dc motor or generator open circuit voltage ÷ RPM
K_{p_i}	Tunnel pressure loss coefficient, $\Delta p/q_{TS}$, between station (i-1) and station (i)
L	(1) tunnel flow segment length (2) turbulence characteristic length

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Symbol	Definition
L_{ff}	DC motor/generator field inductance, henrys
L_{aq}	DC motor/generator armature inductance, henrys
ℓ_{TS}, ℓ'_{TS}	Model geometry parameters, ft.
$\dot{m}$	Tunnel mass flow rate, slugs/sec.
M	Mach number
n_p	Number of poles in synchronous machine
p	Pressures, psf.
P_e	Electrical power, watts or per unit
q	Flow dynamic pressure, $\frac{1}{2}\rho V^2$, psf.
Q	(1) Fan aerodynamic torque; heat flux
R	(1) Universal gas constant, 1715 ft-lb/slug$^{\circ}$R; (2) fan radius, ft; (3) flow resistance, lbs.
r	Resistance, ohms
s	(1) Slip, $s = 1-\omega/60$; (2) Laplace operator; (3) turn-table edge motion, ft.
T	Temperature, $^{\circ}$R or $^{\circ}$F.
T'_{d_o}	Synchronous motor field time constant, sec.
U	Fan inflow velocity at fan blades, fps
u	Local velocity, fps.
V	(1) Velocity, fps (2) fan inflow velocity at fan unit, fps; (3) direct or quadrature axis synchronous machine voltage, per unit
W	Work input to airflow as heat or compression; ft-lb/sec.
$x_{(\cdot)}$	Synchronous motor direct or quadrature impedance, per unit
$x'_{(\cdot)}$	Synchronous motor transient direct or quadrature impedance, per unit

Symbol	Definition
z_{TS}	Model support geometric parameter, ft.
z_m	Model support geometric parameter, ft.

SUBSCRIPTS

Symbol	Definition
a	Armature
CMD	Commanded value
D	Derivative gain in controller
dc, DC	Direct current
d	Direct axis (synchronous machine)
e	Electric
f	Electric motor/generator field
g	Atmospheric disturbance, gust
HZ	Hertz (cycle/sec)
H	Operator's handle
I	Integral gain in controller
i	Tunnel flow station
m	Model (test article)
o	Stagnation conditions
P	Proportional gain in controller
q	Quadrature axis (synchronous machine)
R, ref	Reference value
s	Static conditions (also indicated by no subscript)

SUBSCRIPTS

Symbol	Definition
TS	(1) Test section (2) tail strut
TOT	Total value
w	Wind (external to open-circuit tunnel)

GREEK

Symbol	Definition
γ	(1) Thermodynamic constant, ratio of specific heats; = 1.40 for air; (2) model support geometry parameter
δ	(1) Synchronous machine power angle; (2) pressure ratio p/p_{ref}
ϵ	Error quantity
θ	(1) Model pitch attitude rel. to horizontal; (2) rheostat rotation; (3) temperature ratio, T/T_{ref}
Λ	Fan inflow ratio, $U/\Omega R$
μ	Microprocessor computer
ξ	(1) Blade stagger angle, deg., angle from freestream direction to blade reference chord; (2) model geometric parameter
ρ	Density (thermodynamic)
σ	Induction Frequency Changer slip
Φ	Power spectral density
ϕ	Synchronous machine power factor angle, $\cos^{-1}$ (power factor)
Ψ	Model yaw angle

GREEK

Symbol	Definition
Ω	Shaft RPM, RPM or rad/sec
ω	(1) Arbitrary frequency, rad/sec (2) A.C. supply voltage frequency, hz.
ω_e	Reduced electrical frequency, $\omega_{HZ}/n_p/2$

ABBREVIATIONS

CPMS	Critical Parameter Monitoring Subsystem
CMS	Control and Monitoring System
DC	Direct Current
db	Decibels
DAS	Data Acquisition System
HP	Horsepower
IFC	Induction Frequency Changer
I/O	Input/Output
MACS	Model Attitude Control Subsystem
MG	Motor/Generator
M/P	Microprocessor
MCC	Microprocessor Control Center
PF	Power Factor
PB	Pushbutton
P.I.D.	Proportional, Integral, Deviative (Controller)
PER	Peripheral (computer equipment)

ABBREVIATIONS

SQCS	Speed/q Control Subsystem
STDBY	Standby
TMS	Test Management Subsystem

TABLE OF CONTENTS

I. INTRODUCTION AND SUMMARY

1.1 INTRODUCTION

A substantial increase in aeronautical research and development capability will be achieved with modification of the NASA-Ames 40'x80' Full Scale Wind Tunnel to achieve higher test speeds, and with the addition of a new, open circuit test section (80'x120') to evaluate larger vehicles. The expanded test envelope of this new, combined facility makes possible the testing of conventional and powered-lift aircraft configurations over a wider speed range with improved data accuracy and consistency. This increased capability results from the ability to test the same test article at higher dynamic pressures without the need for structurally-scaled models, and at low dynamic pressures without as critical a problem from tunnel boundary corrections in the presence of high powered lift coefficients. Moreover, the ability to do such testing with full-scale, or near full-scale test articles will support state-of-the-art technology in the analysis and understanding of the complex dynamic aero-thermo-mechanical systems that modern aircraft are becoming.

The subject of the present investigation is the dynamic behavior and control characteristics of the facility itself. To produce maximum return on investment, the facility, being a heavy user of electrical energy, must be operated in a responsible, efficient manner to provide maximum useful data output per unit of energy consumed, while satisfying stringent operating constraints imposed by the safety of personnel, the test article, and the tunnel itself. The present investigation was performed in order to: (1) develop analytical means with which to study facility operation tradeoffs; (2) determine the feasibility of automatic wind tunnel airspeed control; and (3) study, to the system specification level, the implementation of a computer-based system to perform speed control and other functions.

1.2 METHOD OF APPROACH

This investigation is comprised of three principal areas of effort:

(1) the development of a computer-based simulation math model of the wind tunnel facilities, incorporating experimental data from previous NASA studies into an analytic model capable of simulating dynamic wind tunnel behavior (time variations of airspeed, fan RPM, motor-generator system parameters, etc.) and the special case of static trimmed operation at a given test condition;

(2) the investigation of automatic tunnel airspeed/q control using a computer-resident feedback control algorithm; and

(3) an investigation of the required system configuration of a series of computer subsystems for speed control, model attitude control, critical parameter monitoring, and test management, and of the required specifications for such a system.

The digital computer program for the simulation math model is coded in FORTRAN and installed on the NASA/Ames CDC 7600 computer. Its structure allows for detailed exploration of tunnel parameter effects and for updating with revised data tables when new data become available, as, for example, on fan performance characteristics. As part of the verification of simulation operation, parametric studies of tunnel steady-state and dynamic behavior were made.

Control system loop development was performed using the math model to achieve maximum validity in the face of the many nonlinearities present in the overall wind tunnel system.

Computer system development represents a translation of known and anticipated tunnel operational requirements into an arrangement of dedicated computer units. The principal objectives of this area of effort were:

(1) to formulate a computer system satisfying the need for both fail-safe redundancy levels (at least) and independence from existing tunnel data acquisition systems;

(2) to propose a system consistent with current state-of-the-art computer technology; and

(3) to propose a system with as much modularity as possible to allow a program of selected implementation.

1.3 PRINCIPAL CONTRIBUTIONS

The principal contributions of this effort are:

(1) an analytical tool for the analysis of wind tunnel behavior, and quantitative results from preliminary investigations using this tool;

(2) a prototype wind tunnel speed/q controller; and

(3) a qualitative description of a computer control and monitoring system which, if implemented, would increase tunnel operational efficiency through enhanced operating accuracy and operating safety.

Specific contributions include the following:

(1) a program for full-nonlinear, digital computer simulation of the 40' x 80' and 80' x 120' tunnel circuit airflow and drive system dynamics;

(2) quantitative studies of tunnel operating power requirements, fan loads, model drag effects, and transition time histories;

(3) quantitative demonstration of automatic tunnel q control; and

(4) detailed discussion of computer system requirements and specifications for speed/q - and peripheral - control functions.

An indirect but significant contribution of this effort is a clearer understanding of the expected operating characteristics of the modified wind tunnel facility. It can be stated, from these initial studies, that:

(1) tunnel motor and fan performance is adequate to reach the maximum planned operating speeds, with significant amounts of model drag present;

(2) fan surge is not a threat during high-speed transition conditions, with currently-planned fan blade pitch rates;

(3) numerous fan RPM-blade pitch combinations are feasible in low-speed (IFC) operation but an apparent power minimum is reached simply with minimum RPM;

(4) the dynamics of the motor-generator system units are generally well-behaved, with certain areas of concern identified as worthy of continued attention.

1.4 SUMMARY

Subsequent sections of this report are organized as follows. Section II describes the theoretical bases of the elements of the simulation math model and provides specific information pertinent to the modeling of these elements for purposes of simulation. This section concludes with a description of the simulation computer program. Section III presents quantitative results of the use of the math model to perform parametric studies of wind tunnel steady-state and dynamic (transient) characteristics, with special emphasis on power usage and fan loads. This section includes a theoretical study of anticipated 80' x 120' tunnel response to atmospheric disturbances, and their nullification. Section IV presents a detailed discussion of the derivation, evaluation, and recommended implementation of the desired speed/q control system, and discussions of the structure and implementation of additional computer subsystems for model attitude control, critical parameter monitoring, and test management. Concluding this section is a discussion of system failure modes. Section V presents comprehensive specifications for the procurement of the computer systems developed and described in Section IV. Finally, Section VI presents conclusions and recommendations for further study.

Details of tunnel geometry and associated modeling information are presented in Appendix A. Detailed simulation computer program descriptions and a program listing are presented in Appendix B; this appendix is the User's Guide for the simulation program.

II. WIND TUNNEL SIMULATION MATH MODEL

2.1 OVERVIEW

A principal objective of this study was the development of a simulation math model computer program to aid in the accomplishment of analysis required in the present effort and to serve as an analytical tool to support future tunnel performance evaluations. This was accomplished through analytical modeling of the three principal elements of the total wind tunnel systems: the flow circuit (open and closed), the fan unit, and the drive motors and units of the motor-generator control system. The dynamic characteristics of the system as a whole are computed from the dynamics of its components through numerical integration of the dynamical fluid and mechanical (including time-varying electrical parameters) equations of motion.

Within limitations imposed by model fidelity, numerical accuracy and model parameter knowledge, the simulation is an exact representation of the actual wind tunnels. No assumptions have been imposed to achieve linearity or time-invariance of equation coefficients, and all known physical limits (such as on rates and position) are represented. This thoroughness is possible because the digital computer "looks up" the tunnel configuration and status at each computation point. There is no limitation on the extent of nonlinearities and constraints that may be specified by logic or by data tables. In particular, it provides for incorporation of such experimental data as are available for a given component, with theoretical models used only as required.

This section describes the principal component models comprising the simulation: flow, fans, and motor-generator system, and concludes with a brief discussion of the simulation computer program. Section III discusses the application of the simulation to static and dynamic analyses. A detailed description of the program, a user's guide, input/output specification, and a listing are presented in Appendix B.

2.2 FLOW MODEL

This section discusses the modeling of airflow dynamics and thermodynamics in the 40' x 80' and 80' x 120' tunnel configurations under study in the current wind tunnel control system feasibility study. It is required to compute the steady-state conditions in the flow at a given operating point within the tunnel's operating envelope (0 to 300 knots with new drive systems), and to compute the dynamic characteristics of transition from one speed to another. One-dimensional, compressible flow has been assumed throughout, and maximum use is made of existing data from prior NASA studies.

2.2.1 40'x 80' Circuit

Figure 2.2.1 shows a plan view of the closed-circuit tunnel and reveals the arrangement of the principal aerodynamic elements: fan section, test section, turning vanes, corners, and ducts. Centerline distance around the tunnel is 1915 ft. The tunnel contains approximately 900 tons of air.

The air in the wind tunnel accelerates or decelerates in response to pressures acting on it at its boundaries and within it. The pressure differential generated across the drive fans, frictional losses along the walls, and the drag of obstructions in the flow (such as turning vanes or the test article) are the governing forces. When the fan pressure rise is balanced by pressure losses in the duct, the flow is in equilibrium and velocity is constant.

Losses due to wall friction and obstructions in the flow appear as a decrease in the momentum of the flow and a transformation of flow energy from kinetic to potential, i.e. from velocity

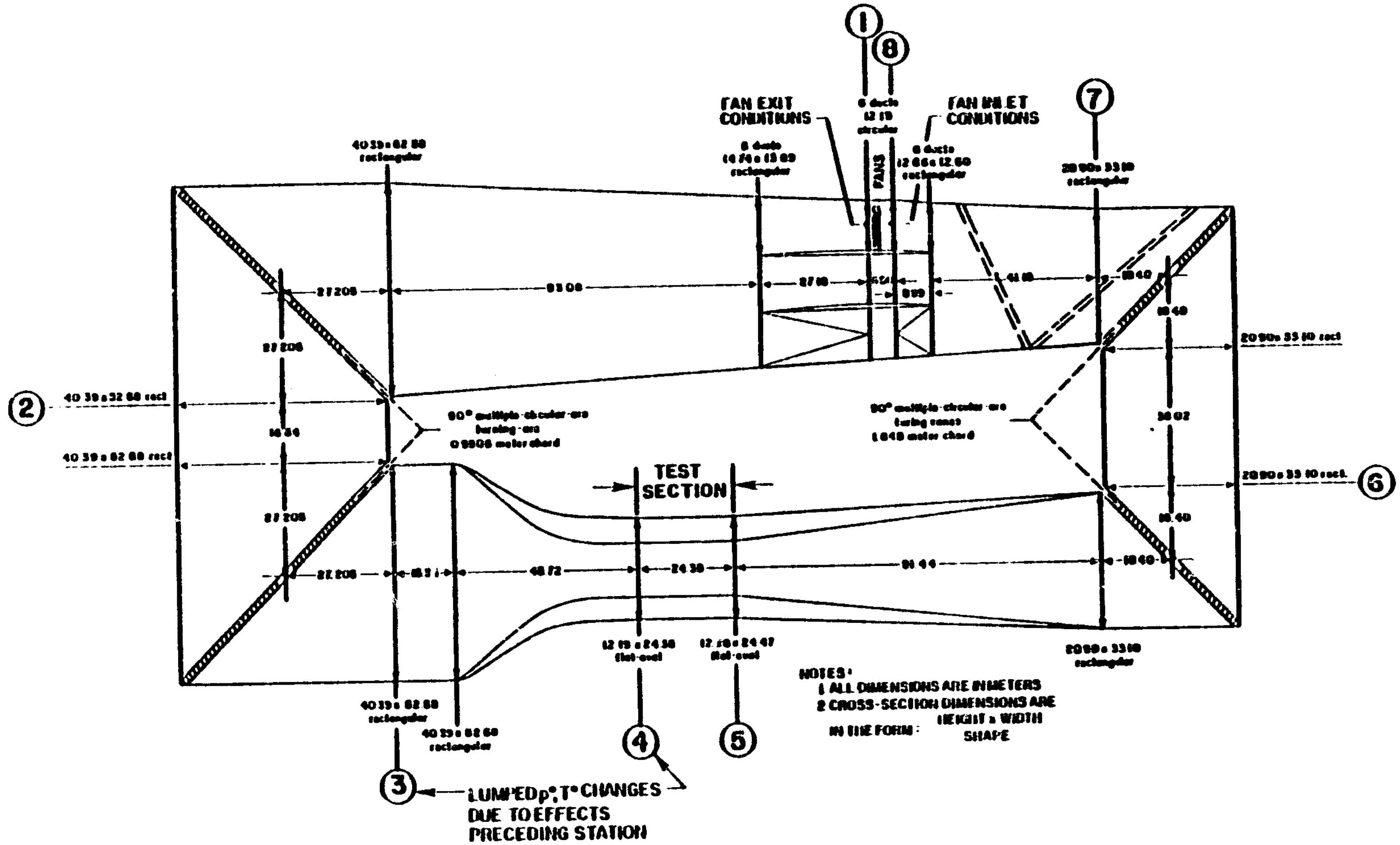


Figure 2.2-1 Present Model Flow Properties Calculation Station Definition 40x80 Ft. Closed-Circuit Wind Tunnel

to heat through the action of dissipative viscous forces. The tunnel drive fans are required to replace momentum and kinetic energy lost as the air travels through the circuit; hence, under steady operating conditions, the total energy of the air in the tunnel must increase with time, and this is in fact measurable as a significant rise in tunnel air stagnation (or total) temperature. The conservation equations of mass, momentum, and energy, combined with the thermodynamic equation of state, completely define the problem.

In the following, the assumptions and equations pertaining to the present analysis are discussed. For background derivations and concepts, the reader is referred to the references.

The basic dynamical equation to be used here is [Refs. 1,2]:

$$\frac{\partial}{\partial t} \int_1^2 \dot{m}\, dx + p_2^0 A_2 G_2 - p_1^0 A_1 G_1 = R_{x_{12}} \qquad (1)$$

which relates the rate of change of mass flow, $\dot{m}$, between two stations (shown as stations 1 and 2) to the pressures on either end and the force R_x acting on the flow between the end points. Here,

$$G = \frac{1 + \gamma M^2}{\left(1 + \frac{\gamma - 1}{2} M^2\right)^{\gamma/\gamma-1}} \qquad (2)$$

p^0 = total pressure, psf;

A_i = local flow cross-sectional area (i denotes the station under consideration), ft^2;

$\dot{m}_i$ = local mass flow rate, $\rho_i V_i A_i$, slugs/sec.

The steady state form of this equation, where $\partial/\partial t \int_1^2 \dot{m}\, dx \equiv 0$ clearly shows the relationship between forces due to flow obstructions, R_x, and the change of momentum of the flow, manifested as a change in total pressure.

Assuming point 1 to be at the fan outlet and point 8 to be at the fan inlet, the dynamical flow equation becomes:

$$\frac{d}{dt}(\dot{m}) = \frac{1}{L_{18}} \{[(p_8^\circ + \Delta p_{FAN}^\circ)G_8 - p_1^\circ G_1]A_{FAN}\} \qquad (3)$$

where L_{18} = tunnel length, A_{FAN} = fan unit reference area, and Δp_{FAN}° = fan total head addition. This equation assumes: (a) mass flow is the same, at a given time, at all points in the tunnel; and (b) the flow is approximately one-dimensional. Flow pressure changes are caused by viscous effects, flow obstructions, and forces on the test article (see Figure 2.2-2).

To compute $d/dt\,(\dot{m})$, hence tunnel speed as a function of time, the terms of Eq. (3) must be evaluated around the tunnel circuit. This is done in a series of eight stations, shown in Figure 2.2-1. Based on NASA data, total pressure is computed by subtracting the intervening section total pressure losses from the total pressure computed at the preceding station. Total temperature is computed from knowledge of heat and work addition, and mass flow, as mentioned above, is assumed to be the same at all stations at a given time. NASA values of pressure loss coefficients (relative to test section dynamic pressure) are used, lumped as required to correspond to the present flow station designation. The NASA values were computed theoretically (Ref. 3) for each element of the wind tunnel circuit, as shown in Figure 2.2-3. To account for Reynolds number effects, the values of the lumped coefficients in the present model are tabulated as functions of test section velocity, using data available from the NASA tunnel performance program at various speeds. These data are shown graphically in Figure 2.2-4, and tabulated in Table 2.2-1. Tunnel sectional area at each evaluation station is given in Appendix A, Table A.1.

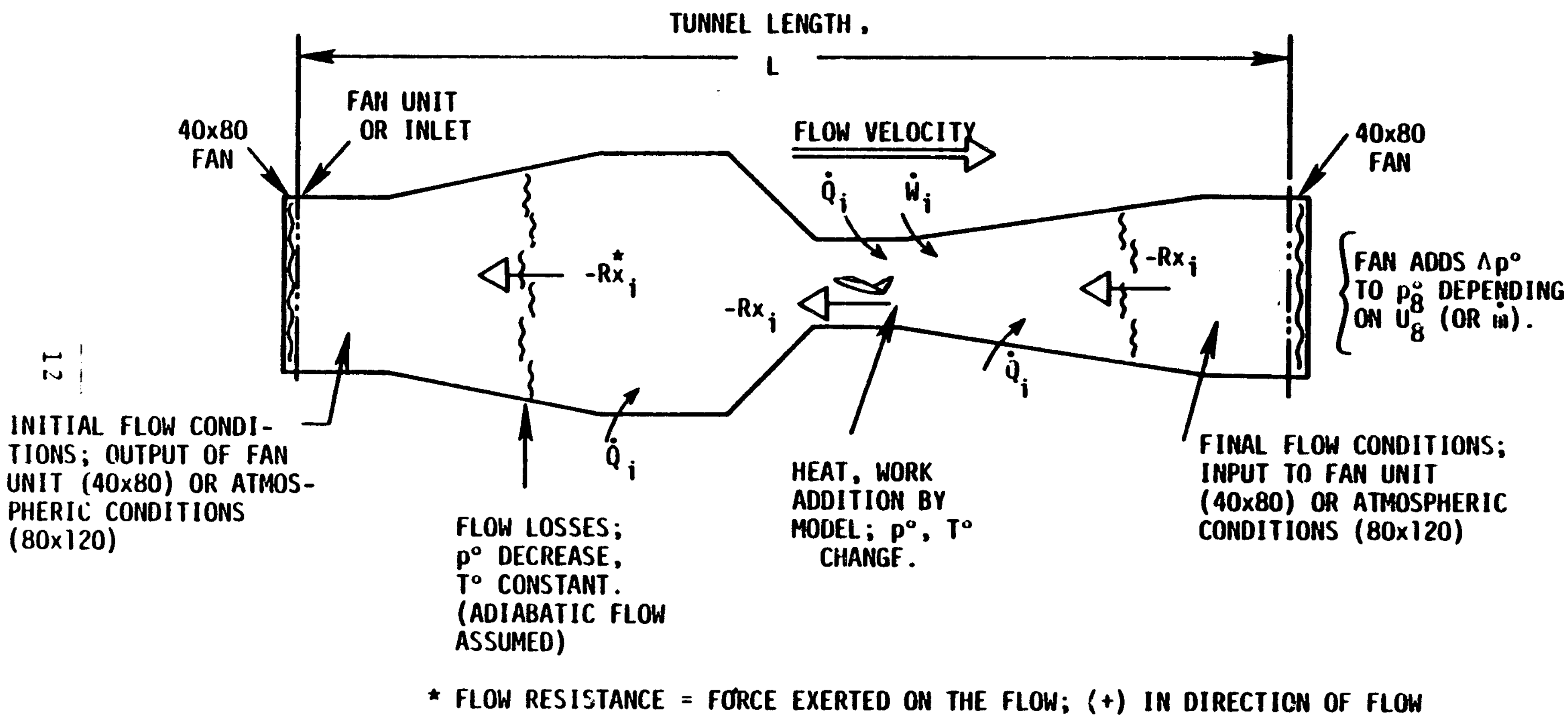


Figure 2.2-2 Wind Tunnel Approximated as One-Dimensional Flow System

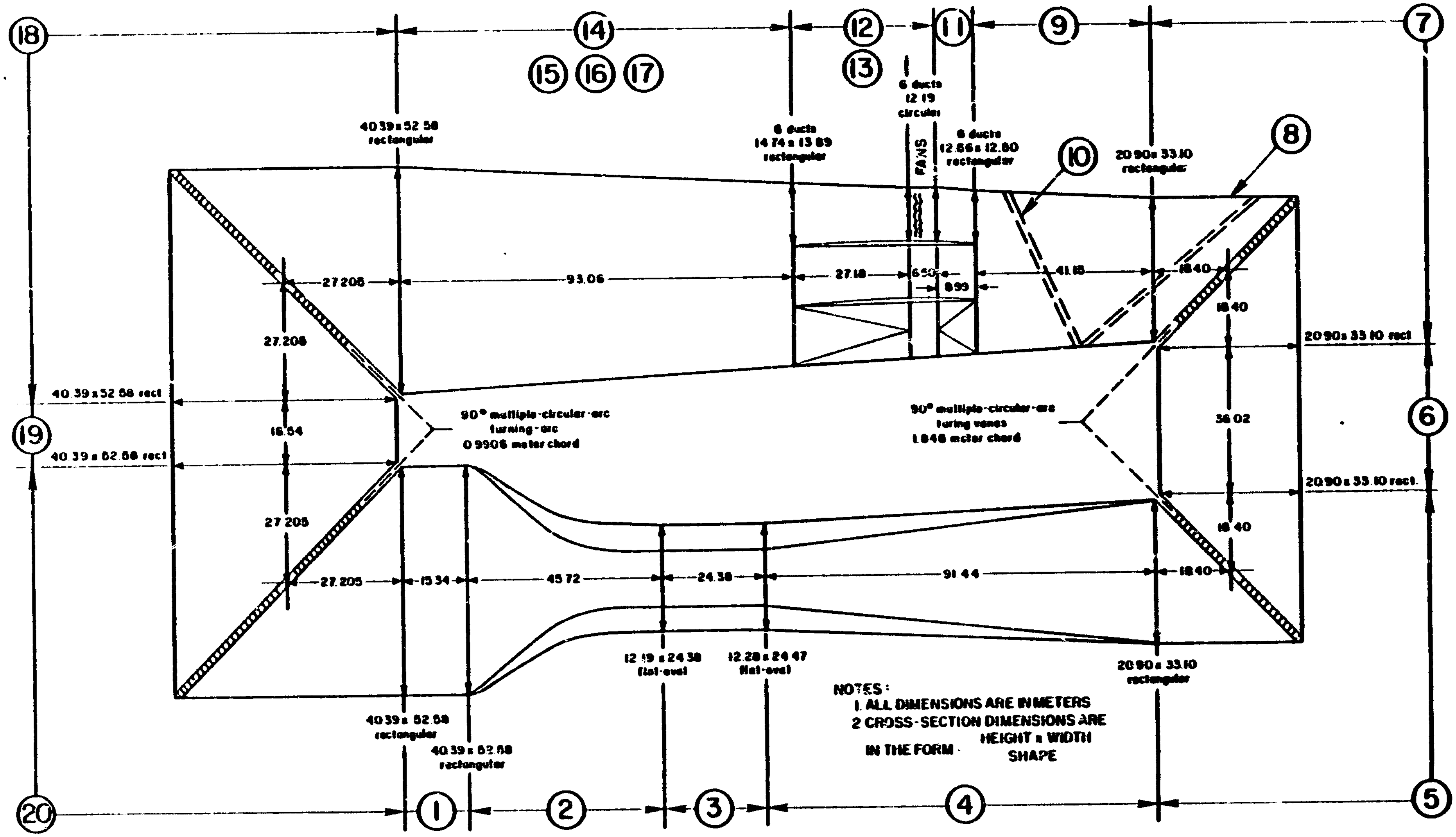


Figure 2.2-3 NASA/Ames Flow Pressure Loss Calculation Segments

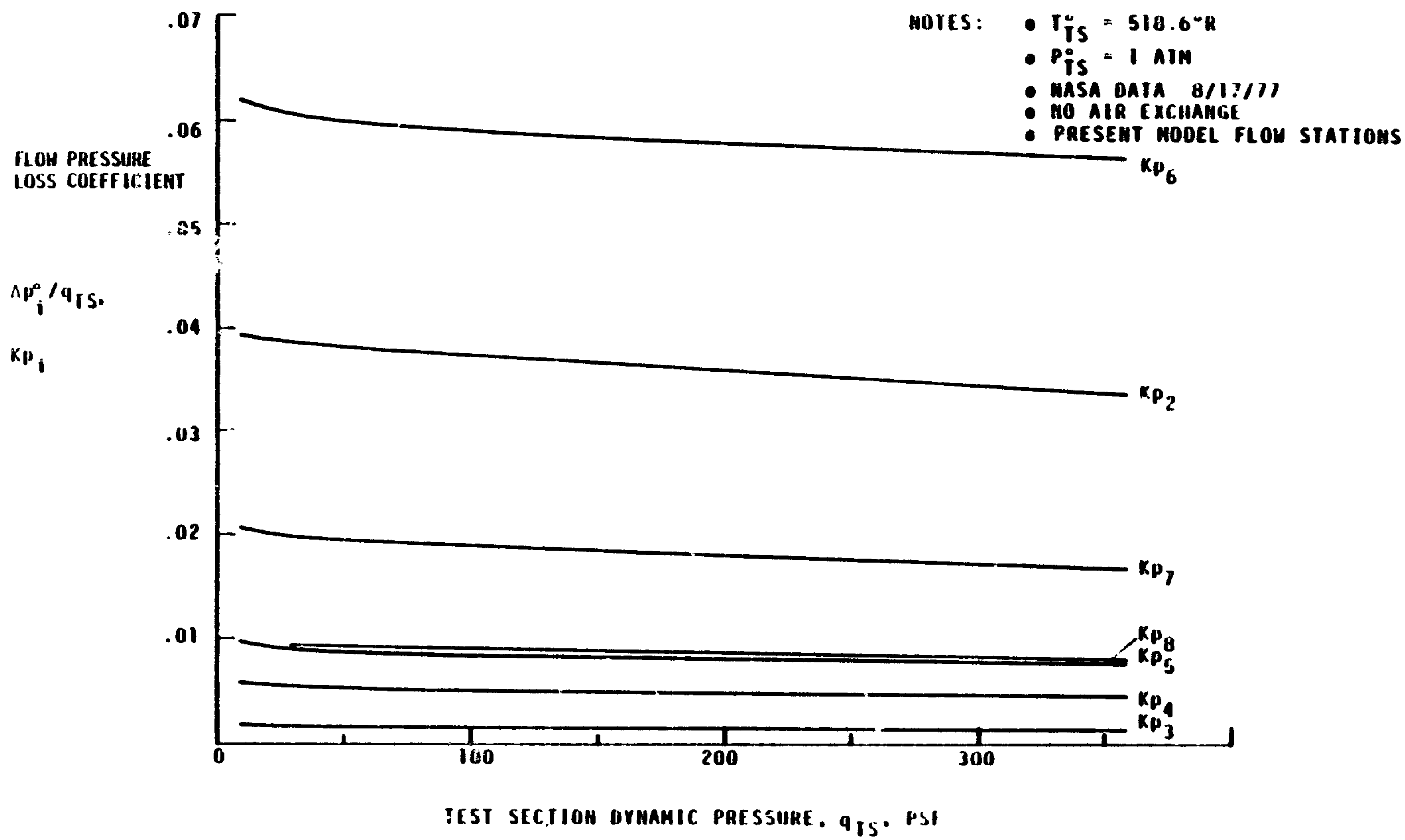


Figure 2.2-4 40 x 80 Flow Pressure Loss Coefficients (Ref. 3)

Table 2.2-1

Modified 40' x 80' Pressure Loss Summary

PRESENT MODEL FLOW STATION (i)	$Kp_i = \Delta p_i^o / q_{TS}$ TEST SECTION SPEED ~ KTS						
	50	100	150	200	250	300	350
1	-	-	-	-	-	-	-
2	.03970	.03883	.03808	.03724	.03627	.03515	.03387
3	.00186	.00174	.00167	.00161	.00154	.00148	.00142
4	.00605	.00552	.00525	.00507	.00494	.00485	.00477
5	.01001	.00914	.00869	.00840	.00819	.00803	.00790
6	.06268	.06091	.05987	.05905	.05832	.05761	.05688
7	.02106	.02014	.01951	.01893	.01833	.01769	.01698
8	.00969	.00945	.00924	.00902	.00876	.00847	.00815
TEST SECTION DYNAMIC PRESSURE, q_{TS}, PSF	8.45	33.51	74.32	129.47	197.04	274.63	359.48

Total pressure at station 1 is computed as a given quantity (for initialization) or as a known function of blade pitch, fan RPM, and mass flow rate; mass flow is either given, as an initial condition, or computed by using Eq. (3):

$$\dot{m}_1(t)^{①} = \dot{m}_1(t-\Delta t) + \frac{d}{dt}\,[\underbrace{\dot{m}(t-\Delta t)}_{\text{From Eq. (3)}}]\Delta t \tag{4}$$

An approximate test section dynamic pressure is computed to evaluate section loss coefficients, which have been referenced to test section dynamic pressure. We have

$$\bar{q}_{TS}(t) = \frac{1}{2p_{TS}(t-\Delta t)A_{TS}^2}\,\dot{m}^2(t),$$

where $\dot{m}(t)$ is that value calculated above and $p_{TS}(t-\Delta t)$ is as computed during the test section analysis of the previous frame.

If the flow has been given increased momentum in the intervening section as, for example, by a propeller in the test section (Section 4-5 in Figure 2.2-1), the total pressure will <u>increase</u>. If the test article is unpowered and contributes only drag, a total pressure decrease occurs in addition to the tunnel-alone quantity. In this case,

$$\Delta p_i^0(t) = K_{p_i}(q_{TS}(t))\bar{q}_{TS}(t) + D_m(t)/A_{TS}$$

---

① Subscripts refer to station numbers in present model.

where

D_m = model drag (thrust is treated as negative drag), lb.

A_{TS} = test section area (2856.64 ft^2)

The principal sources or sinks of heat transfer ($\dot{Q}$) are fan motor cooling air, conduction through the tunnel walls, and electric motors or turbojet engines on the test article. Values of $\dot{Q}$ will be established at each station, depending on operational and environmental conditions. The principal sources of work (W) are the drive fans and propeller- or jet-powered models. For models, the work added is

$$W_{model} = \dot{W}_{model}\Delta t = thrust(t).U_{TS}(t).\Delta t \quad (ft\text{-}lb)$$

For the drive fans,

$$W_{FAN} = \Delta p^{o}_{FAN}\,(t)U_{FAN}\Delta t\;A_{FAN} \quad (ft\text{-}lb)$$

It is important to note that model-produced thrust adds energy to the tunnel, i.e. performs work, and thus increases total temperature, while model-produced drag does not remove energy from the flow, leaving total temperature unchanged. Hence, for an unpowered model, $W_{model} = 0$.

These computations are repeated for each station until the conditions at the fan inlet, station 8, Figure 2.2-1, are known. The flow acceleration is then computed from Eq. (3), and integrated to compute the new value of $\dot{m}$.

The simulation math model contains the tunnel pressure loss coefficients in tabular form and interpolates on tunnel q. The boundary condition requiring atmospheric static pressure in the settling chamber is applied at station 2. Once total pressure, total temperature, and $\dot{m}$ are determined, the remaining flow variables are computed from:

$$M = \left[\frac{\zeta}{1.40\ \dot{m}} - \frac{\zeta^2}{\dot{m}^2} - \frac{1}{0.7}\right]^{1/2}$$

where $\zeta = p^\circ A\sqrt{\gamma/RT^\circ}$

($R = 1715$ ft-lb/slug $^\circ R$; $\gamma = 1.40$)

and:

$$T = T^\circ/(1+.7\ M^2)$$

$$p = p^\circ/(1+.7\ M^2)^{3.5}$$

$$\rho = \rho^\circ/(1+.7\ M^2)^{2.5}$$

$$a = \sqrt{1.4\ RT}$$

$$u = Ma$$

utilizing isentropic relations and an approximate, closed-form expression for Mach number.

2.2.2 80' x 120' Circuit

The solution for the dynamics of the flow through the open-circuit, 80' x 120' test section tunnel differs from the solution for the closed-circuit tunnel only in the boundary condition applied to the flow and in the numerical constants of geometry and pressure loss coefficients. Tunnel geometry (areas and segment lengths) is given in Appendix A.

Figure 2.2-5 shows the layout of the open-circuit tunnel; it shares the drive system (fan unit) of the closed-circuit tunnel, the air being directed along its new path by movable vanes. The

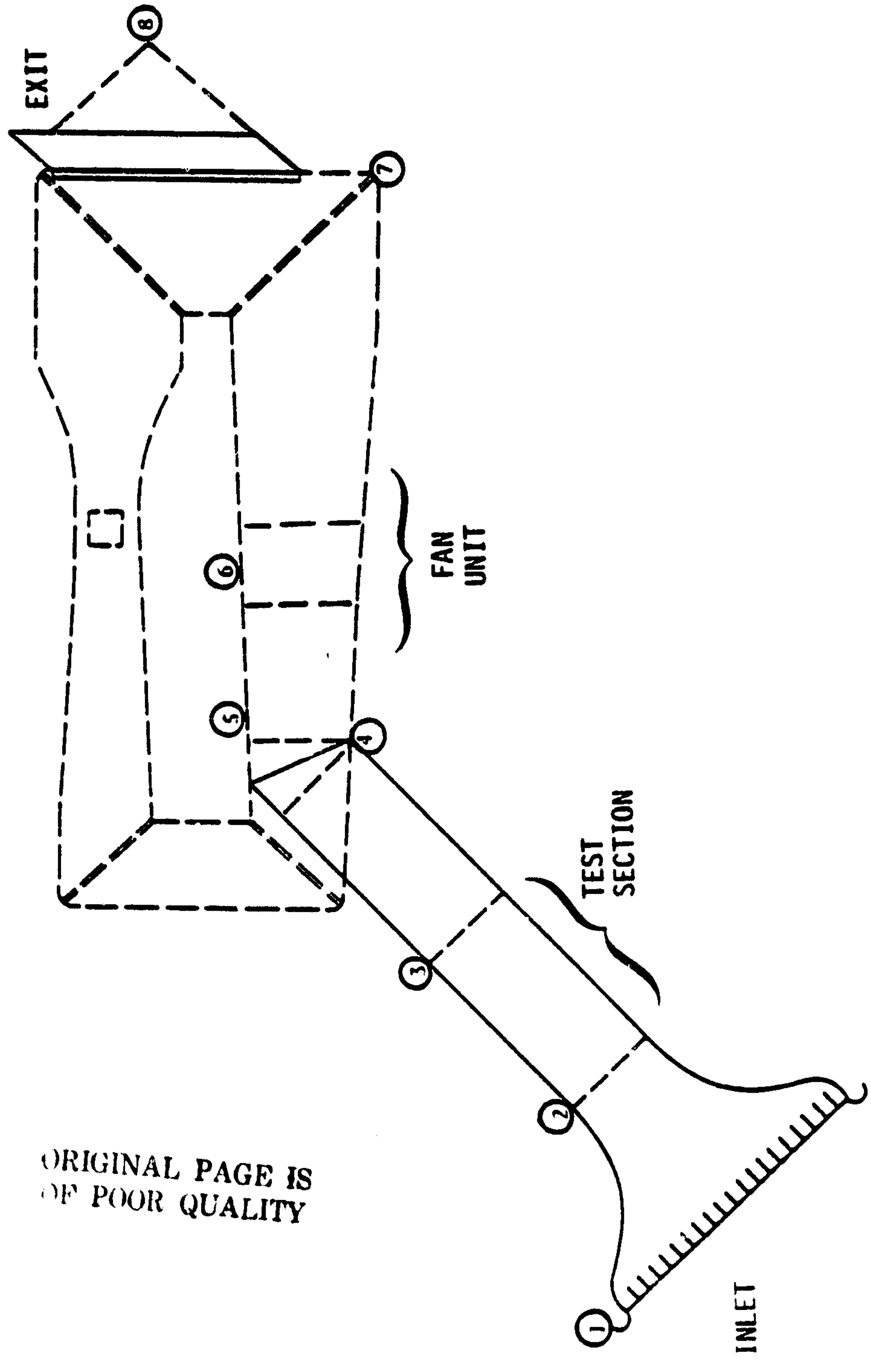


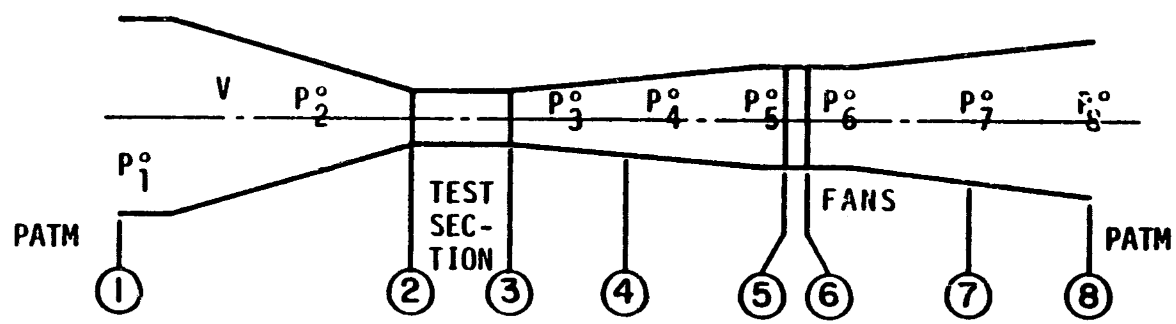
Figure 2.2-5 80' x 120' Tunnel Geometry and Flow Station Definition

boundary condition on the flow requires total pressure at the entrance to be atmospheric and static pressure at the exit to be atmospheric. With the fan unit now in the middle of the tunnel flow stations, the theoretical representation of the flow is as shown in Figure 2.2-6, and tunnel airflow dynamics are determined from:

$$\frac{d}{dt}(\dot{m}) = \frac{1}{L_{eff}}\{p_5^\circ G_5 + \Delta p_{FAN}^\circ - p_6^\circ G_6\} A_{FAN} \qquad (5)$$

Air outside the wind tunnel entrance must be accelerated to enter the tunnel, hence its mass must be added to the mass of air within the tunnel when computing flow acceleration. This is accomplished by increasing the effective tunnel centerline length beyond its time length. As noted in Ref. 4. the mass of air external to the tunnel may be assumed to be half of that contained in a hemisphere at each end of diameter equal to tunnel diameter at that end. Applying this rule and proportioning lengths and area leads to a 43.5-ft. extension at the tunnel entrance and a 27.3-ft. extension at the tunnel exit, increasing the effective tunnel length from 1393.2 to 1464 ft. and, as seen in Eq. (5), causing slightly lower accelerations as a result of the increased air mass.

Flow pressure and temperature calculations are performed exactly as for the closed-circuit tunnel, upstream of the fans. Downstream of the fan unit, total pressure (p_6°) is adjusted until the static pressure at the exit (p_8) is equal to atmospheric, considering the pressure losses from the fan to the exit that depend on flow rate. This value of p_6° is used in Eq. (5). Flow loss parameters for this tunnel are tabulated in Table 2.2.2 and are plotted in Figure 2.2.7.



$$\frac{d}{dt}(\dot{m}) = \frac{1}{L_{Eff}}\left[P^\circ_4 + \Delta P^\circ_{FAN} - P^\circ_5\right] A \cdot G$$

BOUNDARY CONDITION: P°_1 = PATM

P_6 = PATM, SATISFIED BY ITERATION

Figure 2.2-6 Open-Circuit Tunnel Flow Model

Table 2.2-2

80' x 120' Pressure Loss Summary
(Ref. 3)

PRESENT MODEL FLOW STATION (i)	$Kp_i = \Delta p_i / q_{TS}$			
	20	40	80	120
1	-	-	-	-
2	.03862	.03681	.03651	.03593
3	.01446	.01317	.01205	.01146
4	.04464	.04390	.04309	.04280
5	.16718	.16558	.16443	.16424
6	.31232	.30915	.30848	.31163
7	.28993	.28848	.28620	.28358
8	.21514	.21297	.21041	.20810
q_{TS}	1.36	5.41	21.52	48.0

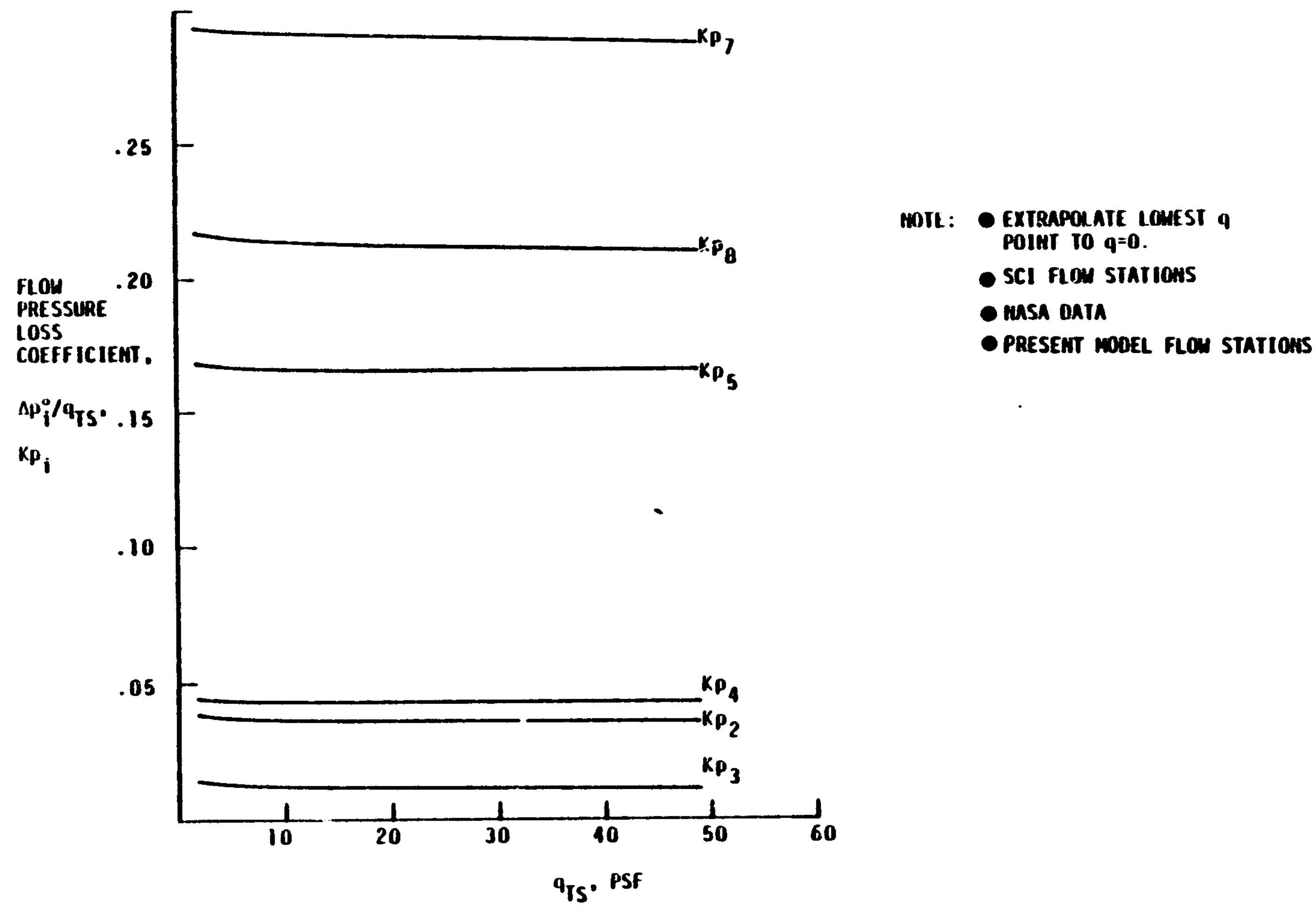


Figure 2.2-7 80' x 120' Flow Pressure Loss Coefficients (Ref. 3)

Flow parameters are computed from p°, T°, and $\dot{m}$ at each station as described for the closed-circuit tunnel.

2.3 FAN UNIT MODEL

This section describes the model of the tunnel drive fan unit, comprised of six 40-ft. diameter fans arranged as shown in Figure 2.3-1. The data represent the pressure-generating capability of the new, 15-blade fans, based on experimental NASA data from a 6-ft. diameter scale model (15% full-scale) fan. All six fans are treated as one unit, hence citation of conditions upstream and downstream of the fans refers to assumed uniform flow conditions prior to flow splitting and after re-mixing. Fan unit total head rise as a function of RPM and speed is tabulated in the math model, and fan aerodynamic torque is expressed as a function of blade stagger angle as suggested by additional experimental data. Fan reference dimensions are shown in Figure 2.3-2.

A functional model of the blade pitch actuation system, based on an electric motor driving through a gearbox, is presented. It contains nominal rate and position limits and provisions for various command and failure inputs.

2.3.1 Fan Aerodynamic Model

Basic NASA fan pressure rise data are shown in the curves of Figure A.1, Appendix A. These curves show total head rise across the fan at various blade angles (i.e. stagger angle) settings, at a constant model fan tip speed of 377 ft/sec (1200 RPM, model radius 3 ft.). The following operations were performed to convert these data to full scale (details of the steps are given in Table 2.3-1).

(1) Compute model inflow velocities, U and V, at a selected value of mass flow (100% model mass flow = 11.41 slugs/sec);

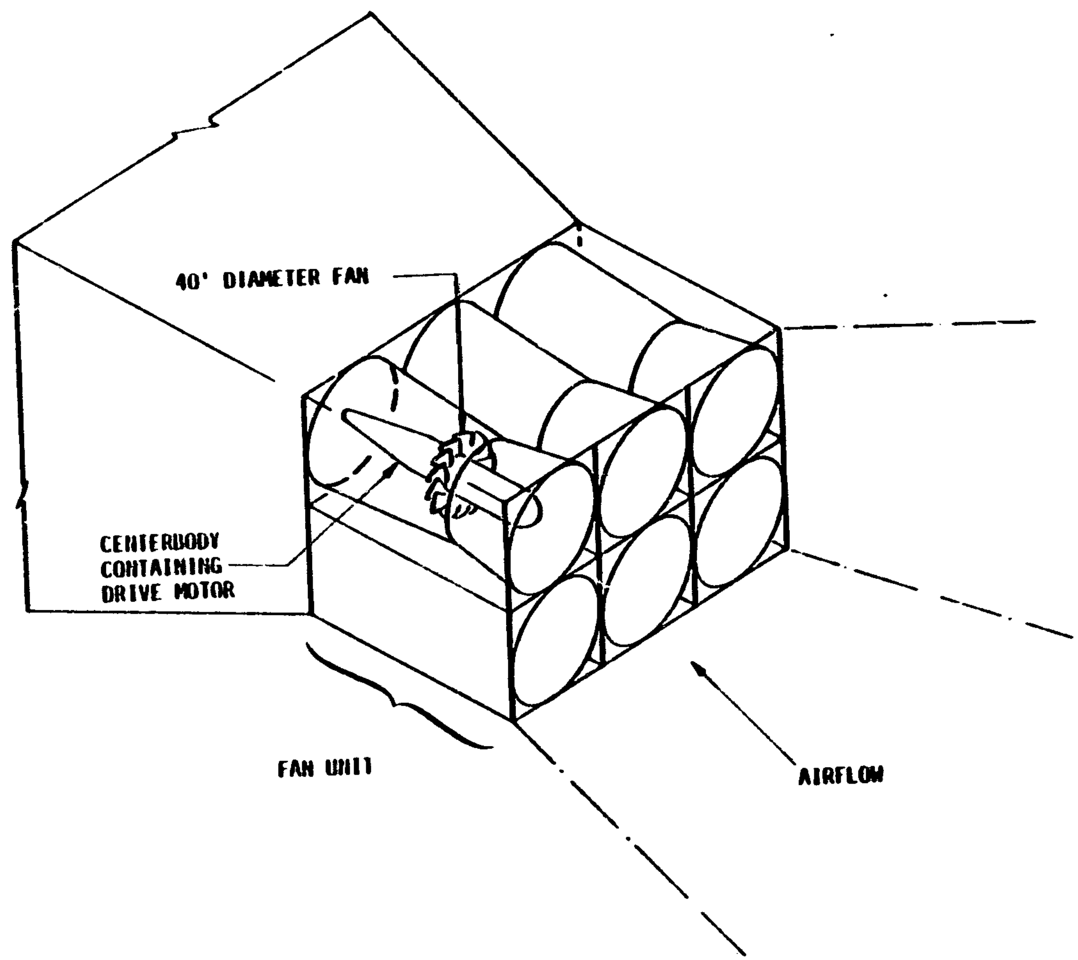
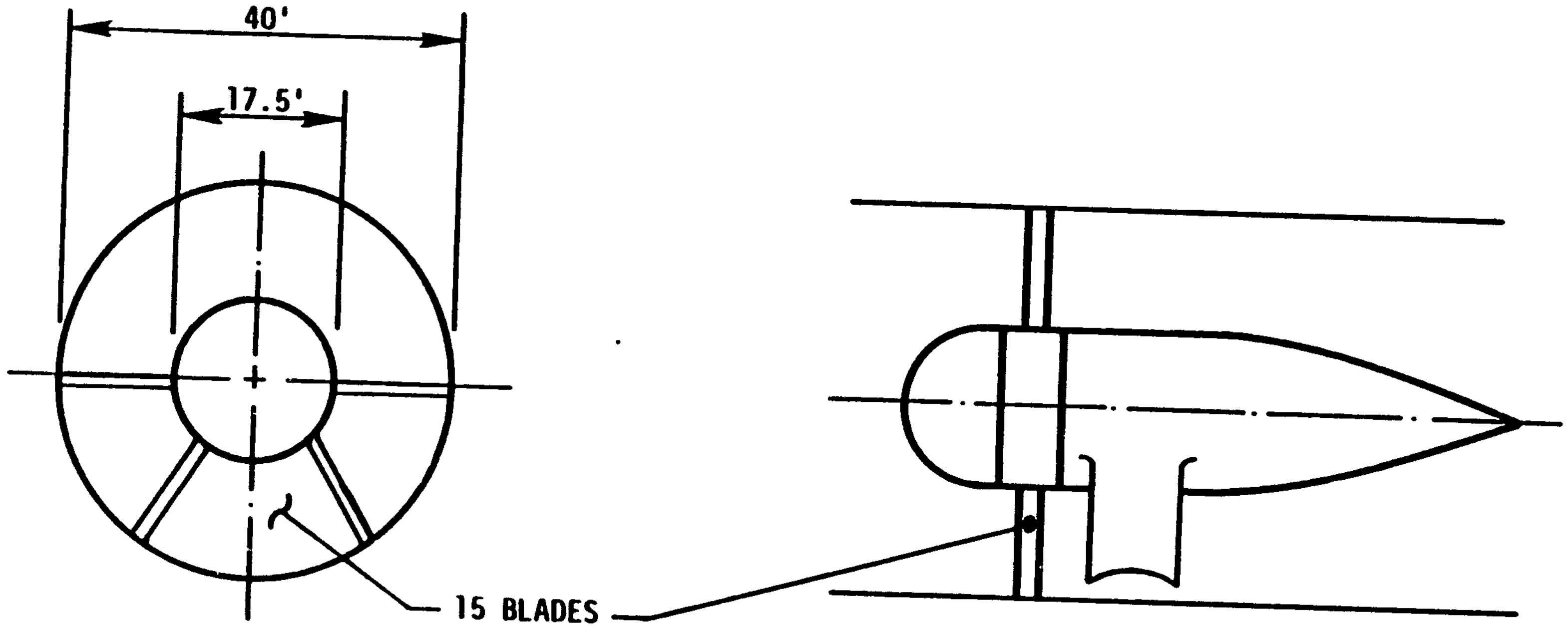


Figure 2.3-1 Fan Unit Schematic



NOTE: NOT TO SCALE. ACTUAL NACELLE FINENESS RATIO IS 7.9:1

Figure 2.3-2 One Main Drive Fan (of Six)

Table 2.3-1
Scale Model Pressure Data Conversion to Full Scale

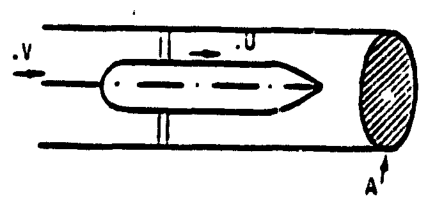
1. **Convert Model Data to Nondimensional K_{TS} Curves**

$\dot{m}_{model} = 11.41\ (\dot{m}_{model}(\%)/100)$

$V_{model} = \dot{m}_{model}/(\rho A_{model})$ $\rho = .002378\ s/ft^3$

$U_{model} = 1.237 \cdot V_{model}$ $A_{model} = 28.77\ ft^2$

$\Lambda_{model} = U_{model}/377$



$\Delta p_{FAN,\ model} = (\Delta p^{o}_{FAN}(\%)/100) \times 52\ lb/ft^2$

$K_{T_{V_{model}}} = \Delta p^{o}_{FAN,\ model}/(\tfrac{1}{2}\rho V^2_{model})$

2. **Generate New Fan Map for Full-Scale Fan**

$U_{FS} = \Lambda\Omega_{RPM}(2\pi/3)$

$V_{FS} = U_{FS}/1.237$

$q_{FS} = \tfrac{1}{2}\rho V^2_{FS}$

$\Delta p^{o}_{FAN,\ FS} = K_{T_V} \cdot q_{FS}$

$\dot{m}_{FS} = \rho A_{FS}\ V_{FS}$ $A_{FS} = 7539.82\ ft^2$

$(\dot{m}/\dot{m}_{REF})_{FS} = \dot{m}_{FS}/3098.41$

(2) Compute the model inflow ratio, $\Lambda_{model} = U/\Omega R = U/377$;

(3) Compute the model pressure rise coefficient,

$$K_{T_V} = \Delta p^{\circ}_{FAN}/\tfrac{1}{2}\rho V^2;$$

(4) At a selected full-scale RPM, set

$$\Lambda_{full\ scale} = \Lambda_{model}$$

(5) Compute full-scale pressure rise, Δp°_{FAN}

(6) Compute full-scale mass flow rate.

Repeating this procedure for the various blade-angle settings yields the set of full-scale fan pressure rise curves shown in Figures 2.3-3 to 2.3-7. Atmospheric conditions were assumed as standard and incompressible for the NASA data. Non-standard conditions are compensated by computing reference conditions (denoted by an asterisk) from actual flow properties:

$$\dot{m}^* = \dot{m}_{actual}\sqrt{\theta/\delta}$$

$$p^{\circ *}_{FAN} = p^{\circ}_{FAN_{actual}}\ \delta$$

$$RPM^* = RPM/\sqrt{\theta}$$

and entering the charts at the reference conditions. Here, $\theta = T_8/T_{8_{ref}}$ and $\delta = p_8/p_{8_{ref}}$, where the subscript (8) refers to conditions at closed circuit tunnel station 8, just upstream of the fans.

Areas in which pressure rise data are lacking are noted by dashed lines, and are conjectured to be as shown, by knowledge that the fan will "stall" or "surge" at inflow speeds lower than normal, resulting in a rapid loss of pressure rise, and that it will gradually "blow back" at speeds higher than nominal,

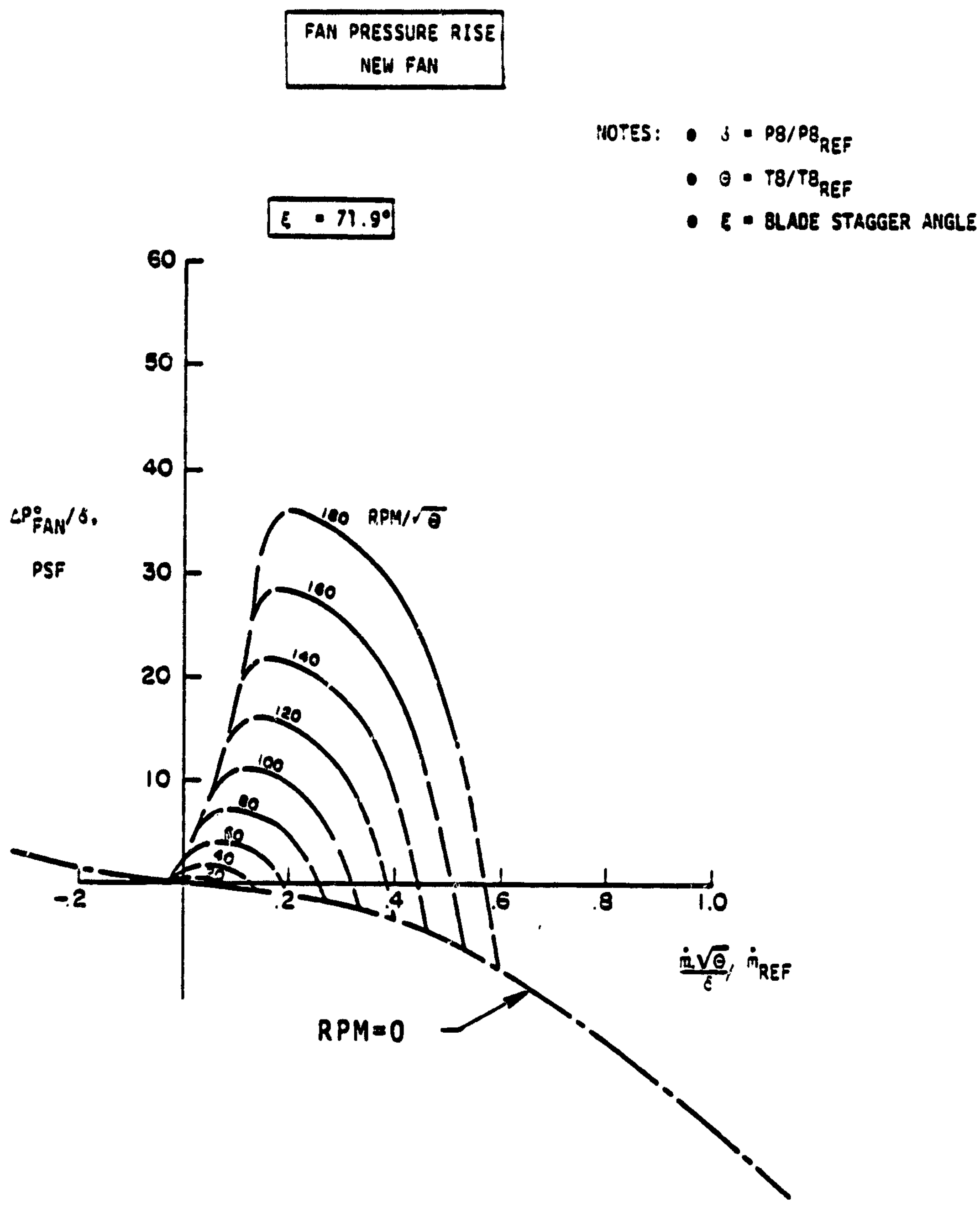


Figure 2.3-3 Fan Pressure Rise, $\xi = 71.9°$

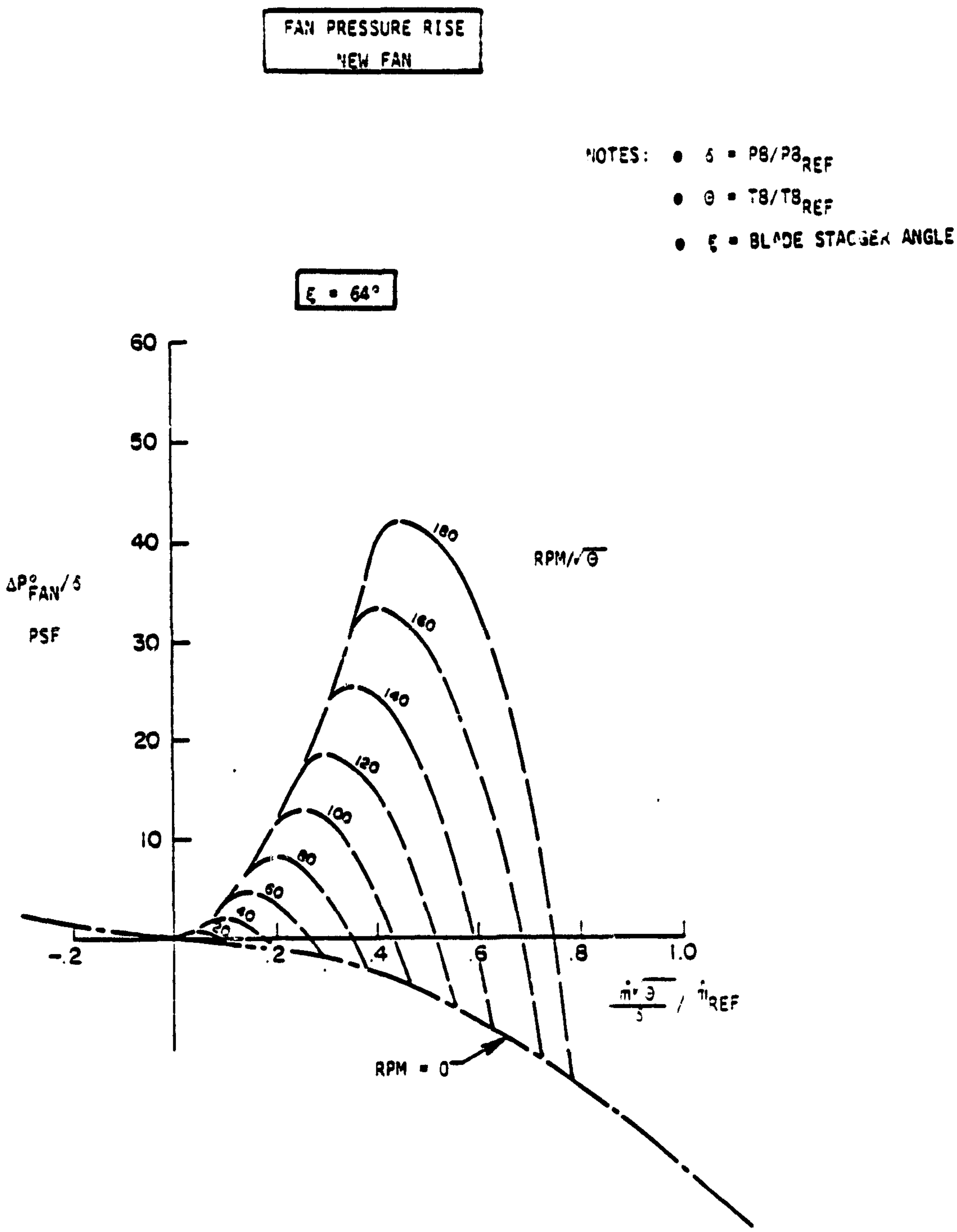


Figure 2.3-4 Fan Pressure Rise, ξ = 64°

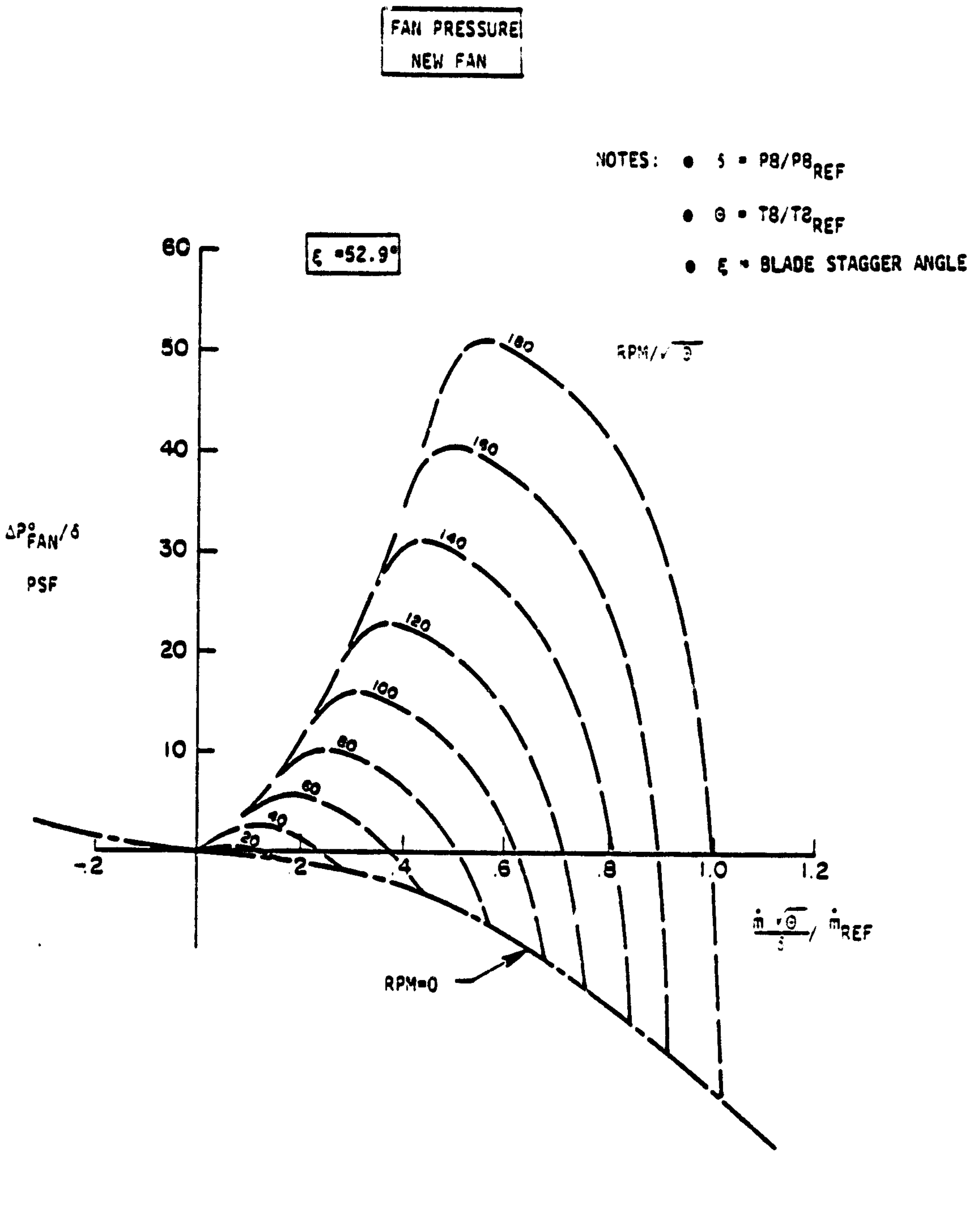


Figure 2.3-5 Fan Pressure Rise, ξ = 52.9°

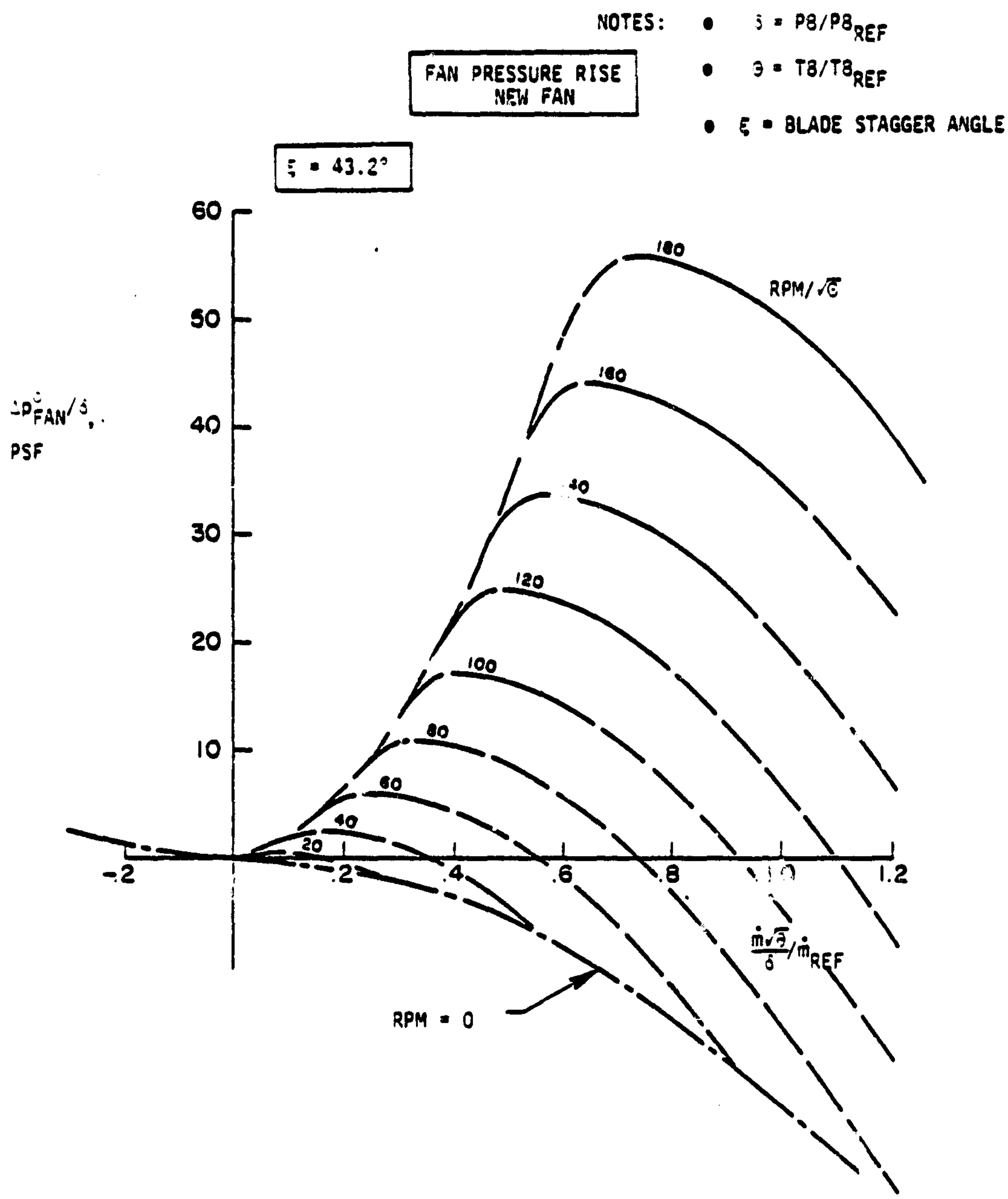


Figure 2.3-6 Fan Pressure Rise, ξ = 43.2°

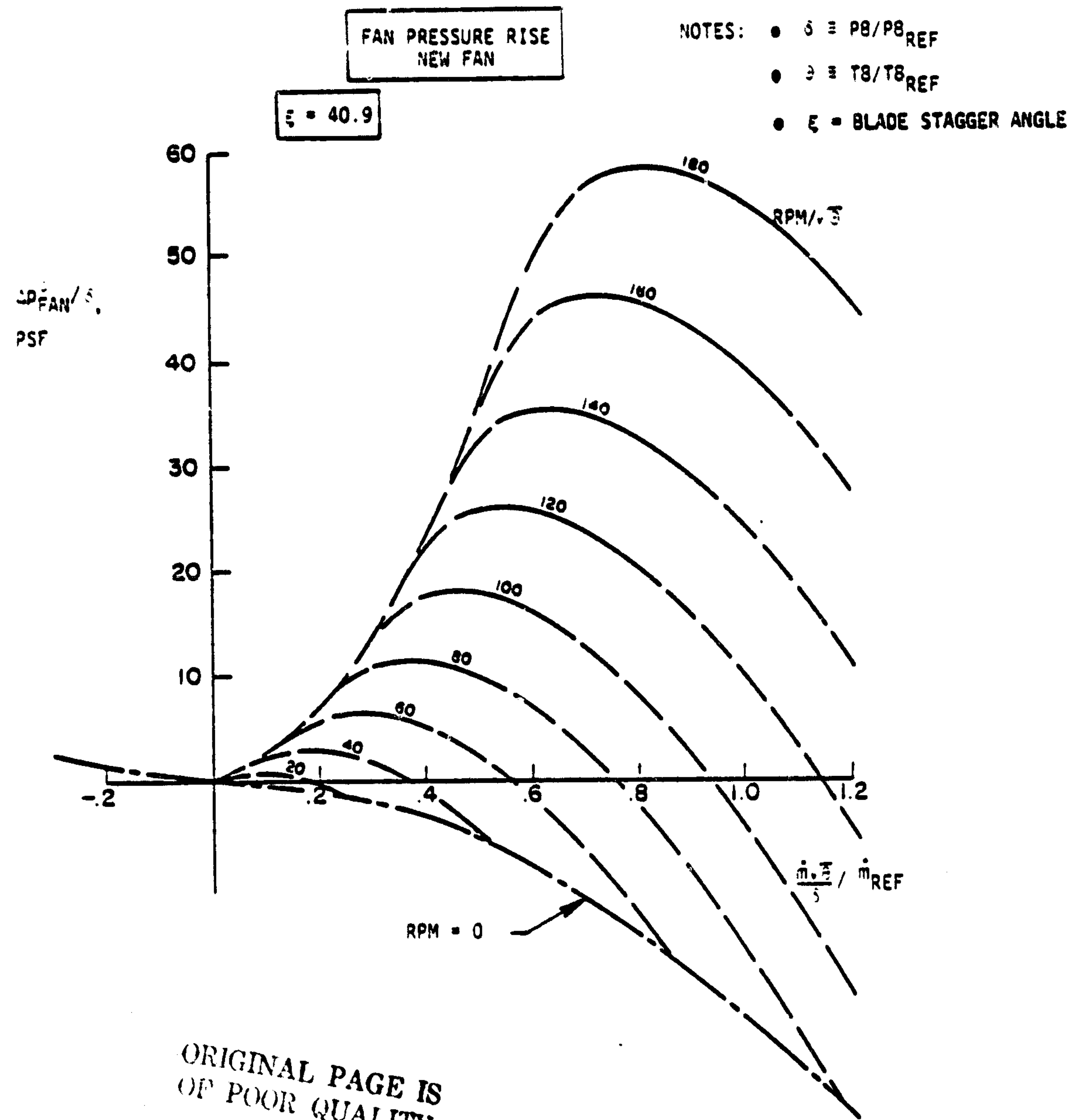


Figure 2.3-7 Fan Pressure Rise, ξ = 40.9°

resulting in a more gradual decrease of pressure rise with inflow speed. In this model, pressure values at $\zeta = 98°$ (the zero-pressure, zero-$\dot{m}$ stagger angle) are assumed to fall on the same curve as RPM = 0 data.

Fan torque data were obtained by NASA from a torque cell mounted on the 0.15-scale model fan. Using these data for torque at various blade angles and the corresponding nominal inflow speeds, and recognizing that torque essentially reflects blade profile drag, which varies quadratically with angle of attack, a parabolic curve was fit to torque coefficient data to show torque coefficient, C_Q, as a function only of stagger angle, ξ:

$$C_Q = .000022(\xi-98)^2 + .01$$

This functional, shown plotted in Figure 2.3-8, is used to compute aerodynamic torque. The assumption that this is valid over a range of inflow speeds is suggested by the data and is felt to be acceptable for present purposes. If further, improved data become available, they can be included in the simulation like the pressures. However, no useful speculation is possible about torque levels in the surge or blow-back regions, and the most likely current error of an offset in the steady-operation power level is acceptable in this study. NASA torque data are shown in Appendix A, Figure A.2.

2.3.2 Blade-Pitch Actuation System

The blade-pitch actuation system is a key controller whose characteristics affect overall system response, particularly if high-rate actuation is found necessary or desirable. The

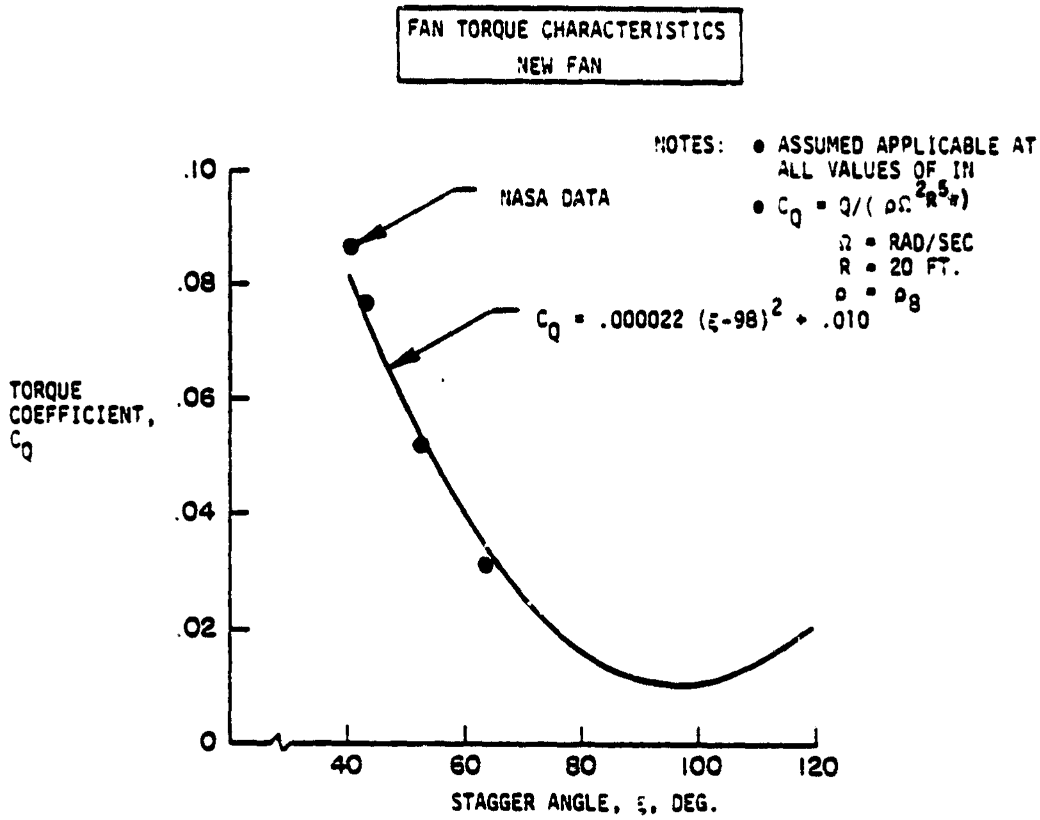


Figure 2.3-8 Fan Aerodynamic Torque Coefficient

model shown schematically in Figure 2.3-9 provides the following features:

(1) Command input switching between manual and automatic modes;

(2) Variable blade rate limits;

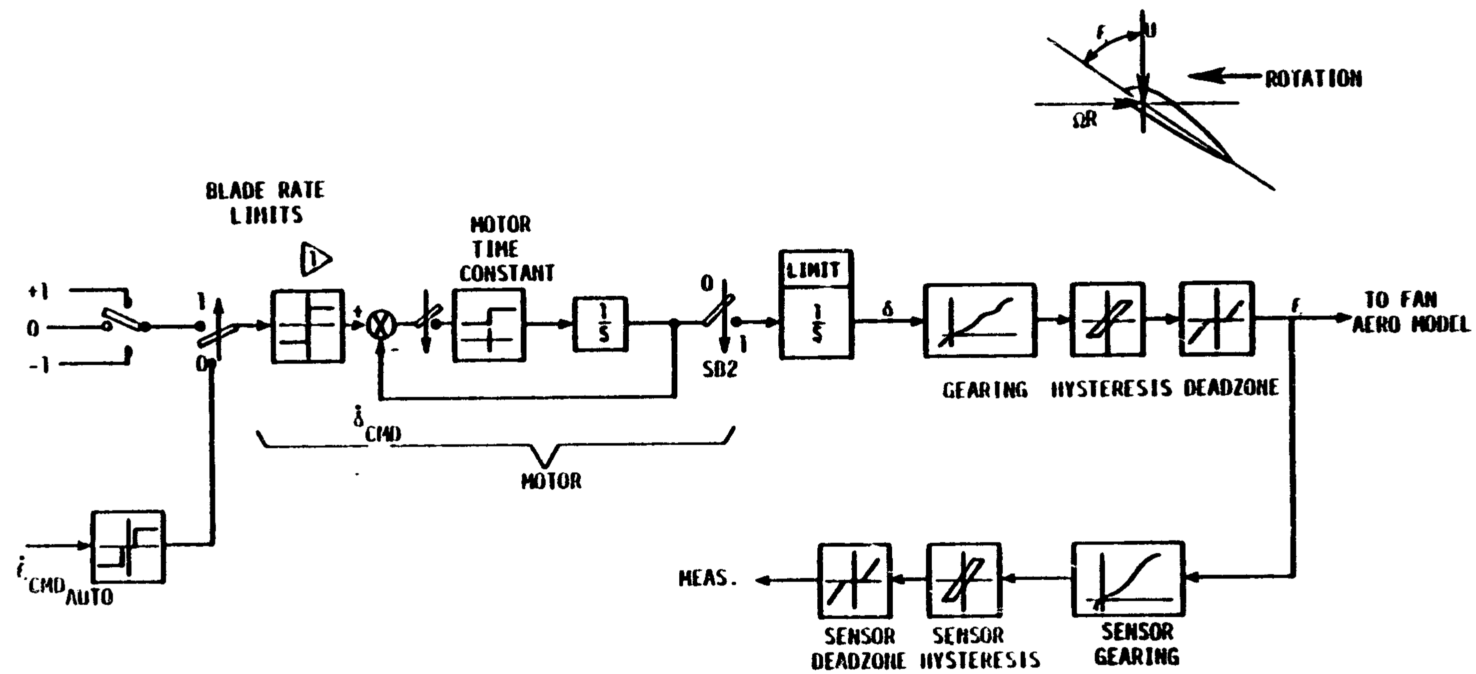
(3) Variable motor response time constants, including provision for different accelerate/decelerate time constants;

(4) Linkage (kinematic) nonlinearities, hysteresis, deadzone;

(5) Sensor gearing and nonlinearities;

(6) Failure switching to simulate runaway or other failure modes.

Nominal values of the parameters of the blade actuator model are defined in Figure 2.3-10.



SWITCHES

SB1 SB1=0 FOR AUTOMATIC OPERATION, =1 FOR MANUAL OPERATION
SB2 NORMALLY CLOSED (SB2=1); OPENS FOR ACTUATOR FAILURE
SB3 CLOSED FOR NORMAL OPERATION; OPENS IF LIMITER 1 IS REACHED AND $\dot{\delta}_{CMD}$ IS OF SAME SIGN.

NOTES

1. LIMITS SHOWN FIXED. MAY BE MADE VARIABLE FOR ADVANCED SYSTEMS.

Figure 2.3-9 Blade Pitch Actuation System Model

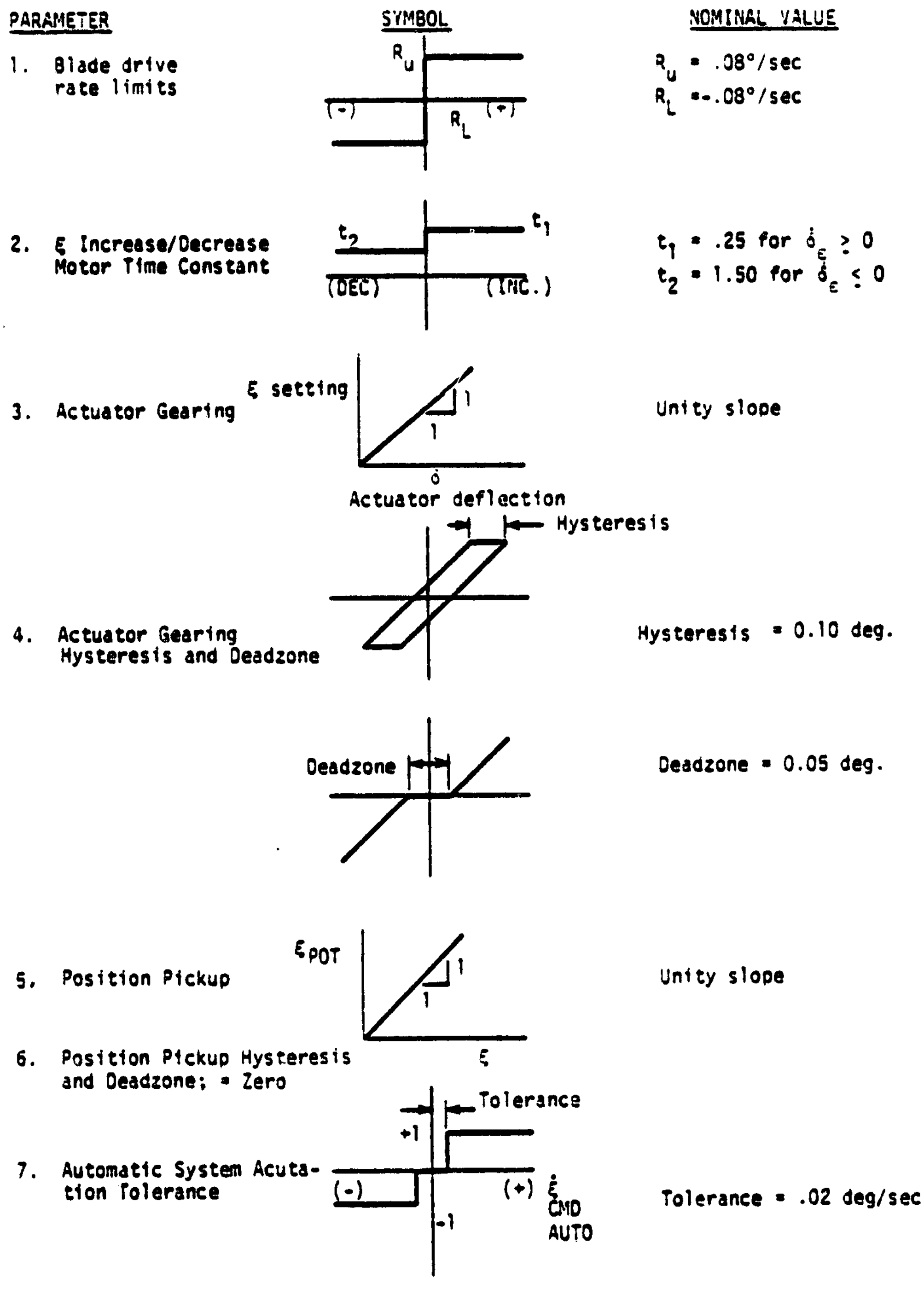


Figure 2.3-10 Blade Actuator Model: Nominal Parameter Values

2.4 MOTOR-GENERATOR SYSTEM MODEL

2.4.1 Overview and System Description

This section describes the model developed to simulate the principal functional characteristics of the multi-element wind tunnel motor-generator drive system. The objective is a model that will predict, with reasonable accuracy, the generation of power by the main drive motors and their significant dynamic characteristics, as well as the behavior of voltages and currents in the other AC and DC machines in the system, since changes in fan RPM in the IFC operating regime disturb all elements of the system. In the line power regime the system is considerably simpler, being that of a synchronous motor tied to an assumed infinite bus.

Many assumptions were required pertaining to DC machine time constants, machine inertias, IFC torque/slip characteristics, and synchronous machine damping constants (amortisseur winding effect) because these machines either do not yet exist or have been long installed without the data required in this study ever having been taken, since the performance requirements imposed on the original system were for steady-state operation. Constants, where otherwise unavailable, were estimated from comparison to similar machines.

The machines comprising the motor-generator system are shown in Figure 2.4-1. As noted above, for high speed tunnel operation the synchronous drive motors are switched directly to the utility line, at 60 Hz, and rotate at 180 RPM. For lower speed operation (for $q < 50$ psf, approximately), the variable-frequency system is engaged and fan RPM may be varied from approximately 18 to 179.5 RPM. This RPM adjustment, combined with blade pitch control, is used to regulate tunnel q. Details of motor operation are given in Ref. 5.

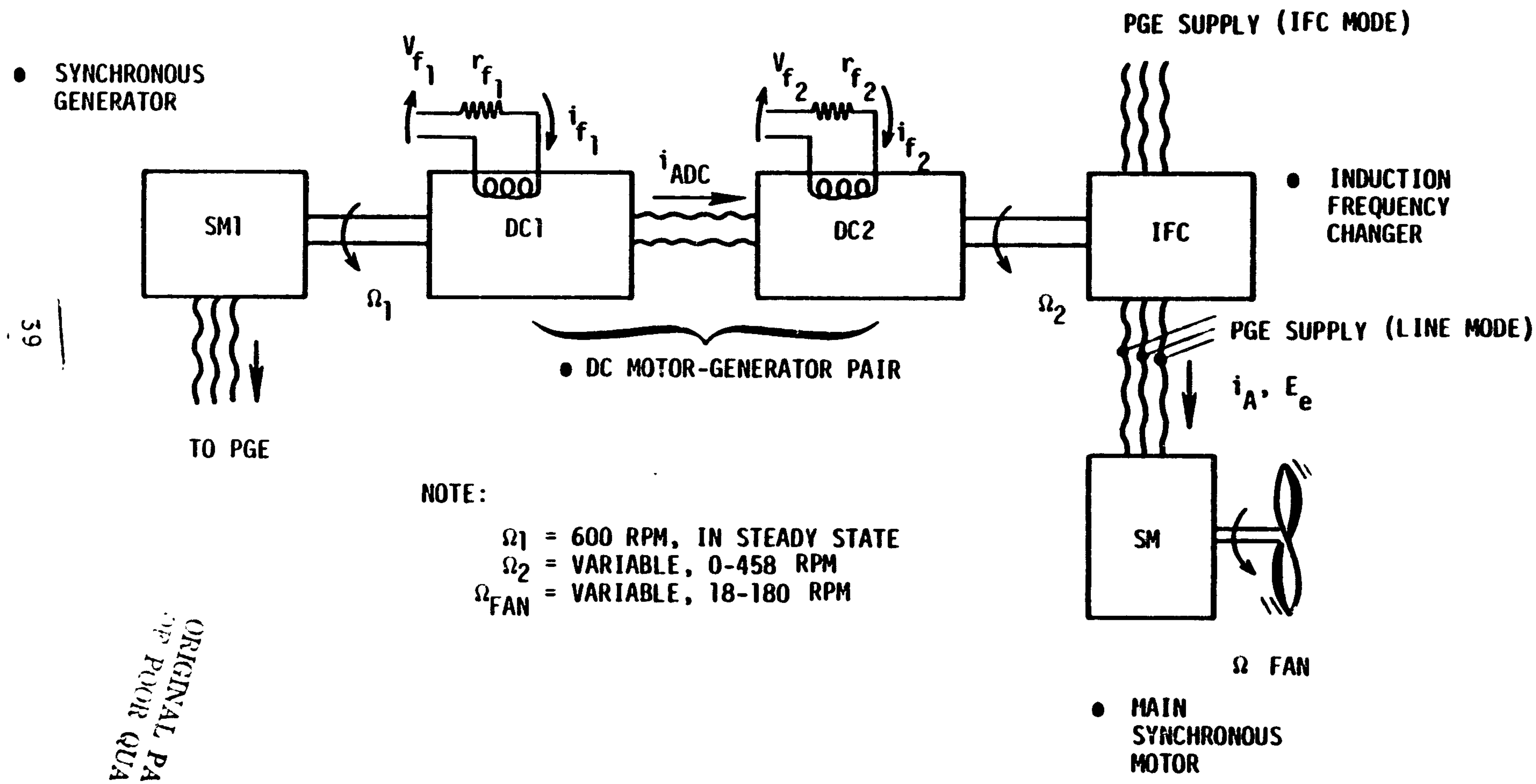


Figure 2.4-1 Motor-Generator System Schematic

The change to line power is required by a 28,000 HP total power limit on the IFC, which actually reflects an electrical current limit.

In the following sections the elements of the system shown in Figure 2.4-1 are discussed in detail, and the models used to represent the functional characteristics of the machines are described. It was assumed at the outset:

(1) not to attempt to simulate "fast" electrical transients that would require an integration step time on the order of a millisecond; the electrical characteristics of the machines are not considered as important to the purposes of this study as shaft rotation dynamics arising from gross changes in mechanical or electrical variables, as these alter fan RPM and couple with tunnel q; and

(2) not to simulate the switching process from IFC to line power mode or back as this is determined from the design of the machines and outside the scope of the q control system; the control system function ends (for the more sophisticated systems) at commanding the initiation of transition when required.

It should be noted with respect to the modeling of all the rotating machine elements, that the models contain no simplification due to linearization requirements and, therefore, reflect all of the nonlinear effects implied in the governing equations. Such effects include magnetic saturation, products of independent variables such as voltage and current, and the significant nonlinearities due to changes in RPM of the various machines. The model described here is thus more general than a linear model comprised of transfer functions. Such a linear model, useful for certain theoretical analyses, may be derived from the nonlinear simulation. In this analysis. the behavior os the nonlinear system was studied directly by inputting specific control commands and other disturbances at various operating conditions and observing the nature of the output time history, and the q control system, discussed in Section IV, was also developed for and using the nonlinear model.

The new motor-generator system might be referred to as a "modified Modified Krämer." The modified Krämer system (described in Ref. 6) is a speed control system for an induction motor, currently in use in the 40' x 80' drive system, which employs induction main drive motors. In both the old and new systems, the RPM of the main drive fan is regulated by controlling the RPM of a synchronous machine coupled to it electrically; in the old system, this is a synchronous motor, while in the new system it is an induction frequency changer, the substitution required by the switch from induction to synchronous motors for the main drive fans. Where main fan RPM was controlled by varying induction motor slip in the old system, it is controlled by varying synchronous motor drive frequency in the new system. Excess power generated by the speed regulating system is fed back to line through a constant speed synchronous generator, at 60 Hz. More detailed descriptions of the operation of the old systems are given in Ref. 7.

In the new system, fan RPM is varied by changing Ω_2, the RPM of the IFC, which changes the frequency to which the main drive motor synchronizes. Ω_2 is, in turn, varied by changing field current i_{f_2}, as in the old system. It is found, in inspecting DC machine characteristics, that i_{f_1} may also be used for RPM control, and is in fact required to vary when Ω_2 becomes low during operation at high fan RPM. This observation is in agreement with the function of the rheostat now used to control fan RPM, which includes a nonlinear, simultaneous variation of i_{f_2} and i_{f_1} at high fan RPM.

In the line power mode, this system is switched out, and the drive motor becomes quite simply a synchronous motor operating at 60 Hz line frequency, drawing current as required to meet power requirements imposed by fan aerodynamic torque.

2.4.2 Synchronous Motor

While the operation of synchronous machines is relatively simple in principle, full analysis requires the solution of four voltage equations involving currents and current rates in the motor phases and 16 mutual and self-inductance parameters, many of which vary with rotor position relative to the armature windings (Ref. 8). Since a model was desired that:

(1) does not require full solution of electrical transients; and

(2) embodies physical parameters in an easily understandable form (to ease checkout and modification),

the well-known Park-transformed equations were used. These transformations reduce many inductance constants to a few experimentally determinable reactances and polyphase voltages and currents to voltages and current in two new, normal axes, called direct and quadrature. The reactances are referred to the new axes. The resulting equation for motor power is then, for the transient conditions.

$$P_e = \frac{E_q' E_e}{x_d'} \text{ Sin } \delta + E^2 \frac{X_d' X_q}{2X_d' X_q} \text{ Sin } 2\delta \qquad (2.4\text{-}1)$$

where E_q' is transformed excitation voltage, E_e is line voltage, and X_d and X_q are direct and quadrature axis reactances.

The power angle, δ, has a simple physical interpretation in terms of load torque and applied power, and provides a convenient point for the introduction of variable-frequency input power. It represents the angular separation (in electrical degrees) between the resultant air-gap flux and the rotor field flux, as shown in Figure 2.4-2a. Thus, in a synchronous motor an increase in load torque is compensated by an increase in δ and a new equilibrium condition is reached at a higher value of power, P_e. The dynamics of electrical power transfer to the motor shaft may thus be examined through the variations in δ, excitation E_q', and line voltage E_e.

In particular, the relation of δ to torque $(Q_e = P_e/\Omega_{FAN})$ provides a convenient means of altering synchronous motor RPM. For a synchronous motor, shaft RPM at a given line frequency, ω, depends on the number of poles, n_p:

$$\Omega = \omega/(n_p/z)$$

which means that the shaft is in synchronism with an effective line frequency ω_e:

$$\omega_e = \omega/(n_p/z)$$

Now ω_e represents the effective mmf or driving flux wave frequency. The rotor rotation rate is identical to this in steady state, but the rotor lags the armature flux wave by the torque angle, δ, set by the magnitude of the applied load, in this case principally aerodynamic torque. This situation is illustrated in Figure 2.4-2b. If ω_e is increased, the ω_e vector in Figure 2.4-2b will accelerate, δ will increase, and Ω will eventually increase. We have for δ, the differential equation:

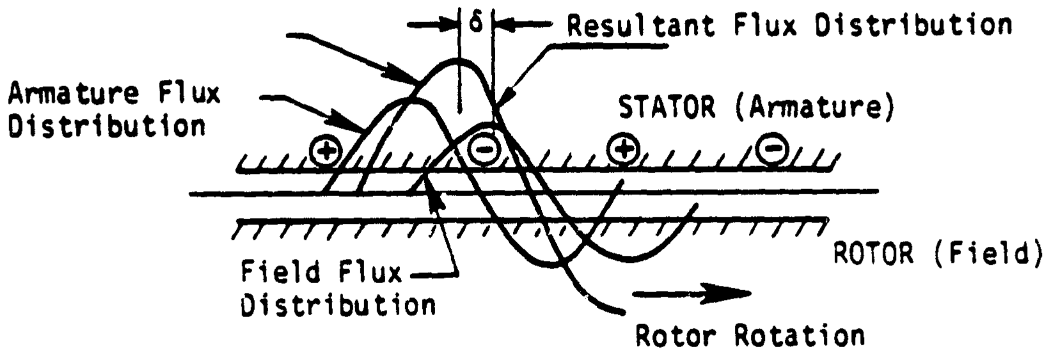


Figure 2.4-2a Motor Air-Gap Flux and Field Flux Orientation

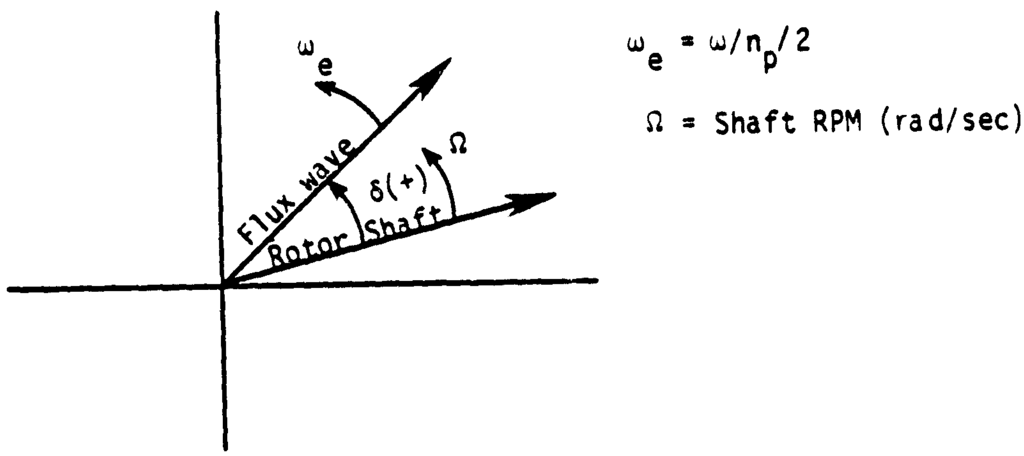


Figure 2.4-2b Line Voltage and Rotor Relation in Phase

$$\dot{\delta} = \frac{n_p}{2} (\omega_e - \Omega)$$

so

$$\delta = \int_t \dot{\delta} dt \ .$$

Similarly, an increase in aerodynamic torque reduces Ω, and if ω_e is held constant, δ will increase so that after a transient oscillation Ω will be the same, but more power will be consumed. Simultaneous changes in ω_e and Ω are thus treatable in the general case.

Care must be taken to adjust the values of E_q and X for changes from the 60 Hz synchronous frequency for which they are commonly derived:

$$E_q' = E_q' \cdot \frac{\omega}{60}$$

$$X = X_{ref} \cdot \frac{\omega}{60}$$

A consequence of this is that significant changes in machine properties may occur during large RPM changes.

The voltage and current equations for a synchronous machine are well discussed in the literature, and the equations used here will only be listed. The basic equations derive from the vector diagram shown in Figure 2.4-3, the consequence of the basic voltage and current laws. For a salient-pole machine:

Direct-axis voltage	$V_d = -E_e \sin \delta$
Quadrature-axis voltage	$V_q = E_e \cos \delta$
Direct-axis current	$I_d = [V_q + r_a V_d/(X_q' \cdot K) - E_q']/(X_d' \cdot K)$
Quadrature-axis current	$I_q = -V_d/(X_q' \cdot K)$
	$K = \omega/60$ (2.4-2)
	ω = line frequency, Hz

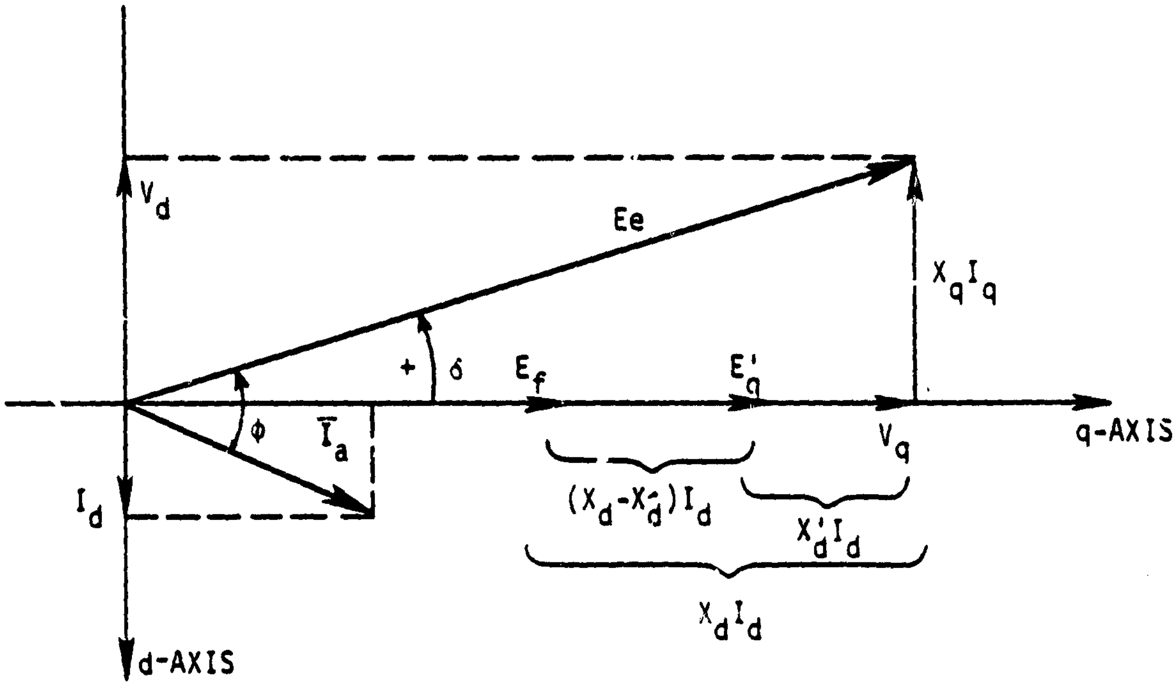


Figure 2.4-3 Synchronous Motor Voltage and Current Diagram

Total current (machine)	$I = (I_d^2+I_q^2)^{1/2}$	
Power factor angle	$\phi = \tan^{-1}(I_d/I_q)$	(2.4-2 Cont.)
Power factor	$PF = \cos\phi$	
Torque (machine)	$Q = P_e/\Omega$ (Ω in rad/sec)	
	Ω = fan rotational rate, RPM or rad/sec	
Excitation	$E_q' = E_{ex}$ (in steady state)	

A table of the characteristics of the two synchronous machines in this system - the drive motor and the constant-speed synchronous motor, is given in Table 2.4-1. The equations are evaluated using per-unit parameters, then re-dimensionalized for dynamics calculations.

Table 2.4-1

Synchronous Motor Characteristics

Motor Constants (Per Unit)	
X_d	= 1.019
X_d'	= 0.334
X_d''	= 0.346
X_ℓ	= 0.295
X_o	= 0.243
T_{d_o}'	= 3.86 Sec.
X_q	= 0.55
X_q'	= 0.65

INERTIA J = 157,600 slug-ft^2 (<u>including</u> fan)

PER UNIT REFERENCES:	
E_{REF}	= 6600 V
P_{REF}	= 9.9 x 10^6 ft-lb/sec
	= 18,000 HP
	= 13.43 MW

Machine dynamics are computed from the following equations:

$$\dot{\Omega} = [(Q_{e_{DIM}} - Q_{AERO}) - Q_{e_{DAMP}} \dot{\delta}]/J_{FAN + MOTOR}$$

$$\dot{E}_q' = \frac{1}{T_{d_o}'} [E_{ex} - E_q']$$

where $Q_{e_{DIM}}$ emphasizes that the equation is in physical units. The value of $Q_{e_{DAMP}}$ was selected arbitrarily to provide net positive damping in the motor. All electrical transients except $\dot{E}_q'$ were neglected in this machine; the field time constant T_{d_o}' may be large, however; the value used here was 3.86 seconds.

As noted above, the transient-condition reactances, denoted by primes, were used in these equations. Under steady-state conditions the values of some of these parameters change significantly. However, Eq. 2.4-1 shows that changes in the reactances merely change the steady-state power angle, δ, so the transient reactances, which give a slightly "stiffer" machine, were used here as constants. The next degree of sophistication in motor modeling might be to make these parameters functions of the applied disturbance, perhaps of $|\delta|$.

Initialization of the simulation requires the solution of Eqs. 2.4-2 for δ and ϕ given initial operating conditions. A block diagram of the synchronous drive motor model is shown in Figure 2.4-4.

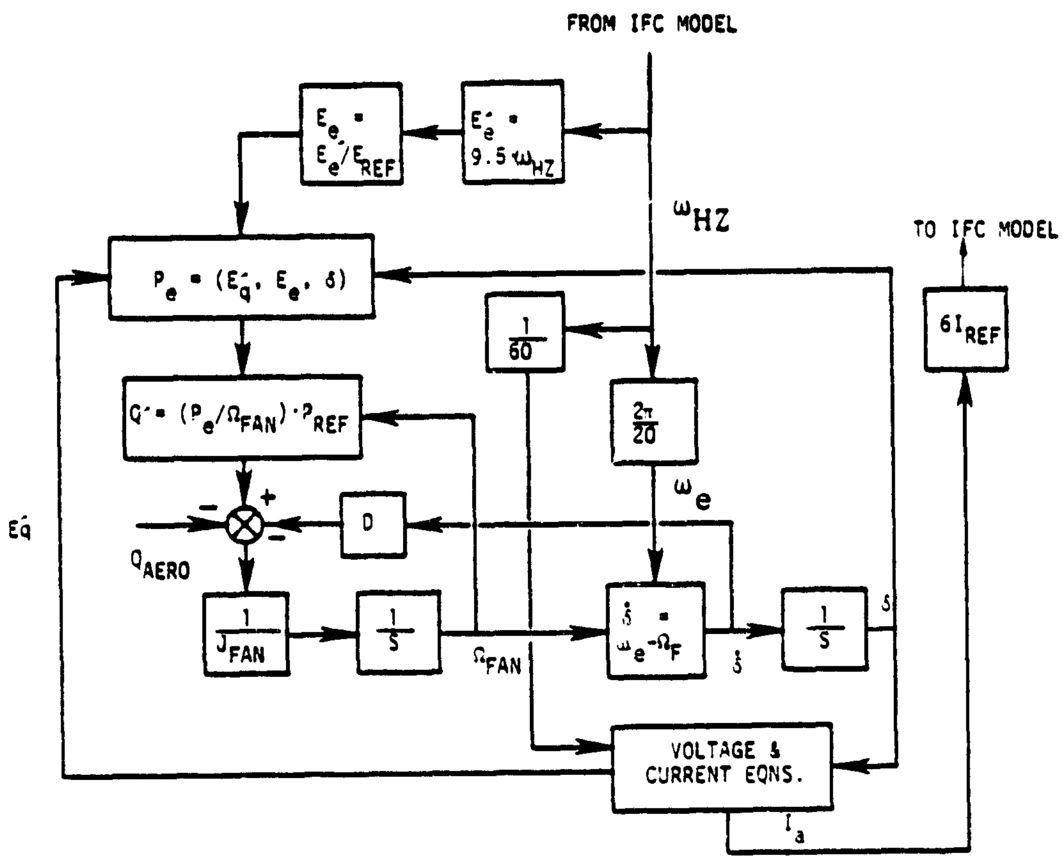
The equations of the constant-speed synchronous motor are identical to Eqs. 2.4-2, except that $\omega = 60$ Hz (constant) and, for simplicity, $\dot{E}'_{q_1} \equiv 0$. A block diagram of this motor model is shown in Figure 2.4-5.

2.4.3 Induction Frequency Changer (IFC)

The induction frequency changer (IFC) provides variable-frequency power to the synchronous drive motors, controlling motor RPM in the low-power mode of operation. Physically, the machine is a rewound synchronous motor receiving 3-phase, 60-Hz power to the armature and delivering 3-phase power from the rotor at a frequency determined by the rotation rate of the rotor (Ω_2 in Figure 2.4-1). While the electrical characteristics internal to this machine are very complex, only certain gross physical parameters are needed for the purposes of this study. This study requires:

(1) the frequency and voltage of the IFC output, which is identical to synchronous drive motor input;

(2) the torque exerted by the machine on the shaft connecting it to the DC machine, DC2 in Figure 2.4-1; and



NOTE: D REPRESENTS ELECTRICAL DAMPING

Figure 2.4-4 Model of Main Synchronous Drive Motor

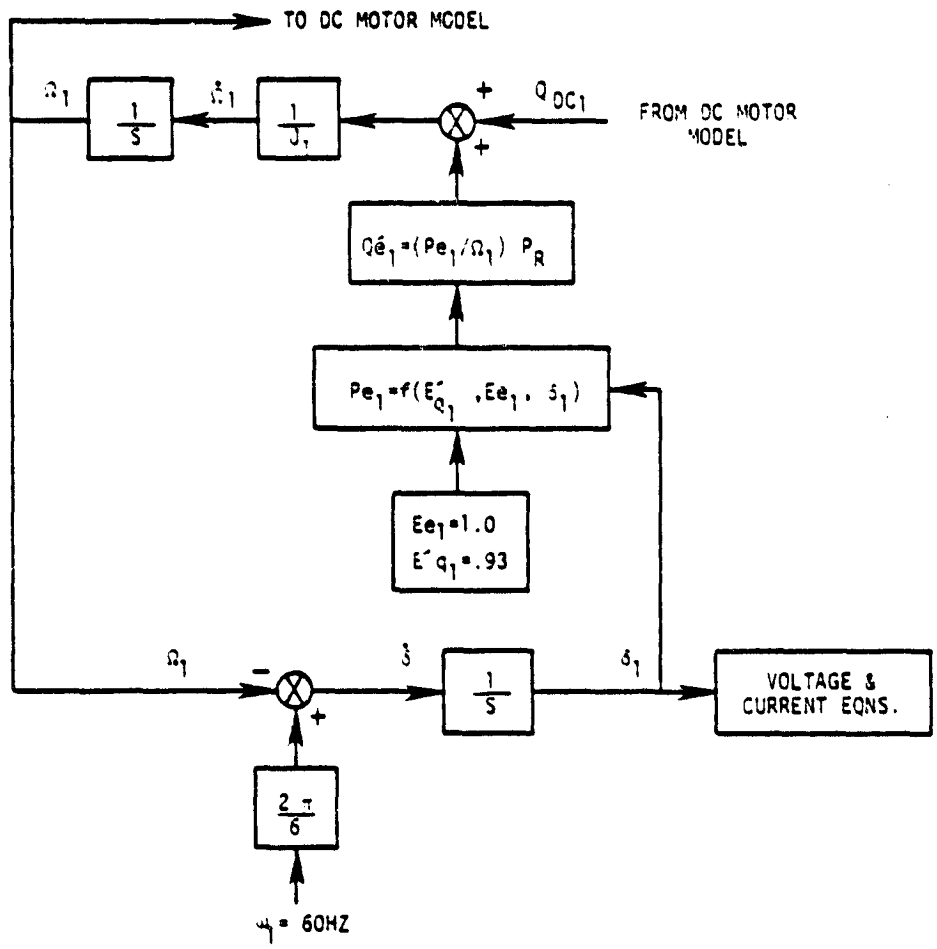


Figure 2.4-5 Model of Constant-Speed Synchronous Motor

(3) the approximate value of machine inertia, J_2.

Maximum power output from the IFC is obtained at the greatest frequency difference between the 60 Hz line input power and the induced frequency due to slight rotation rate, Ω_2. This is expressed by the parameter "slip," σ :

$$\sigma = 1 - \omega_{eff}/60 = 1 - S$$

where ω_{eff} is the frequency generated by the rotation of the IFC and is given by:

$$\omega_{eff} = \Omega_2 \text{ (rev/sec)} \cdot n_p/2 = 7\Omega_2 \text{ (rev/sec)}$$

The frequency of the power reaching the fan motors is:

$$\omega_{Hz} = 60 - \omega_{eff} = 60 - 7\Omega_2 \ (\Omega_2 \text{ in rev/sec})$$

which is transformed to the "effective" line frequency, ω_e, as mentioned above:

$$\omega_e = \omega_{Hz}/n_p/2$$

For example, when $\Omega_2 = 462.6$ RPM,

$$\omega_{eff} = 53.97 \text{ Hz}$$

$$\omega_{Hz} = 6.0 \text{ Hz}$$

and $$\Omega_{FAN} = \omega_{Hz} \cdot 60\ n_p/2 = 18 \text{ RPM}$$

Maximum voltage output of the IFC is 5700, and it varies with frequency ω_e in approximately the ratio 5700/60; hence at any frequency,

$$E_e = \frac{5700}{60}\ \omega_e = 95\ \omega_e.$$

The ratio 5700/60, known as E/f, does vary with RPM, particularly at the lower values of RPM, but the nature of this variation is not yet known and the ratio has been assumed constant for purposes of this study.

The last requirement is to determine the shaft torque produced by the IFC. Relying on DC machine current limits it can be hypothesized that IFC shaft varies as

$$Q_{IFC} = K\ I_a\ E_e$$

where I_a is the armature current drawn by all 6 main synchronous motors and K is an arbitrary constant. Thus, it is assumed that greater IFC torque results from increased voltage (decreased Ω_2) or from increased main motor power at a fixed RPM (seen as an increase in current, I_a), or both. The dynamic system is completed in this way; K is assumed constant. In the actual machine, when true IFC torque behavior is determined, a functional representation of Q_{IFC} can easily be substituted for the above equation in the math model, nonlinearity imposing no restrictions. In the analysis of this study,

$$Q_{IFC} = 30 \cdot I_{a_{TOT}} \cdot (1-\sigma)$$

where $KE_e = K\ E_{e_{ref}}(1-\sigma) \equiv 30(1-\sigma)$, $E_{e_{ref}} = 5700$. It is important to note, as will be discussed below, that IFC torque has a small effect on system dynamics but a large effect on DC loop currents, due to the need to balance torque between the IFC and the DC generator (DC2) and the dependence of DC machine torque on DC loop (armature) current. Thus, a correct understanding of IFC torque is essential to the accurate prediction of internal motor-generator system variables.

The math model of the IFC is shown in Figure 2.4.6. IFC characteristics used in this study are given in Table 2.4-2.

2.4.4 Direct Current Machines

The DC motor-generator loop in the existing and planned systems is similar to the well-known Ward-Leonard system for regulating RPM.

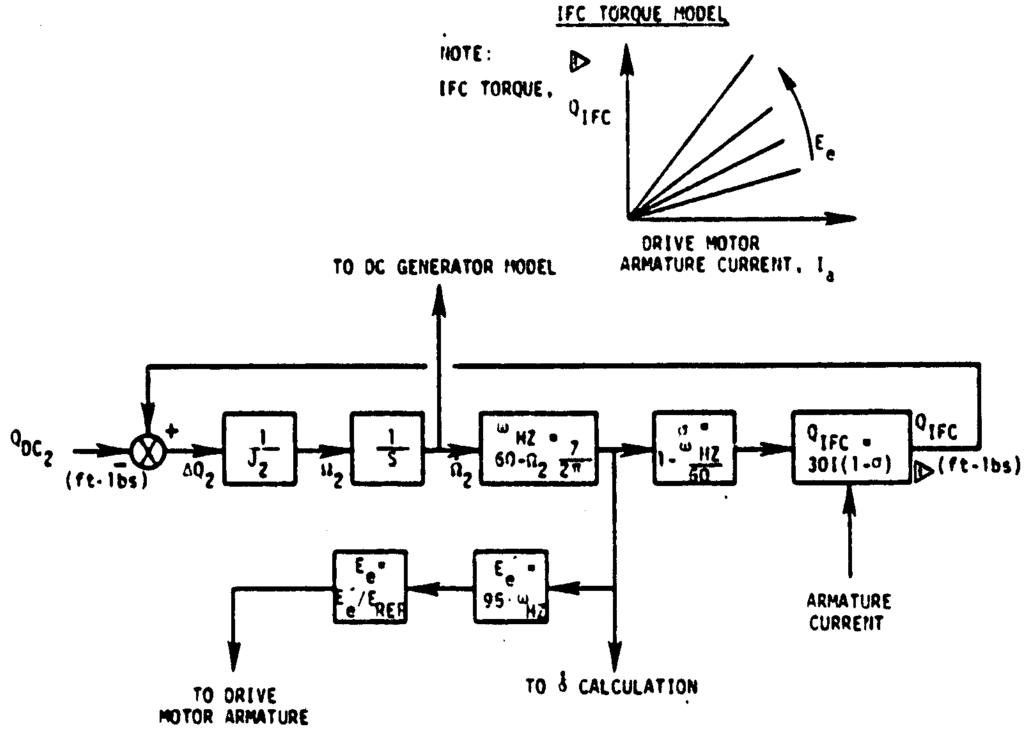


Figure 2.4-6 Model of IFC Voltage and Frequency Output and Torque Production

Table 2.4-2
Assumed IFC Machine Characteristics

Voltage Output	$E_e = (5700/60)\ \omega_{Hz}$
Output Frequency	$\omega_{Hz} = 60 - \Omega_{2_{RPM}} \cdot 7/60$
Inertia	$J = 93200$ slug-ft^2
Torque	$Q_{IFC} = 30\ I_a\ (1 - \sigma)$ I_a = Total drive motor armature currents

The system operates as follows: DC1, a generator, is driven at constant RPM Ω_1 by synchronous motor SM1. A change in the field current of this device, affected by changing field resistance r_{f_1}, causes a proportional change in the output armature current, $i_{a_{DC}}$, at voltage e_{a_1}. This armature current is transmitted to the motor where, with a similarly adjustable motor field current i_{f_2}, torque is produced. The equations governing this system are as follows:

Machine <u>DC1</u> Field current:

$$\frac{d}{dt}(i_{f_1}) = -\frac{r_{f_1}}{L_{ff_1}} i_{f_1} + \frac{v_{f_1}}{L_{ff_1}}$$

Armature voltage: $e_{a_1} = K_1^*(i_{f_1})\,\Omega_1$

where K_1^* is found from saturation curve data, discussed below.

Machine <u>DC2</u> Field current:

$$\frac{d}{dt}(i_{f_2}) = \frac{r_{f_2}}{L_{ff_2}} i_{f_2} + \frac{v_{f_2}}{L_{ff_2}}$$

Armature voltage: $e_{a_2} = K_2^*(i_{f_2})\,\Omega_2$ (also known as "back emf")

The armature current is found from

$$\frac{d}{dt}(i_{a_{DC}}) = \frac{1}{(L_{aq_1}+L_{aq_2})}\,[2(e_{a_2}-e_{a_1})-i_a(r_{a_1}+r_{a_2})].$$

where the factor of 2 multiplying $(e_{a_2}-e_{a_1})$ recognizes the fact that the present system actually consists of a pair of motors and a pair of generators, connected in a series. Having determined $i_{a_{DC}}$ by integrating the above differential equations from $t = 0$

(in initial trim) to t_1, the instantaneous values of torque at time t_1 are found from

$$Q_{DC1} = K_1{*}(i_{f_1})\ i_{a_{DC}} = 2e_{a_1}\ i_{a_{DC}}/(.737\ \Omega_1)\ \text{(ft-lb)}$$

$$Q_{DC2} = K_2{*}(i_{f_2})\ i_{a_{DC}} = 2e_{a_2}\ i_{a_{DC}}/(.737\ \Omega_2)\ \text{(ft-lb)}$$

Saturation data are based on 40' x 80' acceptance test data (Ref. 9) taken under open terminal conditions at a fixed RPM. The voltages are converted to other RPMs by ratioing. Hence, by defining

$$K_1{*}(i_{f_1}) = \frac{e_{a_1}(\Omega = 600\ \text{RPM})}{600}$$

we may write, for a given i_{f_1},

$$e_{a_1} = e_{a_1}\Big|_{\Omega = 600} \cdot \frac{\Omega_1\,(\text{RPM})}{600} \quad K_1{*}(i_{f_1})\,\Omega_1\,(\text{RPM}).$$

Similarly for e_{a_2}. Saturation data for machines DC1 and DC2 are shown in Table 2.4-3.

Machine dynamics are evaluated using torque values for the DC machines and the machines they are mechanically coupled to: DC1 to the constant-speed synchronous motor and DC2 to the IFC. Hence,

$$\dot{\Omega}_1 = \frac{1}{J_1}\ [Q_{e_1} - Q_{DC1}]\ (\text{rad/sec}^2)$$

$$\dot{\Omega}_2 = \frac{1}{J_2}\ [Q_{DC2} - Q_{IFC}]\ (\text{rad/sec}^2)$$

Table 2.4-3
DC Machine Saturation Data

DC1 Characteristics

$\Omega_1 = \underline{600}$ RPM

Line Volts, e_{a1_0}	Shunt Field Amps, i_{f_1}	$e_{a1_0}/\Omega_{1_{RPM}} = K_1^* (i_{f_1})$
0	0	0
300	10	0.50
530	20	0.88
660	30	1.10
730	40	1.22
762	50	1.27
790	60	1.32
812	70	1.35

DC2 Characteristics

$\Omega_2 = \underline{132}$ RPM

Line Volts, e_{a2_0}	Shunt Field Amps i_{f_2}	$e_{a2_0}/\Omega_{2_{RPM}} = K_2^* (i_{f_2})$
0	0	0
245	20	1.86
465	40	3.52
605	60	4.58
6.85	80	5.19
730	100	5.53
762	120	5.77
790	140	5.98
815	160	6.17
835	180	6.33
855	200	6.48

Ref: 40 x 80 checkout data, Ref. 9.

where

J_1 = moment of inertia of coupled DC1-SM1 machines;

J_2 = moment of inertia of coupled DC2-IFC machines.

Values of parameters of these machines used in this study are shown in Table 2.4-4. A diagram of the DC machine system model is given in Figure 2.4-7.

2.4.5 Complete Motor Generator System Model

Figure 2.4-8 shows the elements discussed above combined into the overall motor-generator system model. It is of interest to note the locations of the various parameters affecting control of the system:

(1) the field resistances r_{f_1} and r_{f_2};

(2) DC loop current, $i_{a_{DC}}$ which controls IFC RPM, Ω_2;

(3) the feedback effects of Ω_2 to e_{a_2}, Ω_1 to e_{a_1}, and I_a to Q_{IFC}, which are important to system dynamics;

(4) this input of aerodynamic torque as the shaft load in the synchronous motor model.

Mechanical couplings may be identified with torque summation yielding shaft accelerations ($\dot{\Omega}$, $\dot{\Omega}_1$, $\dot{\Omega}_2$), electrical couplings as voltage or current paths.

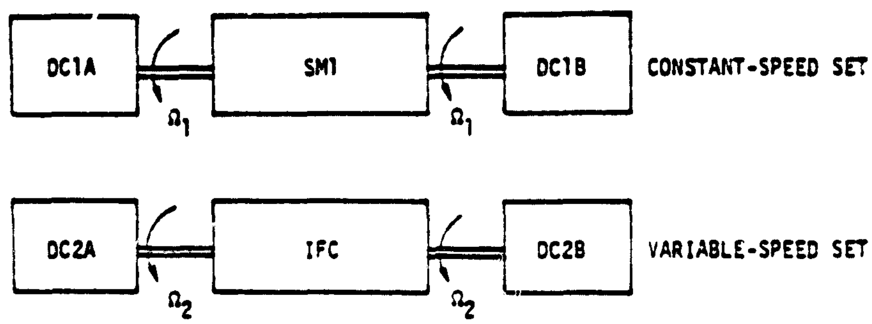
The process of fan RPM control may be clearly illustrated with this figure, and consists of the following steps. To increase fan RPM:

(1) field resistance r_{f_2} is decreased, or r_{f_1} is increased, or both, giving an increase in $(e_{a_2} - e_{a_1})$;

(2) $i_{a_{DC}}$ therefore increases, increasing Q_{DC2};

Table 2.4-4
DC Machine Characteristics

GEOMETRY



CONSTANTS:

	DC1A,B	DC2A,B
MOMENT OF INERTIA, J(SLUG-FT)^2	62,200	62,200
FIELD VOLTAGE, V_f(VDC)	700	700
FIELD RESISTANCE, r_f(OHMS)	10 (variable)	12 (variable)
FIELD INDUCTANCE, L_{ff}(HENRY'S)	100	100
ARMATURE RESISTANCE, r_a (OHMS)	.001578	.00338
ARMATURE INDUCTANCE, L_{aq}(HENRY'S)	.025	.025

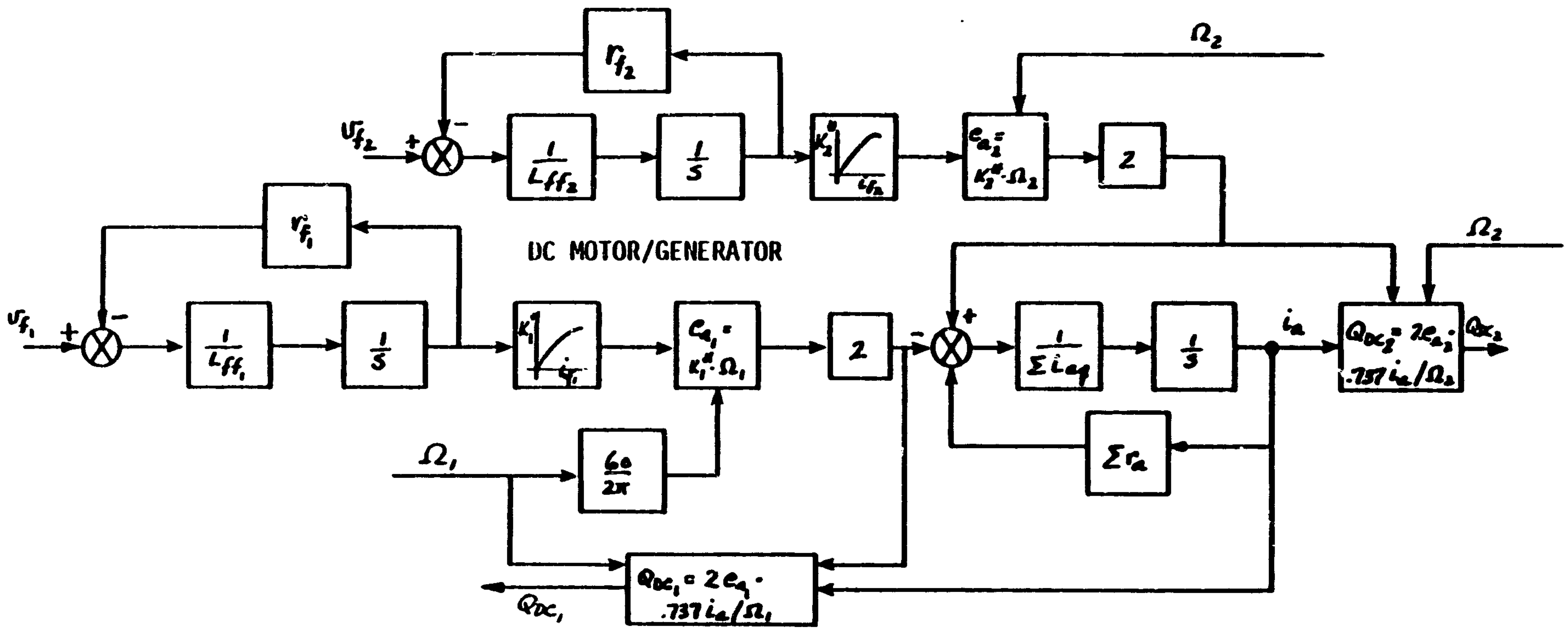


Figure 2.4-7 DC Motor-Generator System Model

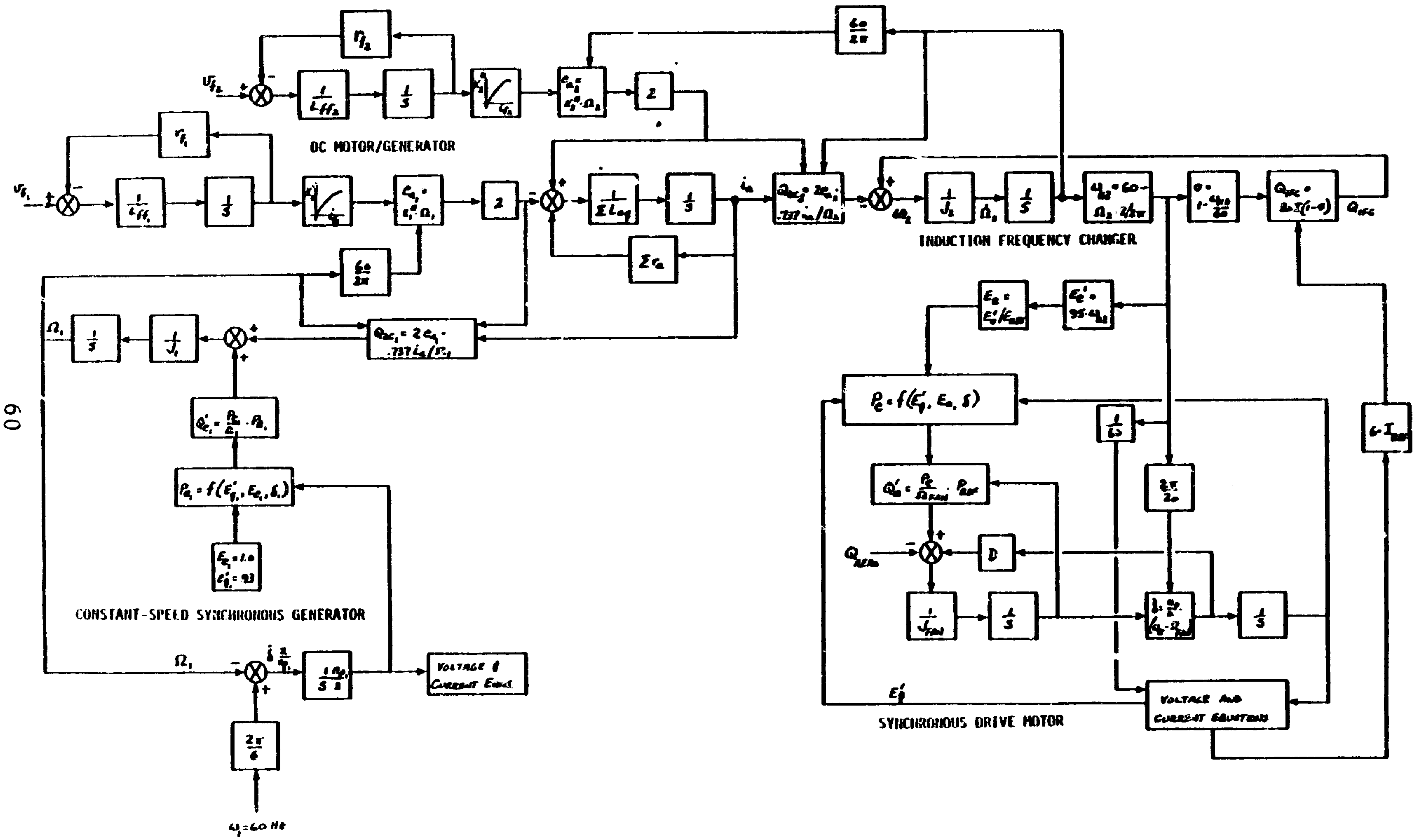


Figure 2.4-8 Complete Wind Tunnel Motor-Generator System Model

(3) increasing Q_{DC2} decreases Ω_2, causing a higher slip in the IFC;

(4) the increased IFC slip sends increased voltage and frequency to the main synchronous drive motor, which increases Ω;

(5) the current drawn by the main motor increases, until Q_{IFC} balances Q_{DC2} in equilibrium.

The system thus adjusts dynamically to an equilibrium condition - through adjustments in voltages, currents, and torques - that satisfies the simultaneous solution of the equation presented in this section.

2.4.6 Motor-Generator System Control

Control of drive fan RPM is accomplished, as noted above, by controlling the field currents in the DC machines of the motor-generator system which in turn control IFC slip. In principal, the field currents may be controlled independently to provide the required DC loop current to control IFC RPM. In an advanced motor-generator system controller, the field current levels might be filtered to obtain improved transient RPM response in the presence of inductive lags in the DC field and armature circuits, though the design of such compensators is outside the scope of the present study.

In the planned M-G system, field current control will be accomplished by the simultaneous adjustment of field circuit rheostats in a manner known to produce the derived DC loop current loads. This method was modelled in the M-G system simulation by varying field resistances r_{f_1} and r_{f_2} according to desired fan RPM; it was found that, with the IFC model used, fan torque had little effect on the fan RPM resulting from a particular DC loop current level. The field resistance schedules are shown in Figure 2.4-9 . This relationship between RPM command and field resistance (current, assuming constant field voltage) is a key feature of both manual and automatic control methods.

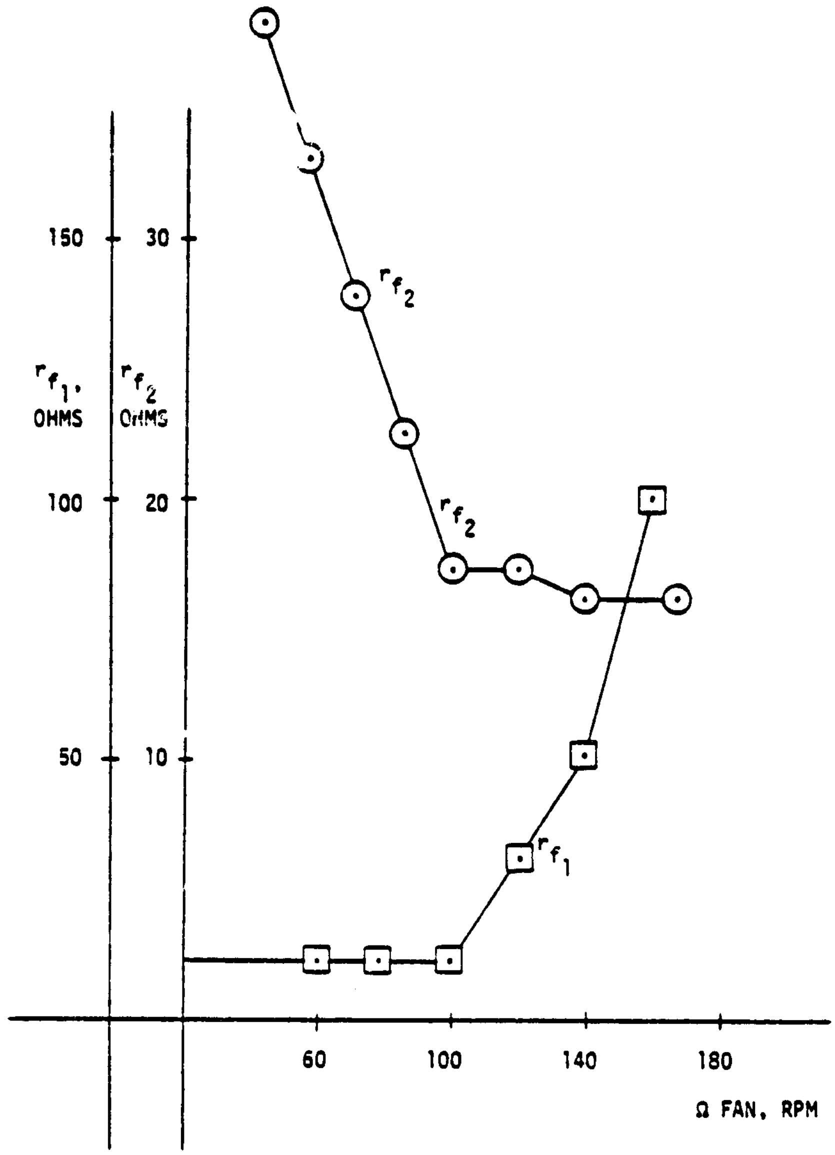


Figure 2.4-9 Nominal Field Resistance Schedules for Fan RPM Control

2.5 SIMULATION MATH MODEL COMPUTER PROGRAM DESCRIPTION

The math models described above have been implemented on a digital computer using the FORTRAN IV language. The computer program was developed originally on the UNIVAC 1108 and then converted and operated on the NASA/Ames CDC 7600. This section presents a general description of the computer program developed; a more detailed user's guide is included in Appendix B.

2.5.1 Computer Program Features

The general features of the wind tunnel simulation computer program are summarized below:

(1) Multiple modes of execution:

  (a) Trim only (used to compute equilibrium conditions for various levels of control);

  (b) Run only (simulate from given initial condition);

  (c) Trim and run (automatically run after trimming as in (a)); and

  (d) Generate linear models (i.e., calculate matrices which represent the linearized dynamics of the wind tunnel states--used for control design).

(2) State variables which represent tunnel mass flow rate and the motor-generator-set shaft and electrical field states.

(3) Numerical integration of the tunnel states by the Euler method, using a user-input step size.

(4) Treatment of both open- and closed-circuit tunnel configurations.

(5) Calculation of flow parameters at eight selected stations in the tunnel circuit.

(6) Three-dimensional fan map (fan RPM, blade pitch angle, tunnel mass flow rate).

(7) Multi-level print capability, capability to print only every Nth point.

(8) Plot capability using the line printer, capability to plot to various time scales.

Selection of the desired mode of operation is accomplished through a NAMELIST data entry format. The user may thus select output completeness, the type of tunnel, IFC or line mode, control on or off, type of control, and one of several standard control and disturbance inputs for developmental studies. Provision is made to select any two of the three controlling wind tunnel states (fan RPM, mass flow rate, and fan blade pitch) and equilibrate the remaining tunnel state and all remaining motor-generator system states accordingly.

2.5.2 Computer Program Description

The FORTRAN names of the subroutines which comprise the wind tunnel math model computer program are shown in Table 2.5-1, along with a brief description of the function of each subroutine. A hierarchy chart showing the inter-relationship of the subroutines (i.e., "who calls whom") is shown in Figure 2.5-1. As mentioned above, a user's guide which describes overall program input and output is included in Appendix B.

Table 2.5-1

Wind Tunnel Computer Program: Primary Subroutines

FORTRAN NAME	EXPANDED NAME	DESCRIPTION
BLADEP	Blade Pitch Actuator	Models the fan blade pitch actuator (lag, hysteresis, deadzone); also accommodates bypassing actuator dynamics.
BLKDTA	Block Data	Contains program data (fan maps, pressure drop tables, etc.).
CNTLW	Controller (Windspeed)	Contains RPM and blade pitch control laws.
DRAG	Drag Model	Calculates drag of the model in the test section.
ENERGY	Energy Parameters	Calculates work and heat flux in the tunnel segments.
EQUILB	Equilibration	Evaluates state variable rates of change so that they may be nulled by the trim initialization routine (SETUP).
EXEC	Executive	Maintains timing and sequencing control.
FANMOD	Fan Model	Calculates pressure and temperature changes across the fans.
FLOMOD	Flow Model	Computes the flow parameters (pressure, temperature, Mach no., etc.) at the eight selected tunnel stations; accommodates both open and closed tunnel circuits.
FLOPAR	Flow Parameters	Called by FLOMOD to perform Mach number and related fluid-dynamics calculations.
LINMOD	Linear Models	Computes matrices which represent the linearized dynamics of the wind tunnel states--used for control design.
MGMOD	Motor Generator Model	Models the functional characteristics of the tunnel motor generator system.

Table 2.5-1
(Continued)

FORTRAN NAME	EXPANDED NAME	DESCRIPTION
PLOT	Plot Routine	Plots selected variables versus time using the line printer.
PRINT	Print Routine	Prints selected variables versus time.
SENSOR	Sensor Models	Models sensor noise and dynamics, if any.
SETUP	Set-up Routine	Performs trim initialization of the wind tunnel states.
STATE	State Integration Routine	Integrates wind tunnel state variables over time.
TABLE1 TABLE2 TABLE3	Table Look-up Routines	Performs one, two, and three-dimensional table look-up.
WTMAIN	Wind Tunnel Main Program	Main program--reads inputs, sets up the run, calls the run executive (EXEC).

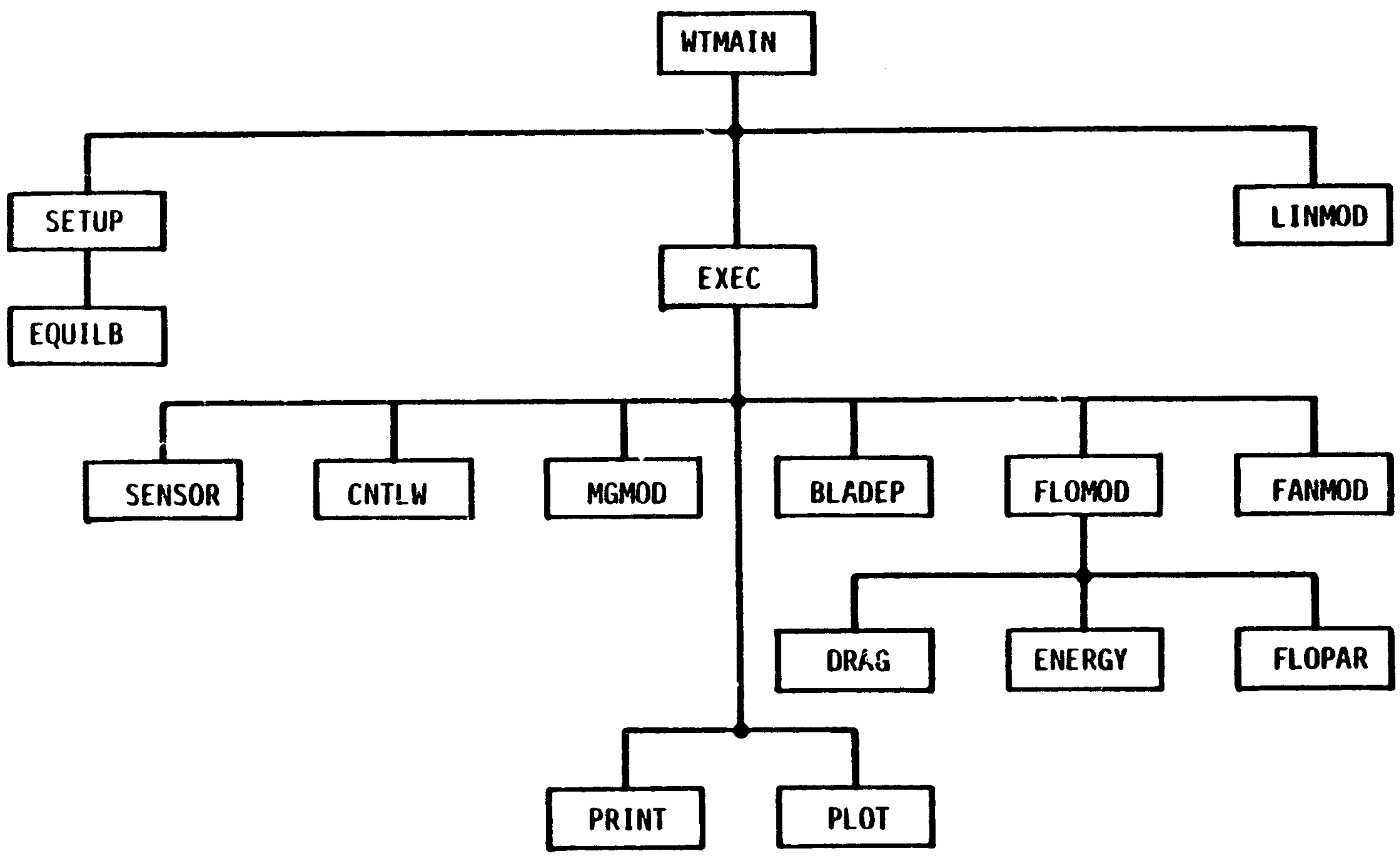


Figure 2.5-1 Wind Tunnel Computer Program: Module Hierarchy

2.5.3 Program Output

The simulation program outputs tunnel flow and motor-generator system parameters on line printers in increasing levels of detail as selected by the user. Table 2.5-2 summarizes the types of output obtained. Detailed description of output variables is given in Appendix B.

Table 2.5-2
Program Output Categories

LEVEL	DESCRIPTION	NOTES
0	Basic trim (tunnel flow and M-G system states and initial conditions); and summary.	
1	As above, plus all tunnel and M-G system states and parameters at specified intervals of time.	Current integration interval is $\Delta t = 0.025$ sec. Printer and plotter output may be printed every n computation points.
2	As above, plus all tunnel flow parameters at each tunnel station at each specified interval of time.	Printer plots available regardless of other line printer output requested.

Printer plots are available regardless of other line printer output requested.

Line printer plots presently consist of three separate plots over the same period of time, with multiple curves per plot. The plots graphically portray certain variables which also appear in the printed-format output; printed output need not be requested, however, in order to obtain the plots. These plots are extremely useful in developmental dynamic and control studies. While the printer-plots are more convenient for program development, line plots (CALCOMP, etc.) are generally more aesthetic. Conversion to CALCOMP is readily accommodated by the modular structure of the computer program. The variables plotted on each of the three plots are listed in Appendix B and below.

Variables Plotted Versus Time - Printer Plots

<u>Plot 1</u>

- Blade pitch setting
- Fan RPM
- $\dot{m}$
- q
- Electrical frequency to drive motors

<u>Plot 2</u>

- Power angle
- Fan RPM
- Electrical power
- Power factor angle
- Drive motor armature current

<u>Plot 3</u>

- Fan RPM
- Synch. generator RPM
- IFC RPM
- DC loop current
- IFC slip
- DC generator field resistor setting

III. WIND TUNNEL OPERATING CHARACTERISTICS ANALYSIS

3.1 OVERVIEW

The simulation math model developed in Chapter II is a powerful analytical tool for exploring the static and dynamic characteristics of the closed or open circuit wind tunnels. The ability to store and interpolate among large amounts of data, coupled with routines to trim all the degrees of freedom, makes possible the rapid evaluation of all system states and parameters regardless of their coupling characteristics; that is, it locates equilibrium solutions to a large number of simultaneous, nonlinear differential equations. To the extent that the basic data are reliable, then, this makes possible accurate detailed examinations of system parameters that may not be convenient or safe to observe experimentally and that may only be determined with great tedium by other methods. One of the biggest assets of the simulation is its ability to include, in both static and dynamic calculations, full representation of nonlinear characteristics of system components.

The effects of changes in important tunnel parameters may be easily studied to evaluate design considerations. Such studies may include the effects of:

(1) fan aerodynamic characteristics;

(2) tunnel pressure loss parameters;

(3) operating ξ-RPM schedules;

(4) speed transition profiles, including emergency stops;

(5) speed/q control system gain settings;

(6) net per-run power consumption; and

(7) open vs. closed circuit operational differences.

In this section, various preliminary study results are shown. These data serve the dual purpose of demonstrating the tunnel model operating envelope and evaluating key static and dynamic tunnel performance characteristics.

3.2 WIND TUNNEL STEADY-STATE OPERATING CHARACTERISTICS

The principal parameters of interest in steady-state operation are:

(1) power usage;

(2) fan pressure rise ($\Delta \dot{p}_{FAN}$);

(3) air flow rate ($\dot{m}$) and test section dynamic pressure; and,

(4) motor-generator system parameters.

These parameters are investigated in the following.

3.2.1 Power

Steady-state electrical power levels needed to sustain a given air flow rate are shown in Figs. 3.2-1 to 3.2-3 for the open- and closed-circuit tunnels under both IFC and line operating conditions. Figure 3.2-2 shows power levels determined from parametric variations of blade pitch angle at constant fan RPM's. These calculations inherently consider the variation of fan efficiency with operating condition, since they contain experimental data for both fan pressure rise and fan torque which together, at a given RPM and power level, determine efficiency. Electrical power shown is real power, not total; total power depends on the power factor at which the motor is operating. Further study is needed of low-RPM excitation and supply voltage characteristics, which control armature current and power factor.

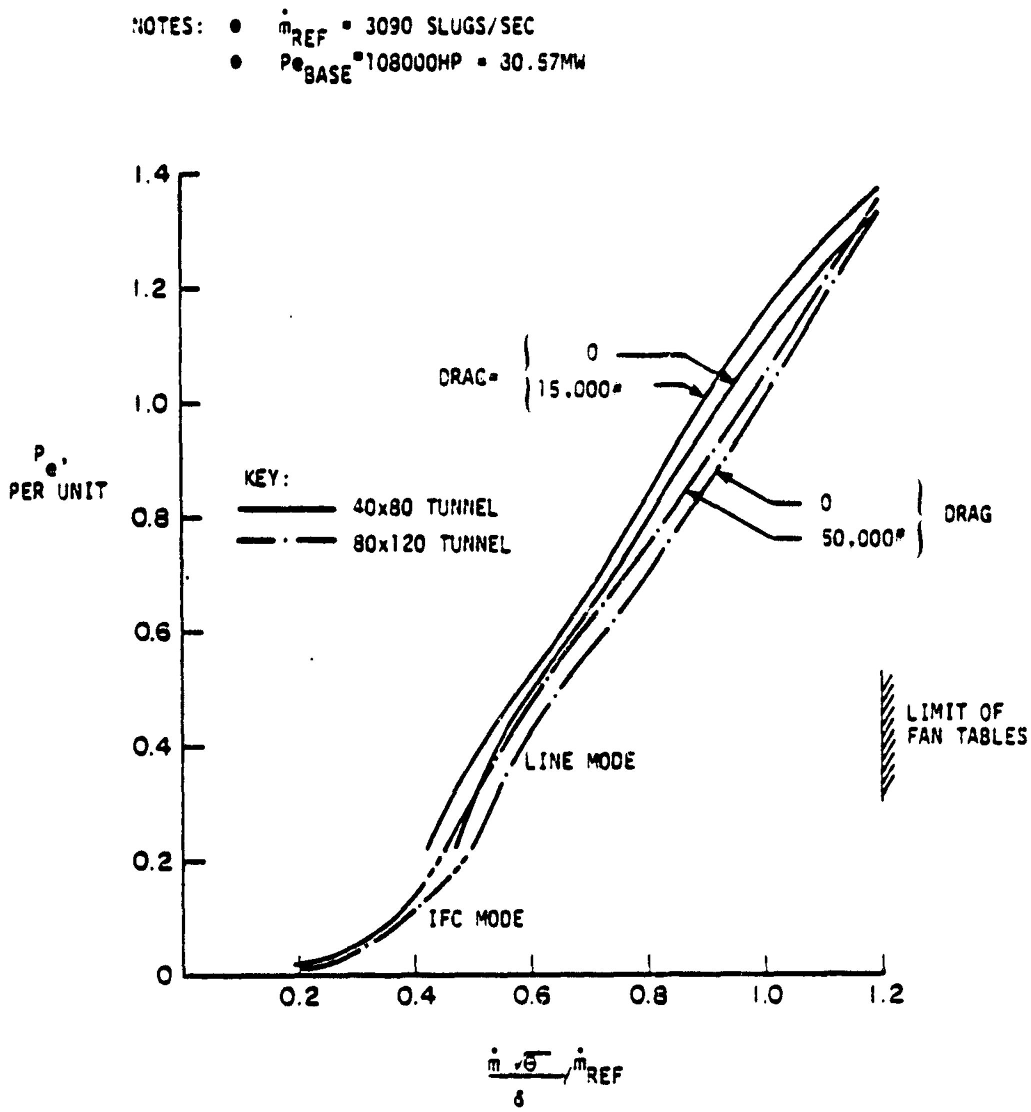


Figure 3.2-1 Steady-State Power Levels from Simulation Math Model

40x80 TUNNEL

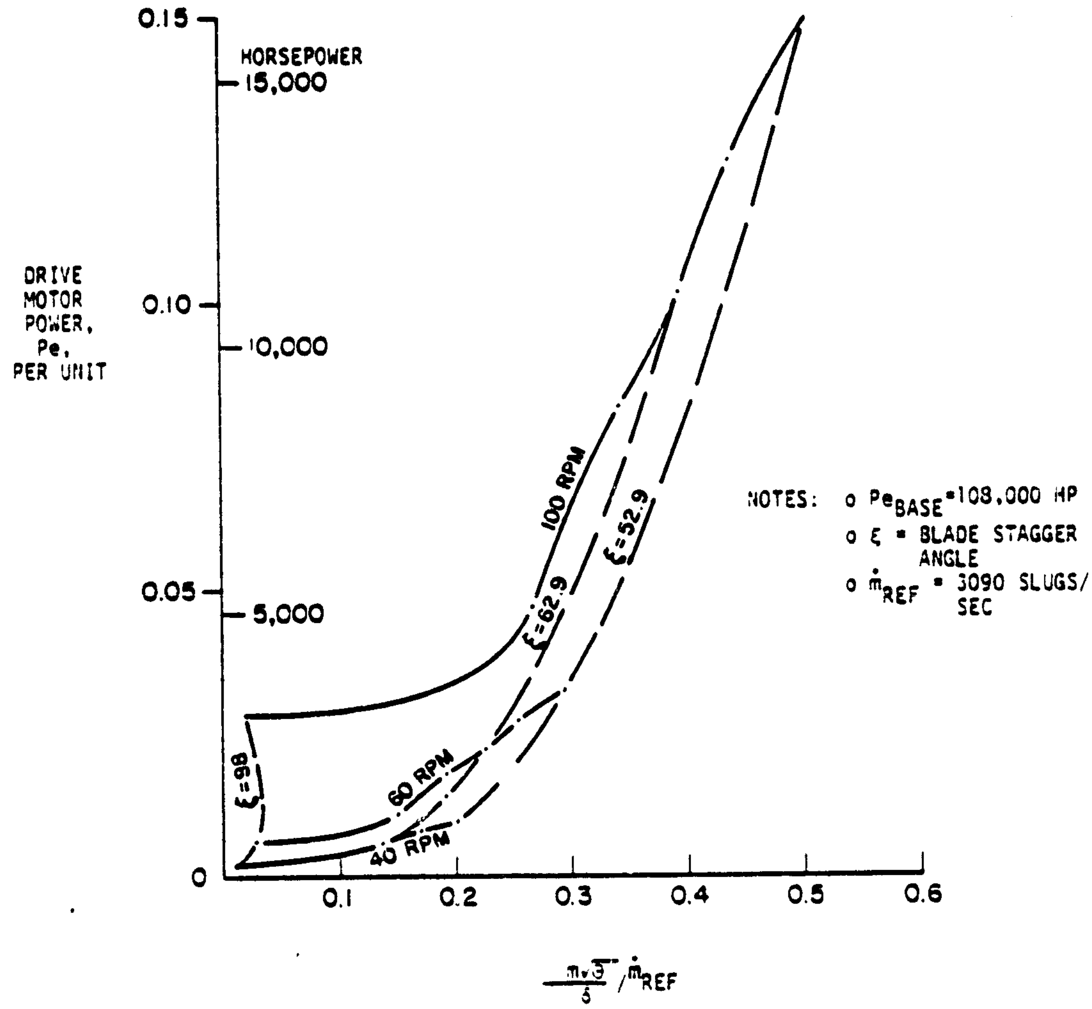


Figure 3.2-2 Steady-State Power Levels, IFC Mode, Various Operating Conditions, from Simulation Math Model

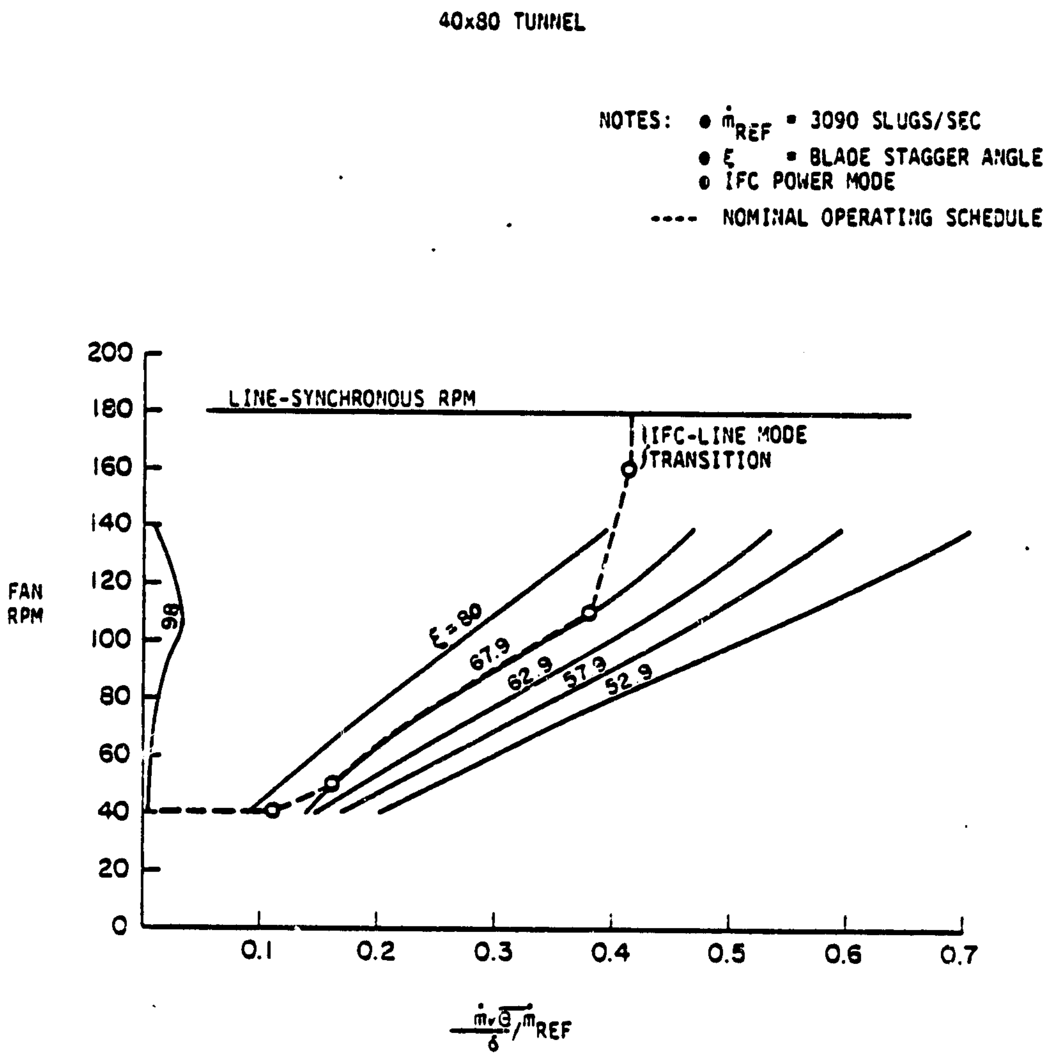


Figure 3.2-3 Steady-State Tunnel Airspeed-Fan RPM Relationship at Various Blade Angles, from Simulation Math Model

In the IFC mode, a nominal schedule of blade pitch angle versus fan RPM should be selected to enable consistent tunnel q settings and known q control procedures. Conflicting requirements on such a schedule are: (1) operating with RPM as low as possible to minimize power usage; and (b) raising RPM such that it is conveniently near the 179.5 RPM IFC-to-line transition point by the time that the IFC current limit is reached.

One possible schedule, selected for purposes of this study, is shown superimposed on a tunnel operation map in Fig. 3.2-3. This schedule utilizes low RPM at low speeds and holds either constant ξ (blade pitch) or constant RPM over most of the permissible speed range.

Power curves such as those shown in Figs. 3.2-1 and -2 are useful in the study of permissible rates of speed change relative to power rate limitations. The points on these curves represent end-point conditions; therefore, the locus of points for an actual transition will be above these curves unless the transition is very slow. Although an actual speed transition demands momentarily higher power to accelerate the flow, rapid transition may be feasible if confined to small speed changes such that one-minute-averaged power rate levels are within limits. The allowable transition rate depends on the initial operating point. More precise definition of instantaneous power rate limits imposed by the power grid or motor capability is desirable.

3.2.2 Fan Pressure Rise

Under steady conditions, the pressure differential across the fan unit is fixed by tunnel pressure losses (including model effects) at the desired airflow. Since pressure differential is the principal indicator of fan blade loads, it is of interest to know how this pressure changes with tunnel operating condition. In particular, it is desired to know how close the fans are operating to the stall (surge) limit and under what conditions this limit is approached.

Steady-state fan pressure rise requirements are shown as a function of tunnel airflow for various line power conditions in Fig. 3.2-4. The fan stall line on this plot was determined from the fan data shown in Section 2.3. These data show adequate surge margin for both tunnels, though less for the 40 x 80 circuit than for the 80 x 120. Dynamic conditions are more critical, as will be discussed in Section 3.3.

3.2.3 Airflow Rate and Dynamic Pressure

The principal flow variable in the tunnel simulation is mass flow rate, $\dot{m}$, which is related to speed by the relation

$$\dot{m} = \rho_i A_i V_i \qquad \text{(slugs/sec)}$$

where density must be computed with respect to compressibility effects and the cross-sectional area (A_i) varies with tunnel station.

The 80 x 120 tunnel, with a test section area 3.36 times larger than the 40 x 80, has proportionately lower test section velocity and q for the same fan airflow. The relationship between test section dynamic pressure and fan airflow for the two wind tunnels is shown in Figure 3.2-5.

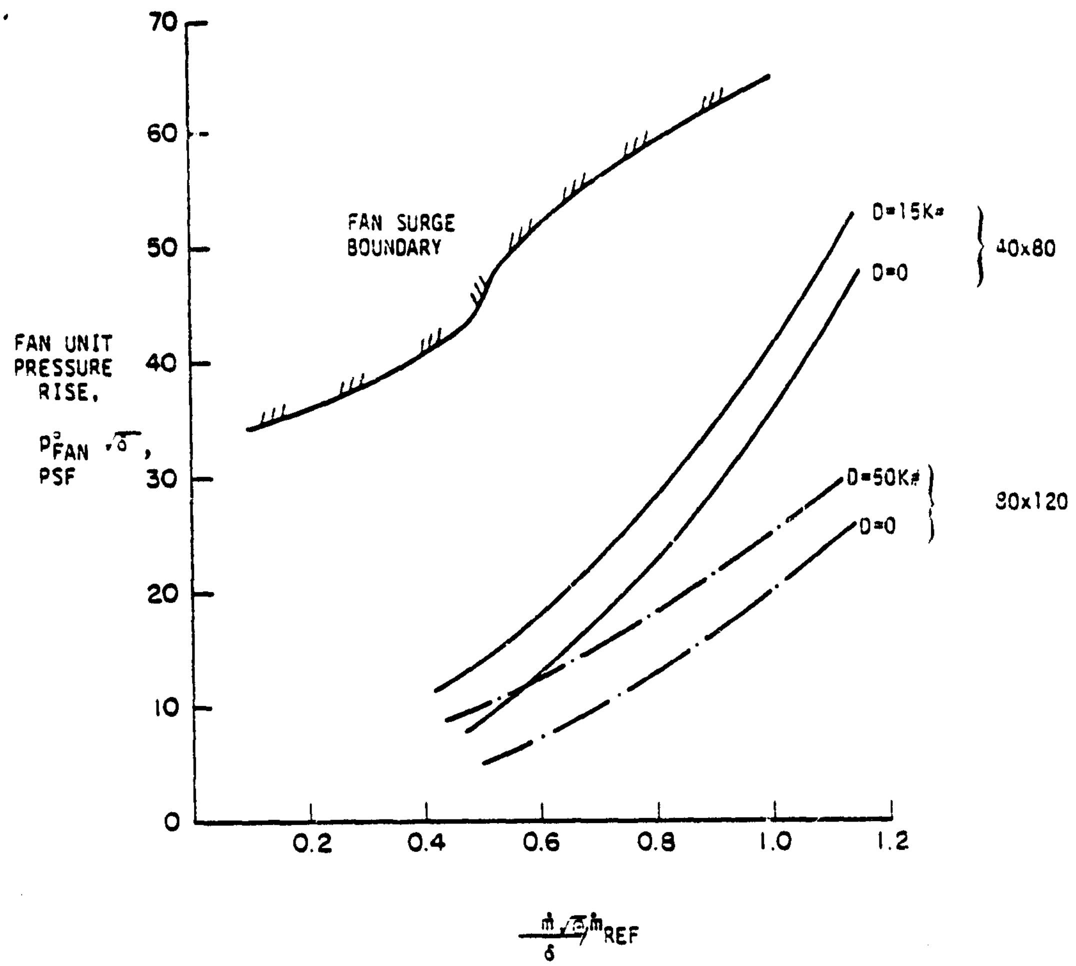


Figure 3.2-4 Steady-State Fan Pressure Rise; Line Power Mode

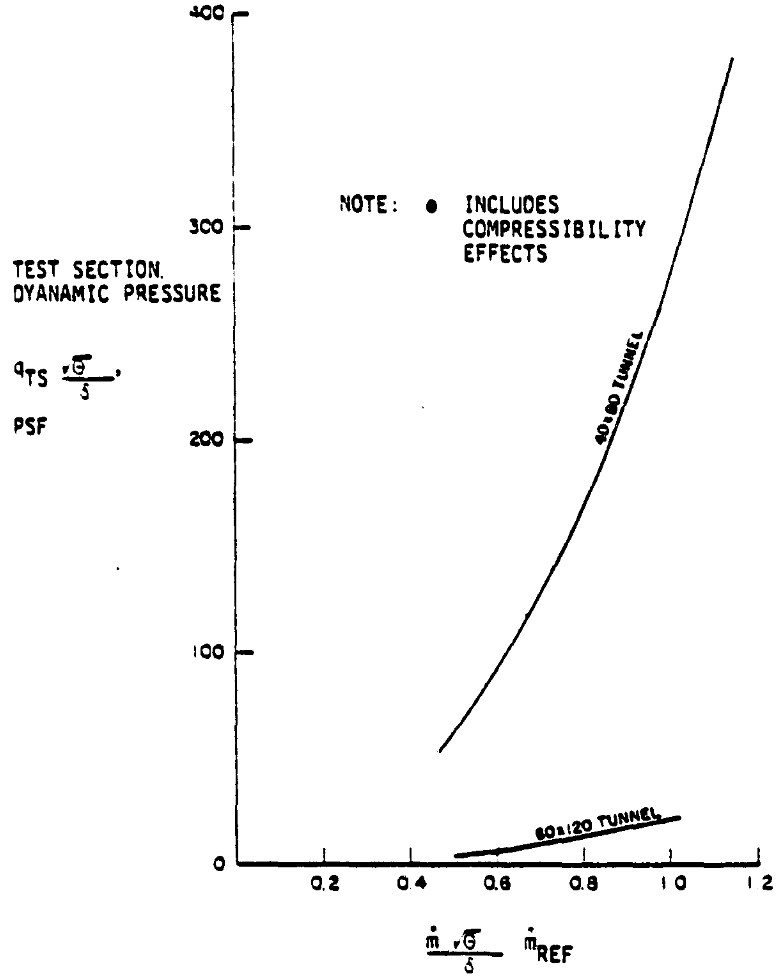


Figure 3.2-5 Tunnel Test Section Dynamic Pressure - Airflow Relationship

3.2.4 Motor-Generator System Parameters

The math models of the motor-generator system elements contain representations of current and voltage levels important to safe operation of the system. While the values of these variables are very dependent on assumed motor characteristics, and at present are not known with high precision, certain trends may be discussed. Fig. 3.2-6 shows the variation of M-G system parameters with power level. Shown are DC loop current, field currents, and synchronous motor power angle in the IFC mode.

Numerous other studies of system steady-state parameters may be performed in a similar manner. (Continued update of math model data should be undertaken to improve the capability to study system parameter variations using this analytical tool.)

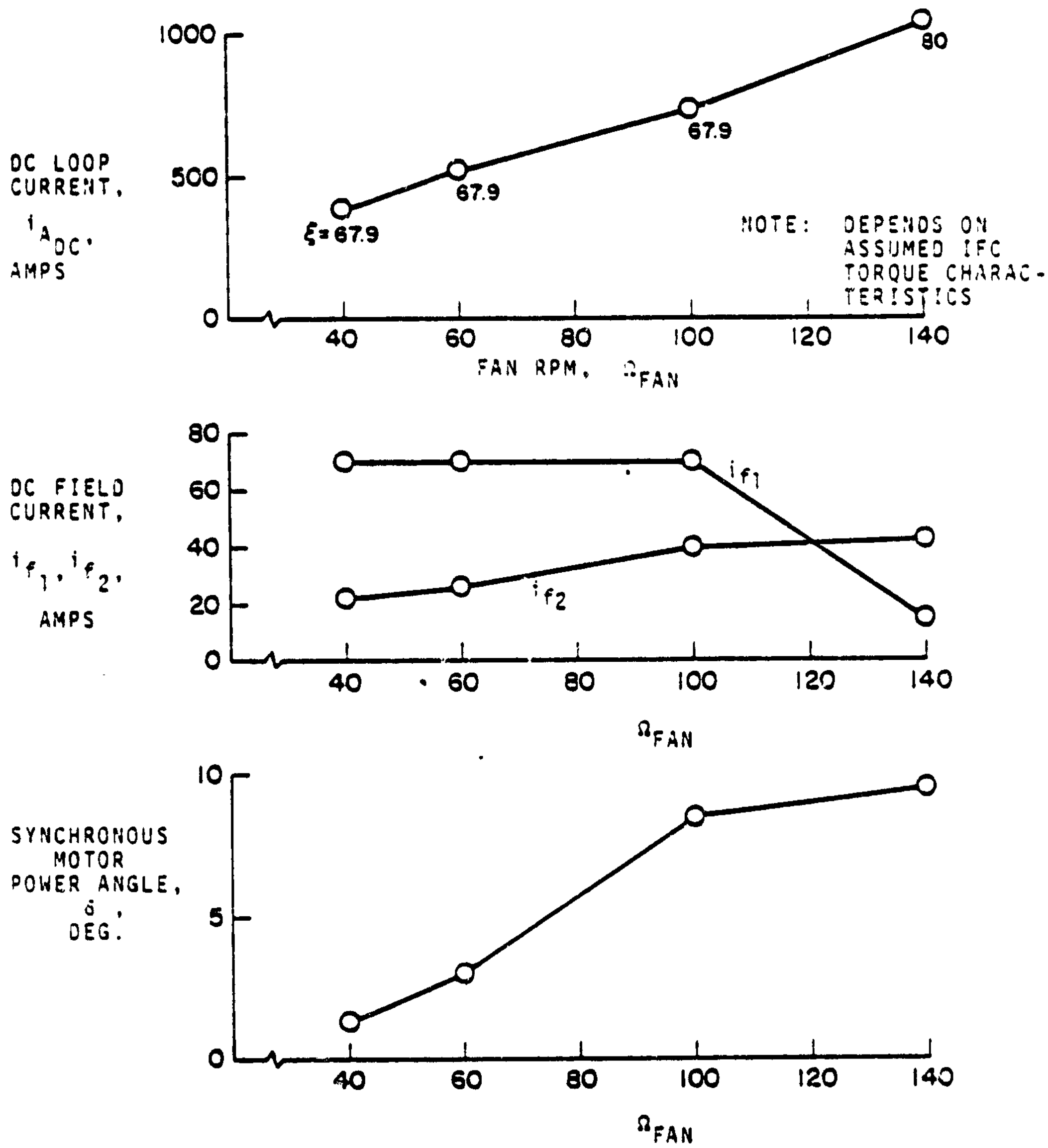


Figure 3.2-6 Variation of Steady-State Motor-Generator System Parameters with Operating Condition

3.3 WIND TUNNEL DYNAMIC OPERATING CHARACTERISTICS

This section considers typical applications of the simulation math model to analyze transient behavior that can only be studied by simulation. Fan loads, motor-generator system states, and tunnel airflow speed variations depend on timewise integrations of forces dependent on the variations themselves, a process that can best be performed numerically when significant nonlinearities are involved. In the following, several important transient phenomena will be investigated:

(1) fan pressure rise variations during speed transitions;

(2) motor-generator set parameter variations (voltages, currents, and RPM's);

(3) tunnel speed and fan pressure rise changes in response to model drag changes;

(4) blade rate limits in the presence of power increase and decrease rate limits; and

(5) tunnel speed and fan pressure rise changes during an emergency stop.

The results of these studies illustrate the tunnels' basic dynamic behavior and the predicted ranges of key variables during typical transient conditions.

3.3.1 Fan Pressure Rise During Flow Acceleration

Fan pressure rise during speed transients is a parameter that can only be determined by simulation, because it depends heavily on just how the tunnel flow accelerates or decelerates in response to changes in fan pressure; it is a coupled system. An initial increase in fan blade pitch or fan RPM causes a large initial increase in pressure rise because the airflow has not yet increased to its equilibrium value. Thus, the fan is carried closer to the surge boundary than would appear from steady-state calculations. The problem is only critical in high-speed, line-power operation.

To investigate this effect, the following trial was simulated: starting from an initial trim condition below maximum speed, in line power mode, blade pitch was increased at a constant rate from its initial setting to the approximate setting for maximum-speed operation (RPM constant at 180). The resulting flow acceleration and fan pressure rise during this transition were noted. This corresponds to a realistic command to rapidly obtain a maximum-speed operating point, as to set up a new run, though the blade pitch rates selected were higher than are actually planned, to emphasize the dynamic results.

The resulting transient time histories are shown in Figs. 3.3-1 to -3 for the 40' x 80' tunnel, and Figs. 3.3-4 to -6 for the 80' x 120' tunnel. It is seen that, while fan surge boundary is closely approached, even the high blade rates used did not surge the fans, because the airflow ultimately accelerated in sufficient time to relieve the fans through increased advance ratio. The margin of safety is small in some cases, however, and if blade pitch continued past the present limit a stall condition could be encountered, particularly if model drag is high. The blade pitch limit in this example was $\xi = 40.9^\circ$ (the limit of the existing data tables), while the actual mechanical blade pitch limit will be approximately $\xi = 38^\circ$. Thus, while normal transient pressure rise levels are predicted to be within fan capability, a runaway failure in the blade pitch drive system at the highest-speed operating condition could force the fan into a surge condition.

When analyzing such tunnel conditions using the math model, it is important to note that the present fan pressure ratio data tables extend only to $\dot{m}/\dot{m}_{REF} = 1.20$, or 20% beyond the reference design speed of 300 knots in the 40 x 80 test section.

3.3.2 Motor-Generator System Transients and Control Response

Several factors significant to the design and effective operation of the motor-generator system, including the IFC, yet normally

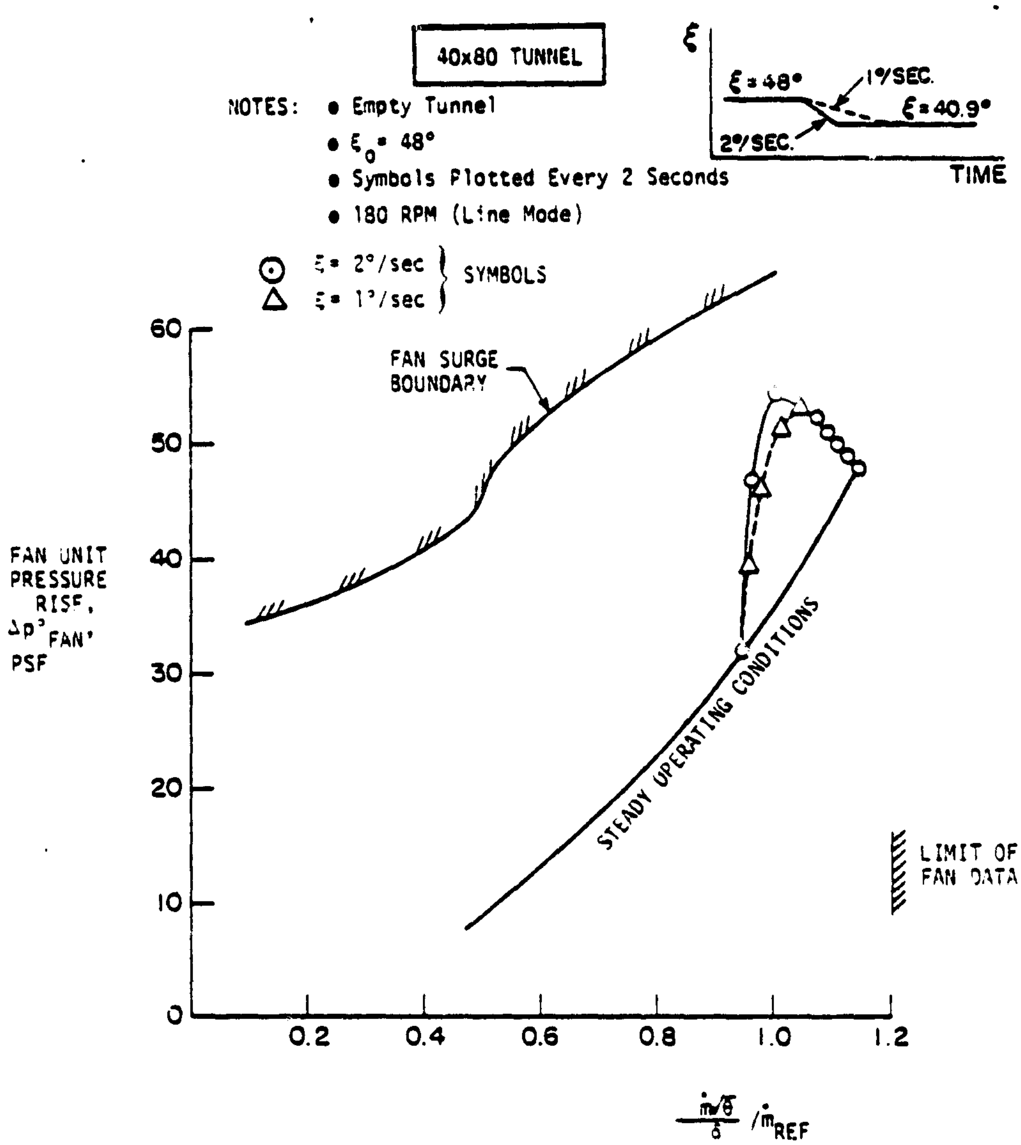


Figure 3.3-1 Fan Pressure Rise and Flow Acceleration Due to Fan Blade Angle Change, 40 x 80 Tunnel, $\xi_0 = 48°$

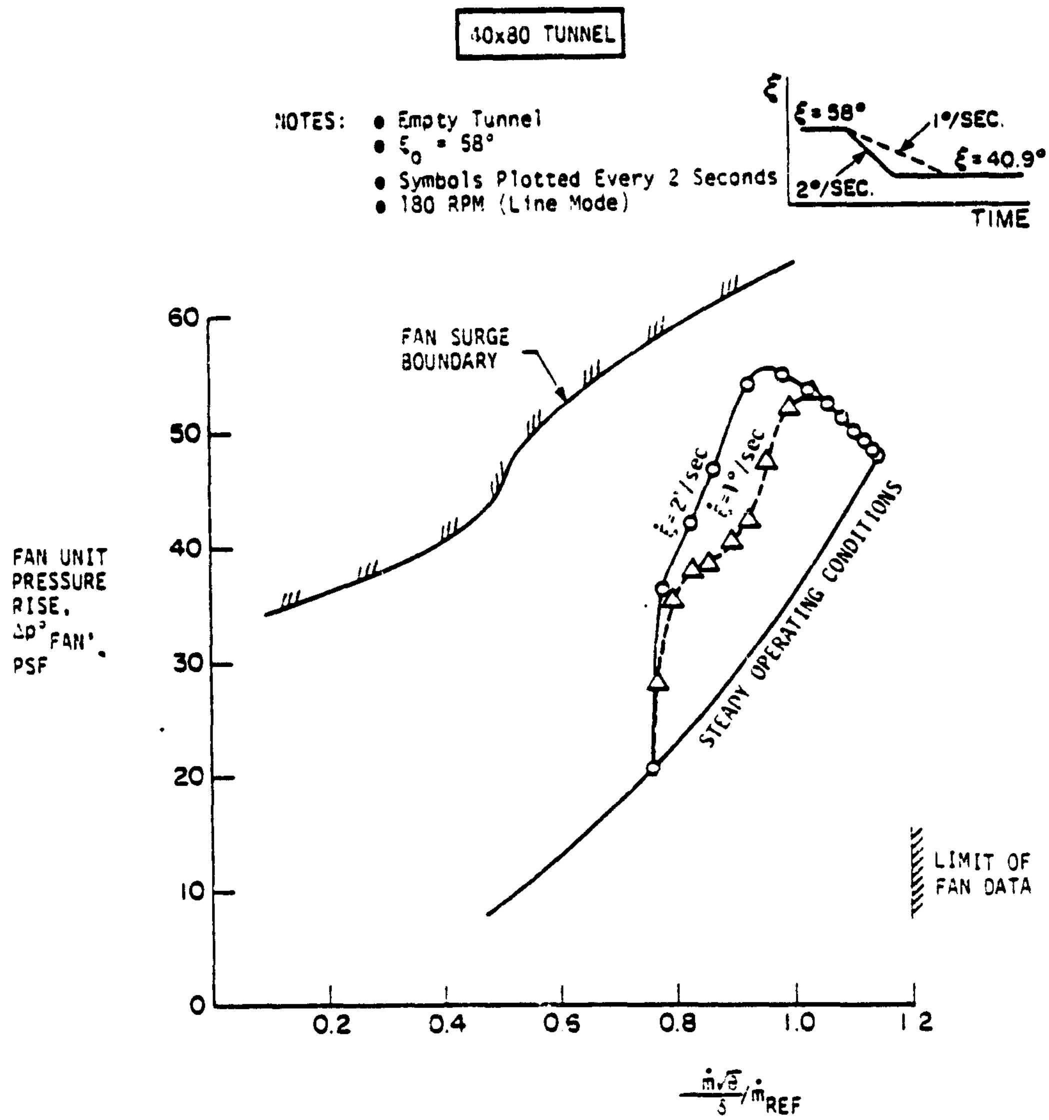


Figure 3.3-2 Fan Pressure Rise and Flow Acceleration Due to Fan Blade Angle Change, 40 x 80 Tunnel, ξ_0=58°

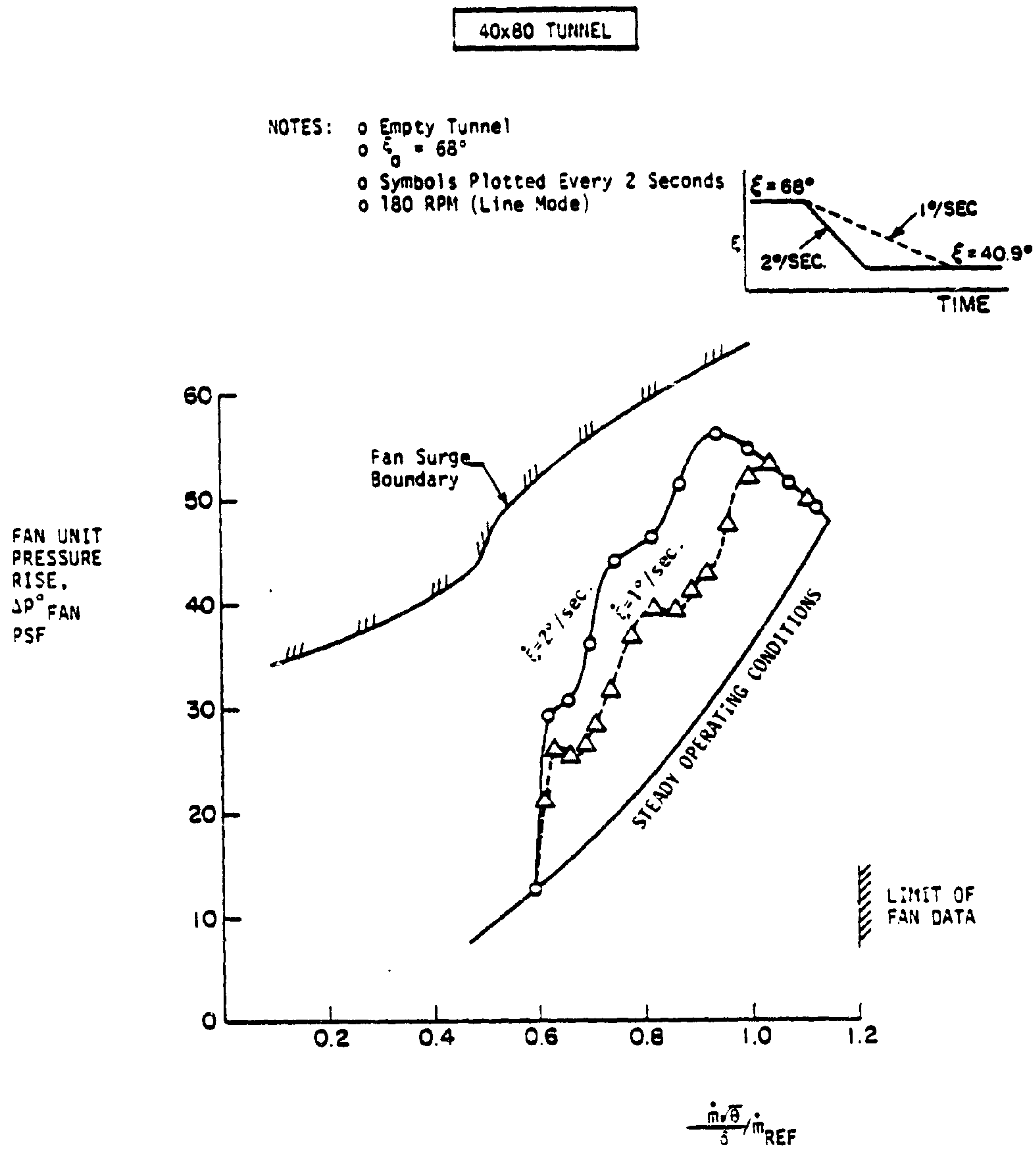


Figure 3.3-3 Fan Pressure Rise and Flow Acceleration Due to Fan Blade Angle Change, 40 x 80 Tunnel, ξ_o=68°

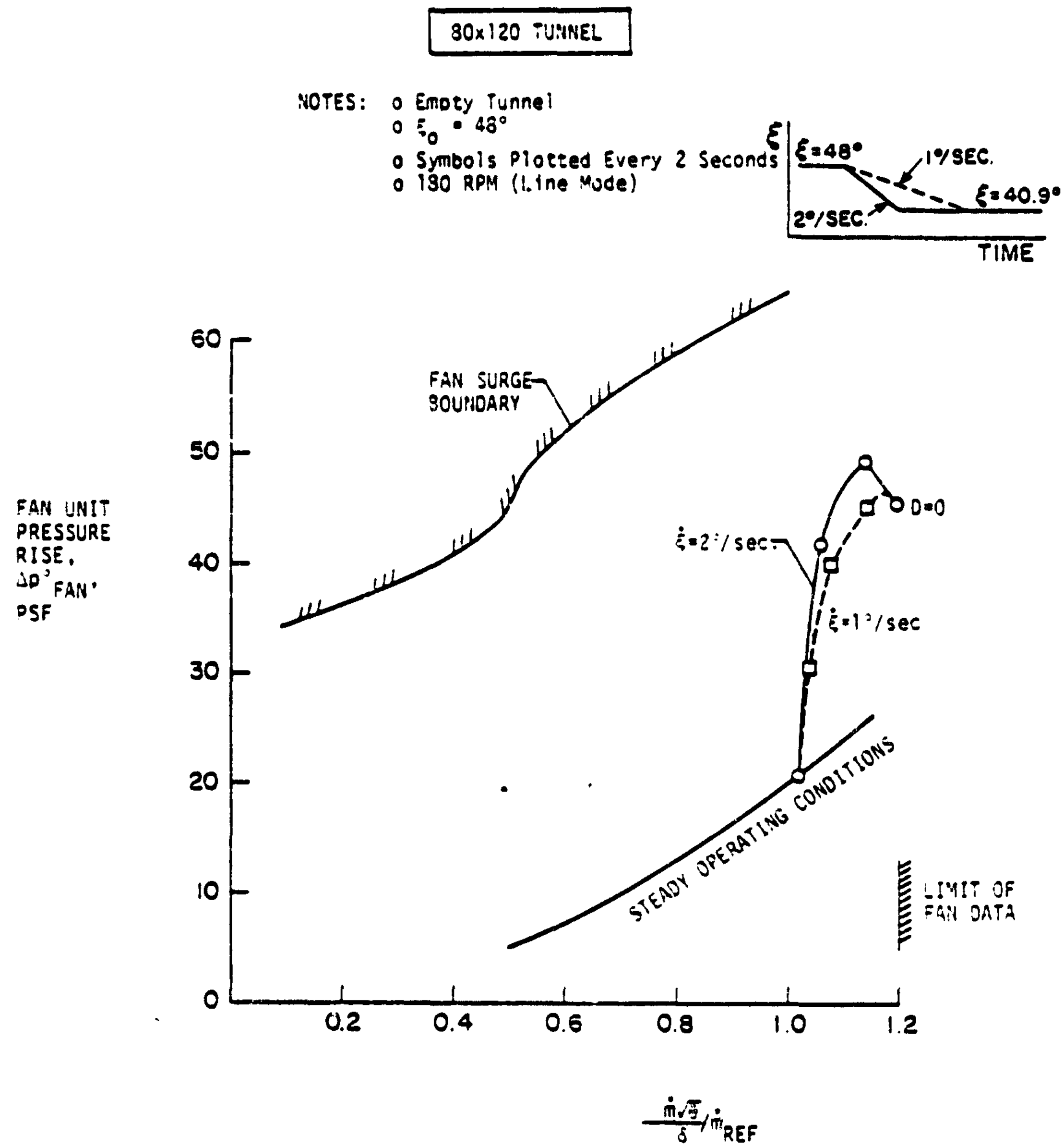


Figure 3.3-4 Fan Pressure Rise and Flow Acceleration Due to Fan Blade Angle Change, 80 x 120 Tunnel, ξ_o=48°

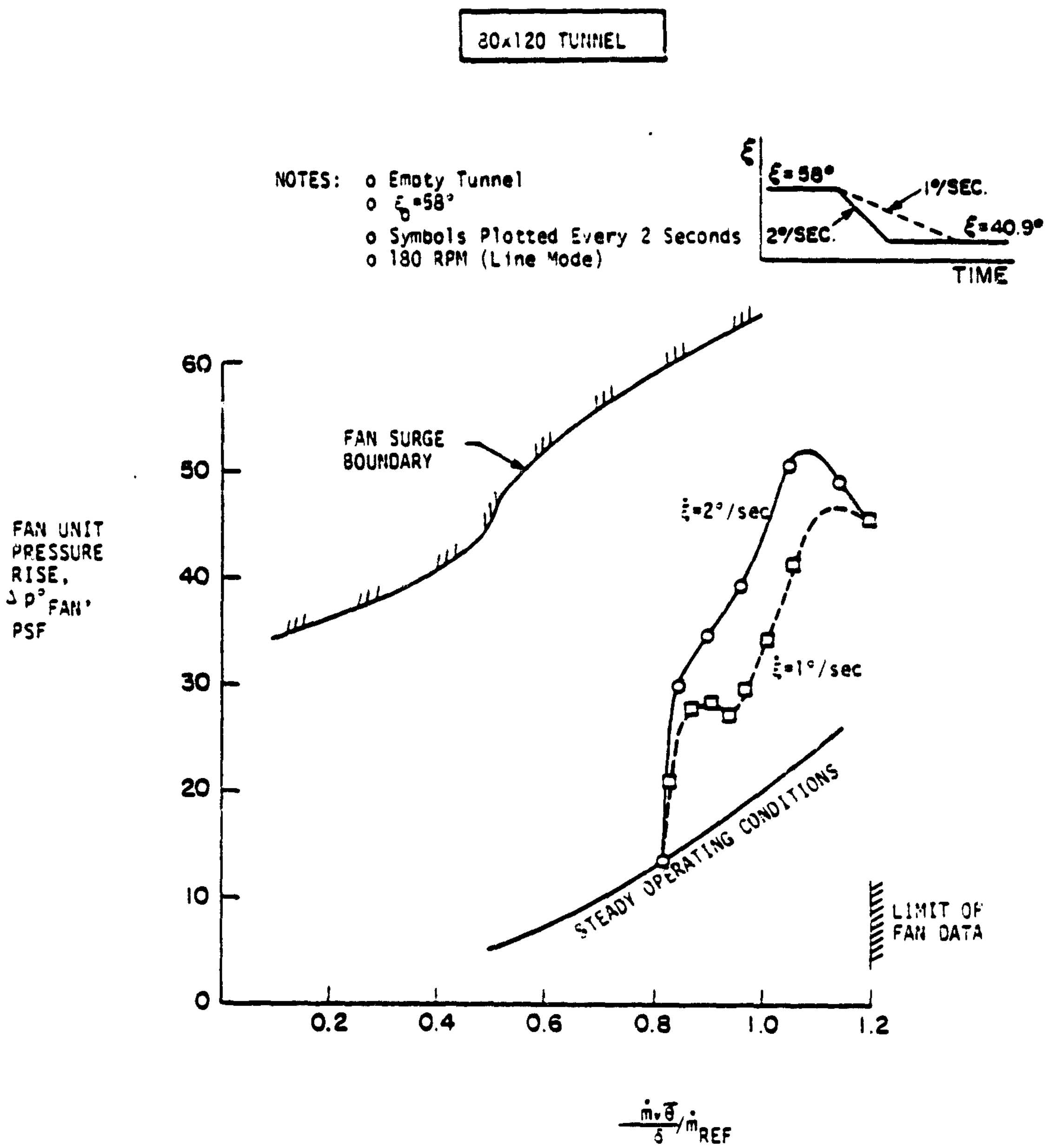


Figure 3.3-5 Fan Pressure Rise and Flow Acceleration Due to Fan Blade Angle Change, 80 x 120 Tunnel, ξ_0=58°

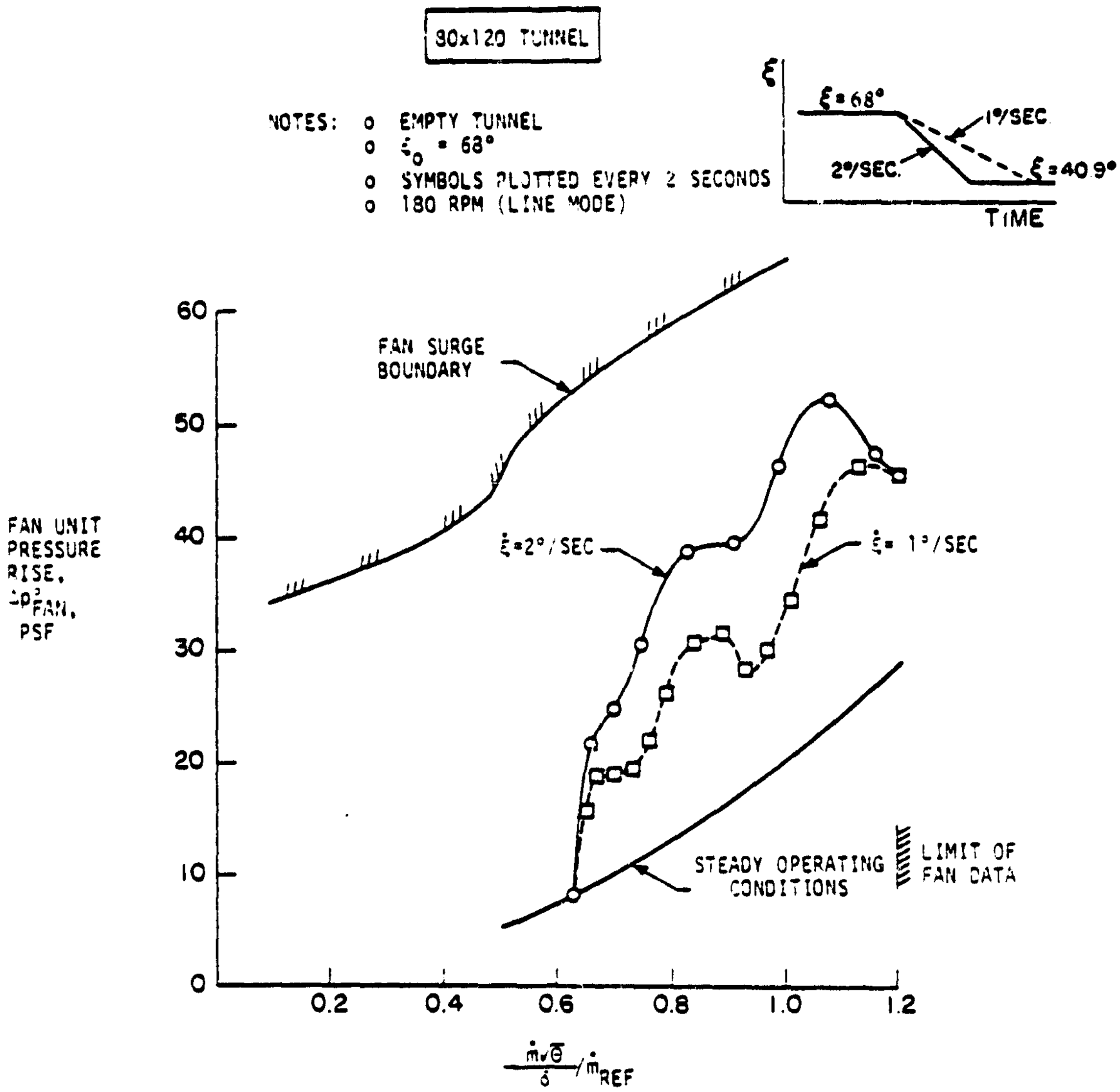


Figure 3.3-6 Fan Pressure Rise and Flow Acceleration Due to Fan Blade Angle Change, 80 x 120 Tunnel, ξ_0=68°

only observable through electrical monitoring instrumentation, may be studied with the math model. Because of the preliminary nature of much of the information about the M-G system machines, present results show mainly trends and relative effects, but point to several significant factors:

(1) DC loop current is dependent upon the torque of the IFC, an as-yet-undetermined parameter assumed in this study to vary proportionally with power level and IFC RPM (or slip). The simulation indicates that very large excursions in loop current may occur during RPM transitions, caused by the time lag in generating back-emf in the DC machine pair. Increasing the steady-state torque levels of the IFC can significantly increase steady-state and transient loop current levels.

(2) Changes in fan torque affect fan RPM in the IFC mode since, under the assumptions of this simulation, higher synchronous drive motor current drawn causes the IFC to accelerate, lowering drive frequency to the synchronous motor. Reference to Fig. 2.4-8 shows how this effect propagates backward through the elements of the system: increased IFC rotation rate (Ω_2) increases generator armature voltage, causing higher DC loop current until the system stabilizes. The higher loop current ($i_{a_{DC}}$) is impressed on the motor, causing a change in the power angle (δ_1) of the "constant'speed" synchronous motor and inducing swinging in that machine that must be damped by an amortisseur or other measures. Better knowledge is needed of all the machines in this system, particularly the IFC.

Adjustment of fan blade pitch or fan RPM to control tunnel airspeed causes transient oscillation in the various elements of the MG system. The effect is more severe in the IFC mode, since in the line mode all electrical power is input directly to the synchornous motors. In the IFC mode, mechanical and electrical interconnections cause disturbances in one part of the system to affect other system elements, in the manner described in Section 2.4.

It is particularly important to predict whether system parameters will reach critical values during transients, and how the effects of transients may be minimized through choice of favorable control options, where possible.

Figs. 3.3-7 and -8 show the response of key system variables to a blade pitch change and a fan RPM change, respectively, in the IFC mode at 100 RPM and 67.9° stagger angle. The former shows the additional torque due to blade pitch increase (stagger angle decrease) to have negligible effect on fan RPM and to increase tunnel q with a time constant of about 12 seconds. The input was a 1-degree blade pitch ramp over 5 seconds. The increased motor power draws more AC current through the IFC, which changes IFC torque and interacts with DC generator voltage through IFC RPM and DC armature current, and results in an oscillation in DC current. It must be noted that many assumptions are implicit in the motor-generator system model that may affect the accuracy of the predictions of the magnitudes of the variables, but that the basic dynamic effects are in fact present in the actual system.

Fig. 3.3-8 shows the response at the same condition to a change in DC generator field resistance, which changes field current in the manner of a rheostat or solid-state device. Two inputs are shown: a ramp resistance change, and a step resistance change The ramp change is seen to have effects similar to the step, but about 3 seconds later in this particular case. Now, fan RPM responds by increasing and tunnel q increases as before. The most significant difference is in DC armature current, which climbs 100% over its initial value due to the delay in regaining emf balance in the DC machines caused by electrical time constants and motor inertia. The subsequent oscillations in DC current cause oscillations in

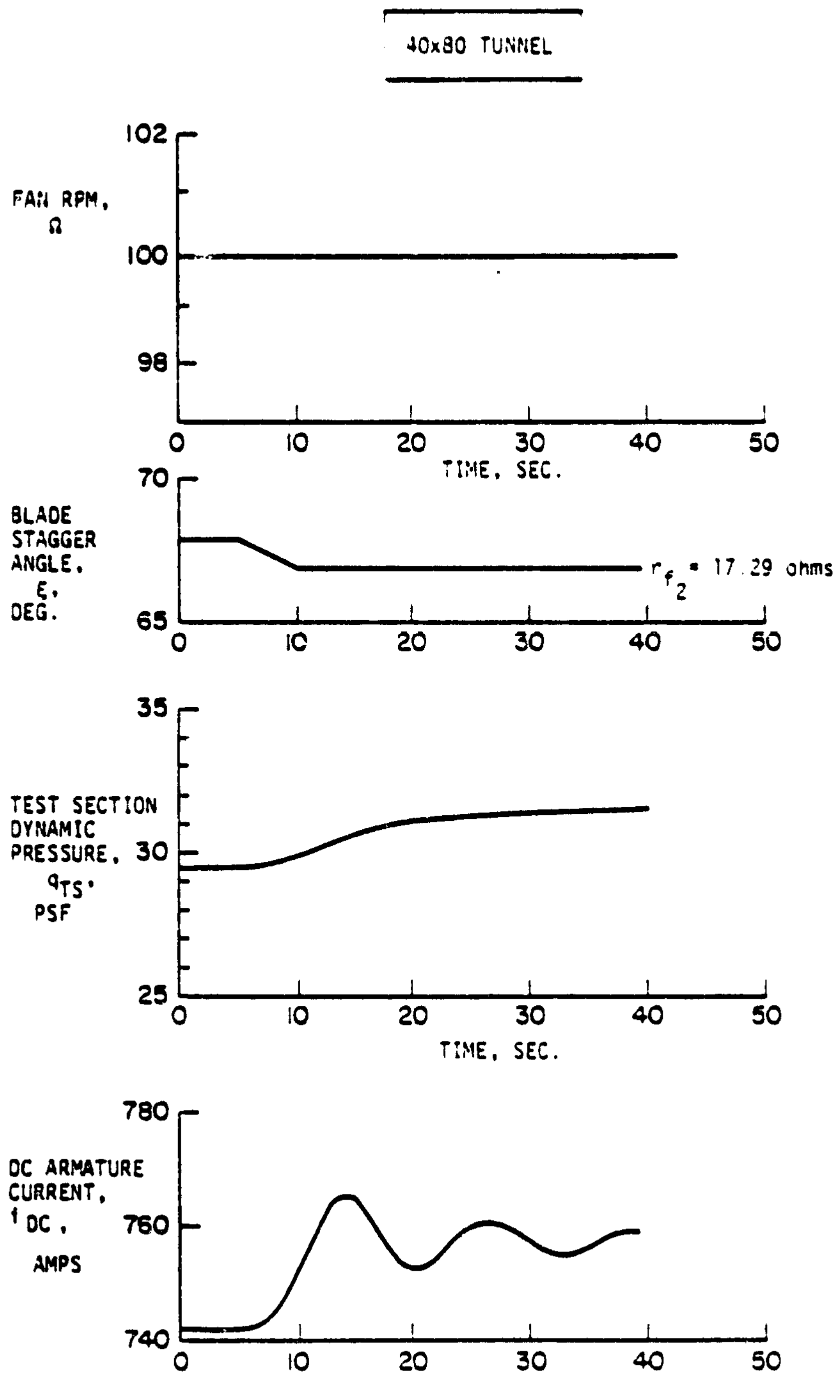


Figure 3.3-7 System Response to Blade Angle Change, IFC Mode

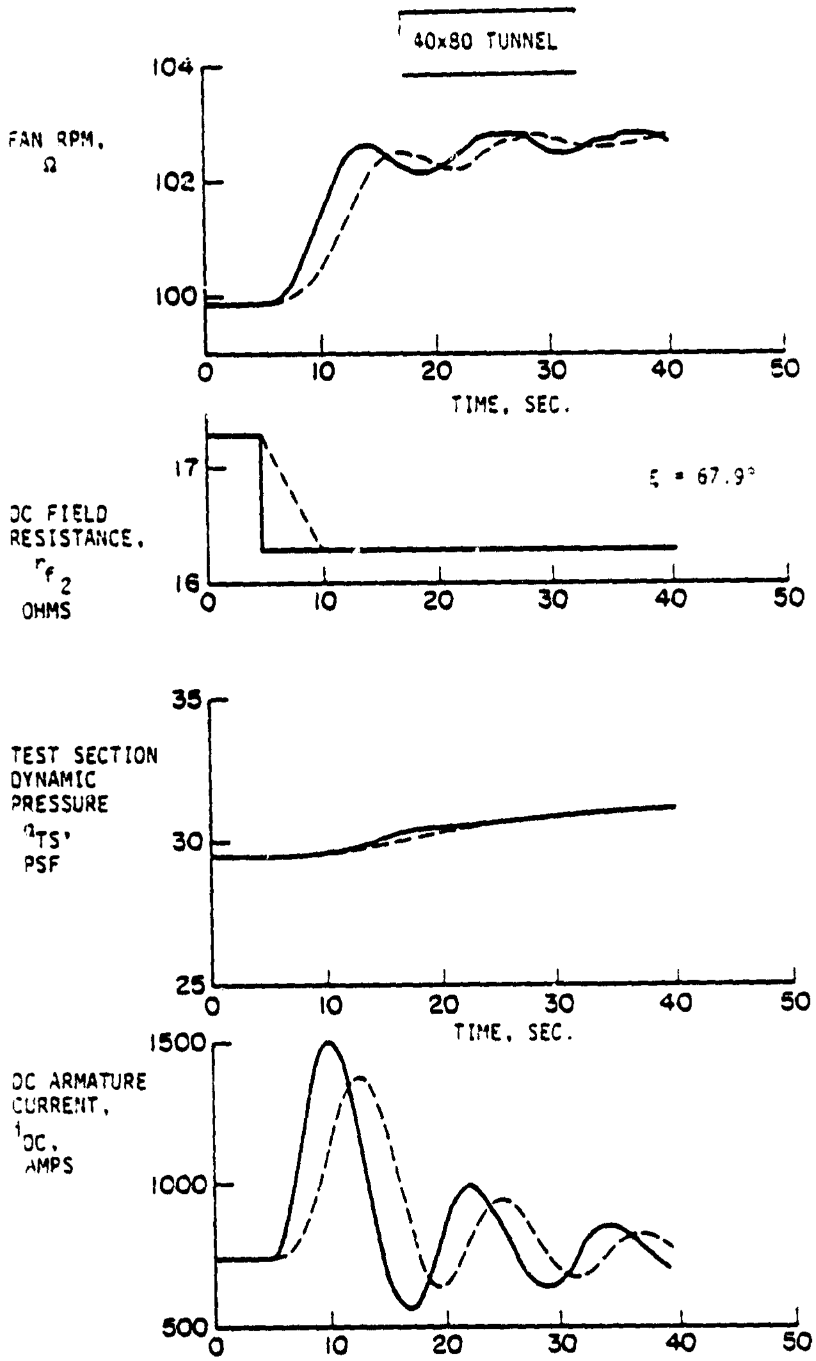


Figure 3.3-8 System Response to DC Generator Field Resistance (Current) Changes; Step and Ramp Compared; IFC Mode

fan RPM, though not of sufficient amplitude to appear in test section q.

If IFC torque is more strongly dependent on AC current than assumed here, the DC armature current fluctuations are more severe. A principal area in which more data are needed is the IFC machine electrical and mechanical characteristics.

This exercise illustrates some of the implications in control technique options. For example, the use of blade pitch rather than fan RPM must be considered against the endurance and reliability of the blade pitch actuation system.

3.3.3 Effect of Model Drag on Airspeed

As discussed in Section 2.2, model drag causes a reduction in airflow total pressure in the same manner as turning vanes, flow separations, and wall friction. An increase in model drag at a given operating condition will cause the tunnel speed to decrease unless the total pressure loss is compensated by increased head rise through the fan unit. The exact magnitude of speed loss depends on: (a) the magnitude of the model drag force; (b) the operating dynamic pressure and inflow ratio (Λ) at the fan unit; and (c) the blade pitch (stagger) angle, ξ. The controlling factor is the gradient $\partial p^o_{FAN}/\partial \dot{m}$ at the initial operating point, derivable from the fan pressure curves shown in Figs. 2.2-3 to -7.

Two cases of drag inputs were examined to illustrate the order of magnitude of the drag effect, each in the line power mode. Fig. 3.3-9 shows the effect of a 5000 lb drag step on tunnel q in the 40 x 80 circuit at initial ξ - settings of 48^o and 68^o, corresponding to q values of about 243 psf and 90 psf, respectively. In the former case the drag caused the q to fall to about 238 psf for a loss of 4.6 psf, and in the latter to about 87 psf for a loss of 2.7 psf. The time constant in both transients is about 5 seconds.

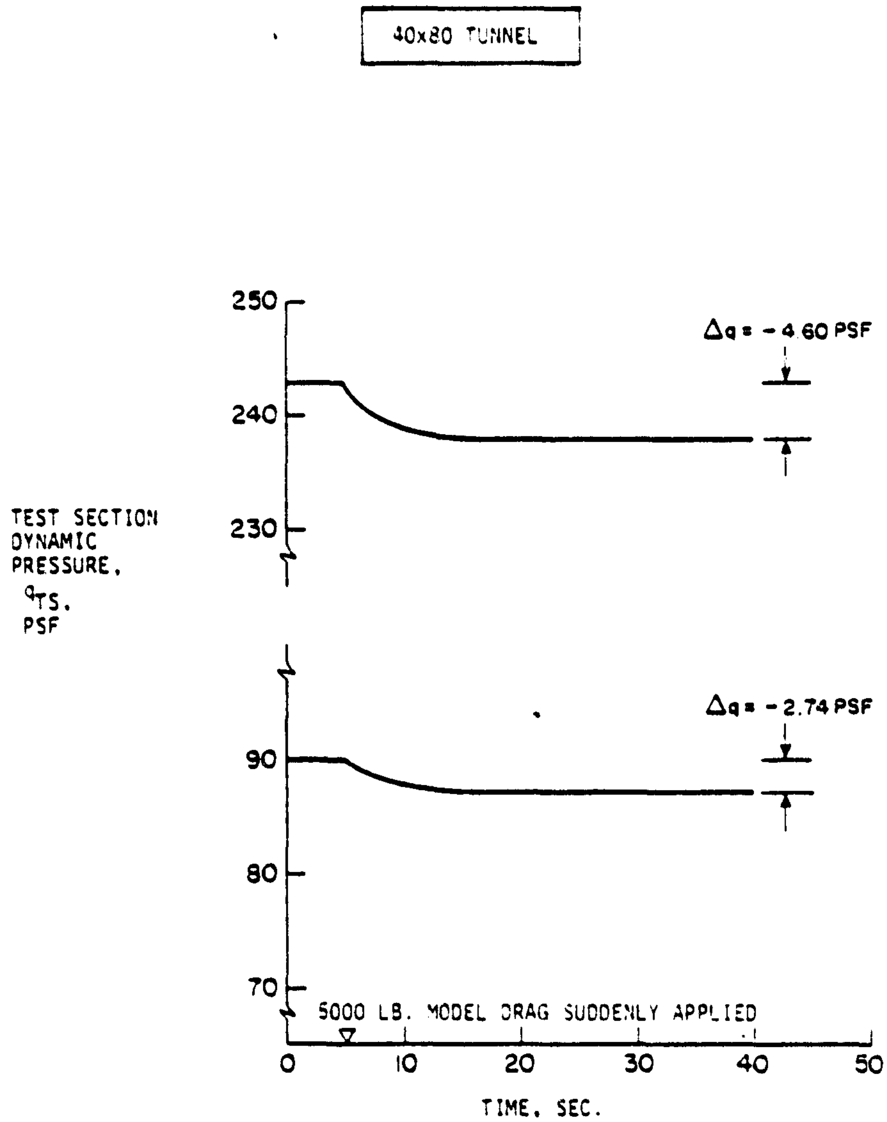


Figure 3.3-9 Dynamic Pressure Reduction Caused by Increased Model Drag, 40 x 80 Tunnel, D = 5000 lb

Fig. 3.3-10 shows the effects at the same operating conditions in the 80 x 120 ft tunnel: line power and $\xi = 48^o$ and 68^o. The initial q in the first condition was about 23 psf and fell to 22.9 psf after 5000 lb of drag was added; in the second condition the initial value of q was about 8.8 psf and fell to about 8.7 psf. The time constant was about 3 seconds in the former and 5 seconds in the latter.

In neither tunnel does the airspeed oscillate about the new equilibrium value: the airspeed mode is critically damped. This is mainly due to the use of synchronous drive motors which hold RPM very closely and thus do not couple with airspeed fluctuations when fan torque changes. Additional studies have shown that in the IFC mode as well, fan RPM is only slightly disturbed by fan torque; that is, fan RPM is tightly controlled by the DC unit field current settings.

3.3.4 Blade Rate Limits Due to Power Rate Limits

Decreasing stagger angle increases relative blade angle of attack and increases fan aerodynamic torque. The power absorbed by the drive motors increases accordingly. Since the tunnel airspeed setting time following transitions is on the order of several seconds while the power increase/decrease rate is specified over a minute, trim condition power levels are a good basis for the evaluation of power rates.

Crossplotting power level versus ξ from Figs. 3.2-1 and -2 yields estimates of the gradient $\partial P_e/\partial \xi$ at various operating points. Then,

$$\frac{dP_e}{dt} = \frac{\partial P_e}{\delta \xi} \cdot \frac{\partial \xi}{\delta t}$$

so,

$$\dot{\xi}_{MAX\ ALLOW.} = \frac{\dot{P}_{MAX\ ALLOW.}}{\partial P_e / \partial \xi}$$

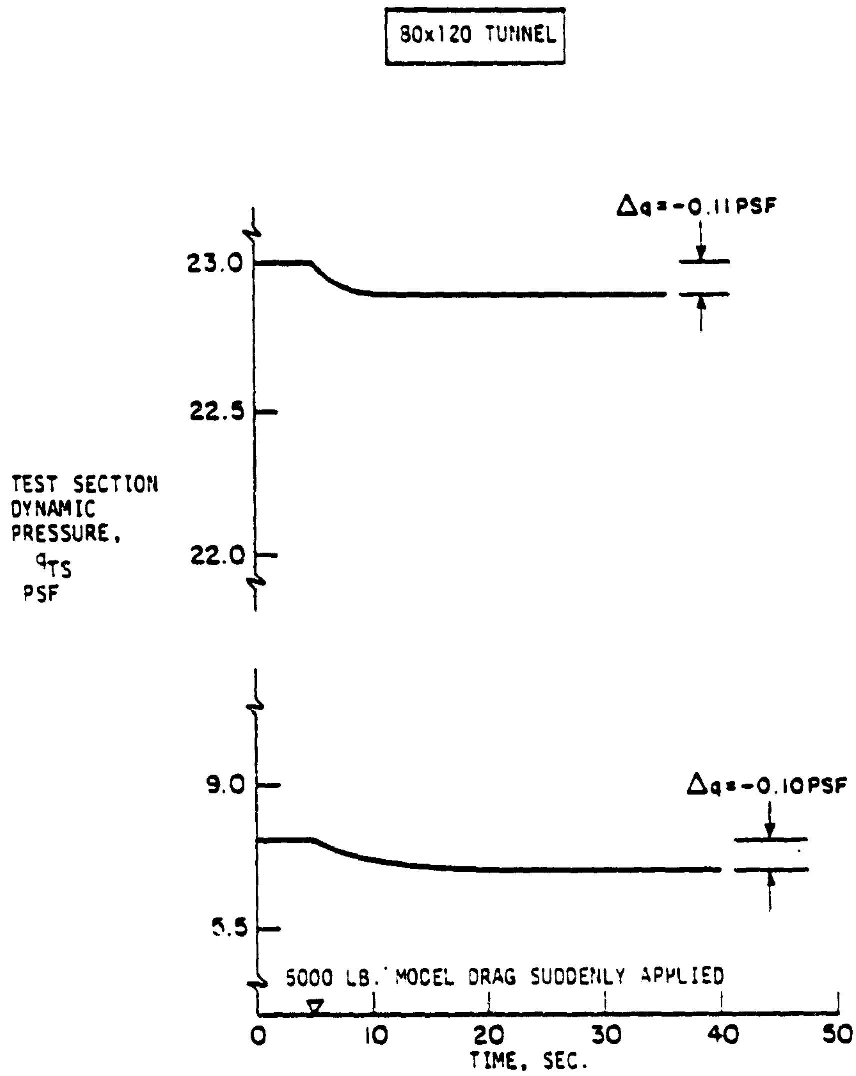


Figure 3.3-10 Dynamic Pressure Reduction Caused by Increased Model Drag, 80 x 120 Tunnel, ΔD = 5000 lb

From given criteria, $\dot{P}_{\substack{MAX \\ ALLOWABLE}} = \begin{cases} +25 \text{ MW/min increasing} \\ -50 \text{ MW/min decreasing} \end{cases}$

Computation of $\dot{\xi}_{MAX\ ALLOW.}$ based on these data are plotted in Fig. 3.3-11.

Power absorption levels are low in the IFC power mode, power absorption limits the blade rate to a minimum of

$$\dot{\xi} = \begin{cases} -.12^{o}/\text{sec} \\ +.24^{o}/\text{sec} \end{cases}$$

at $q = 350$ psf in the 40 x 80 tunnel, the most critical operating point. From the discussion of flow acceleration capability with unlimited power availability, Section 3.3-2, in which blade rates in excess of $\pm 2^{o}$/sec. were found acceptable from the point of view of fan surge, it is clear that the critical design constraint on blade actuation rate will be the power rate limit.

It is notable that the rate of change of the blade rate limit with dynamic pressure is low, increasing only to about $+0.2^{o}$/sec/-0.4^{o}sec as q is decreased to 100 psf.

3.3.5 Emergency Stop Time Histories

The math model contains a provision for setting all electrical power to zero at a selected time, simulating the opening of main circuit breakers in an emergency stop. Of principal interest and concern are the rate of dynamic pressure decay and the process of adjustment of fan pressure rise from a flow-forcing to a flow-retarding condition.

The results of several simulated emergency stops are shown in Figs. 3.3-12 to -15. Fig. 3.3-12 shows the decay of dynamic pressure from two operating conditions in the line power mode, for the 40 x 80 tunnel. Fig. 3.3-13 shows the accompanying changes in fan pressure rise and fan RPM. It is seen that fan pressure rise rapidly changes sign and the fan retards the flow; the peak

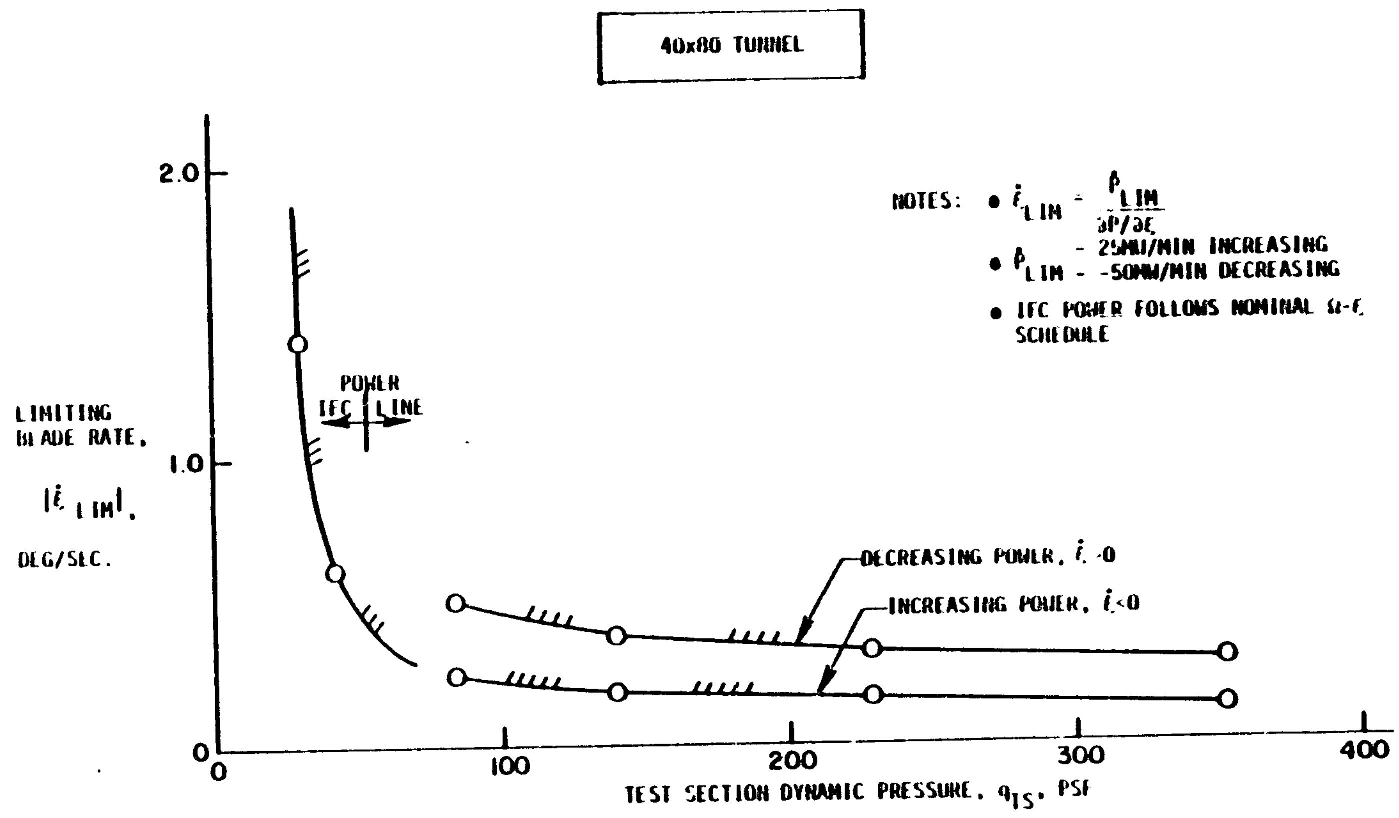


Figure 3.3-11 Blade Rate Limits Required by Power Rate Constraints

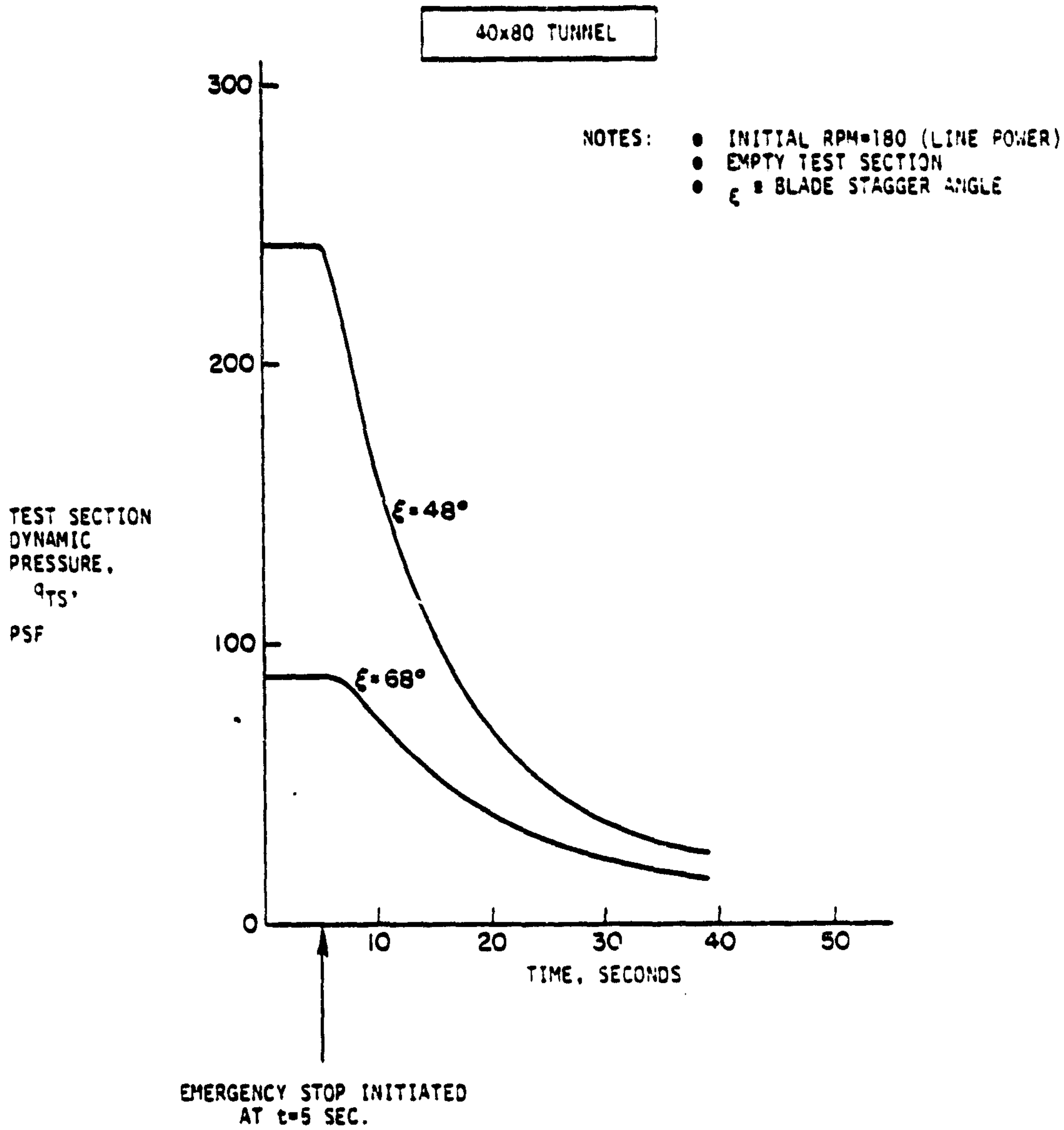


Figure 3.3-12 Dynamic Pressure Decay Following Emergency Stop From Two Operating Conditions 40 x 80 Tunnel (Modified)

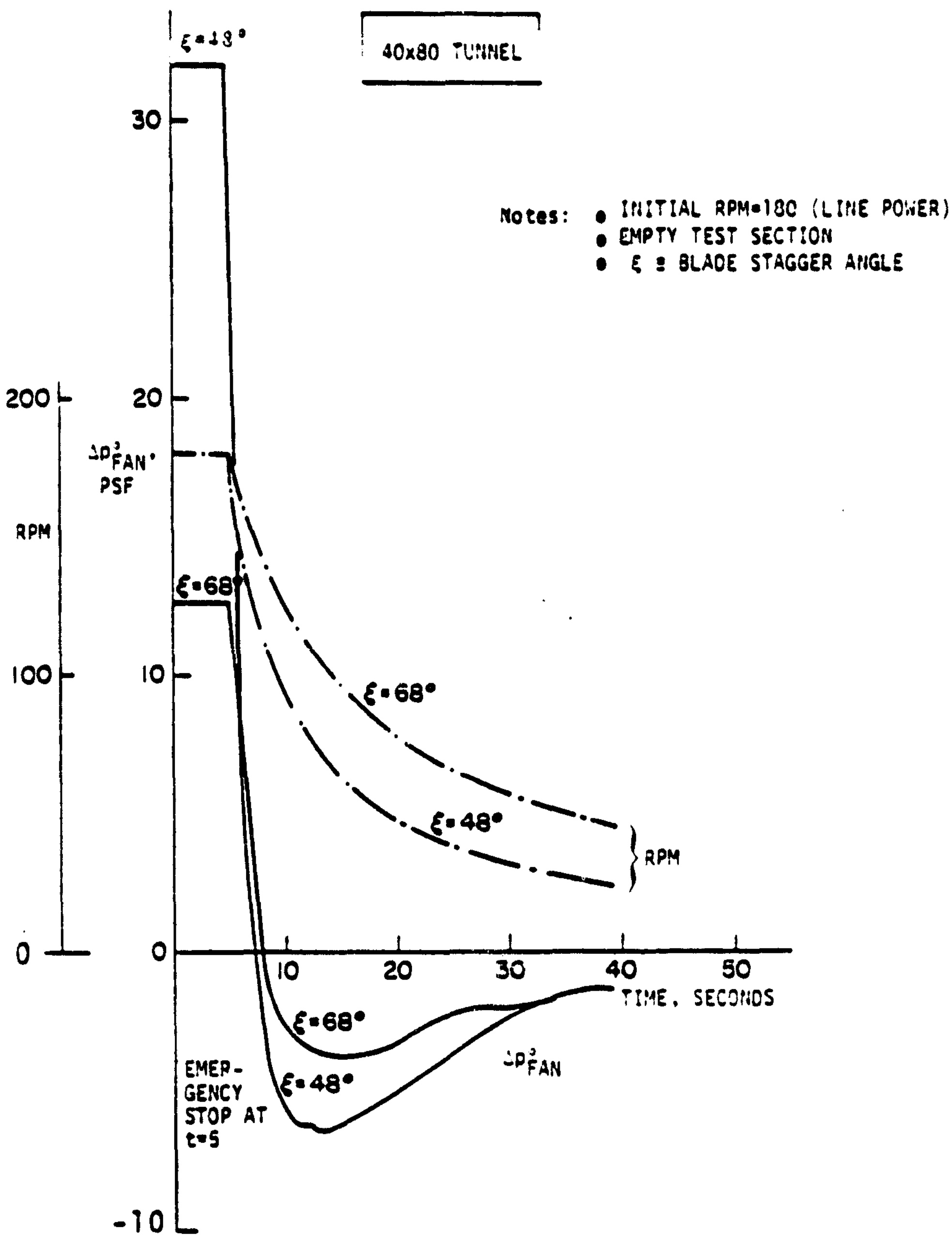


Figure 3.3-13 Fan Pressure Rise and RPM Variations Following Emergency Stop, From Two Operating Conditions, 40 x 80 Tunnel (Modified)

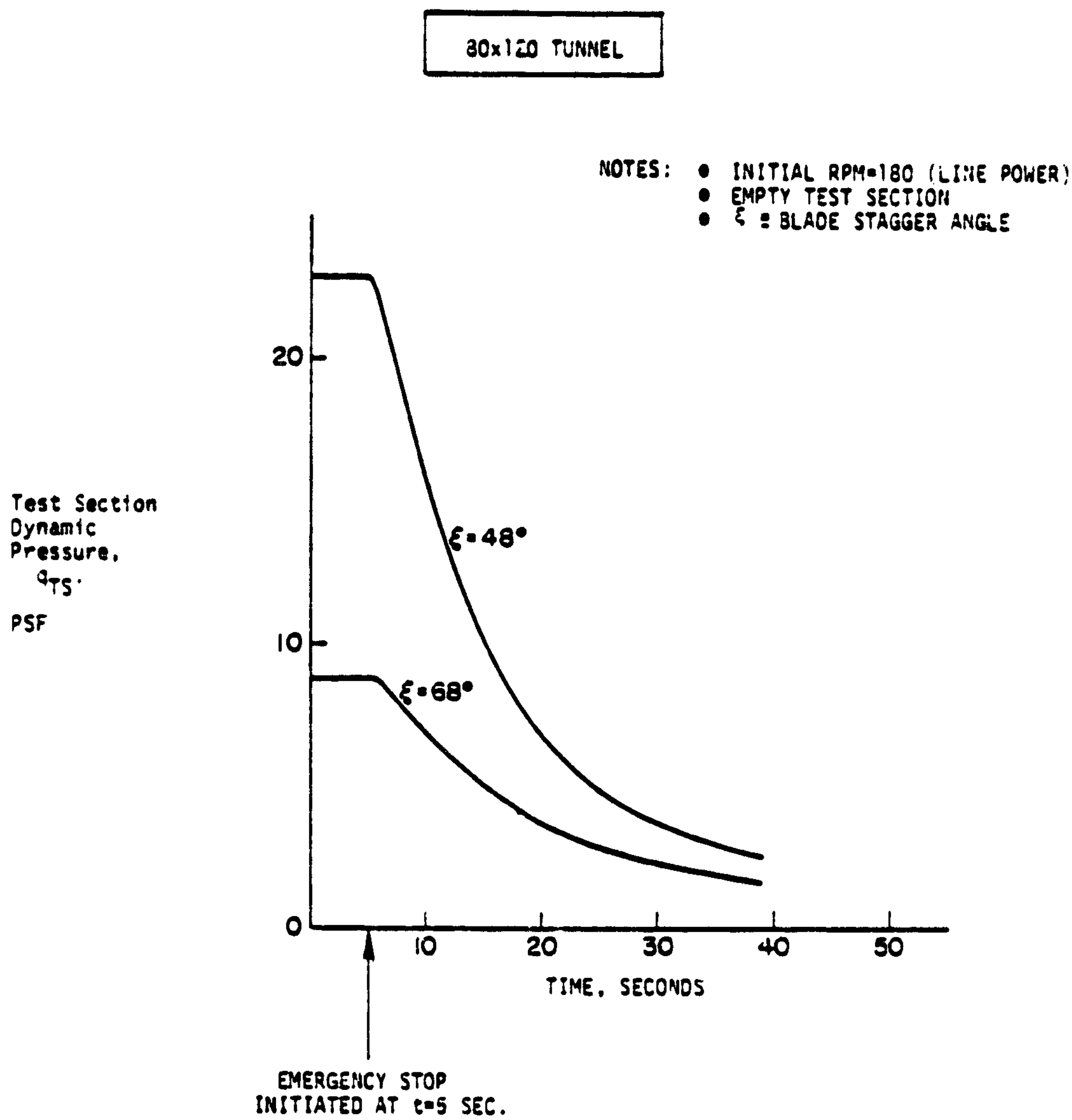


Figure 3.3-14 Dynamic Pressure Decay Following Emergency Stop, From Two Operating Conditions, 80 x 120 Tunnel

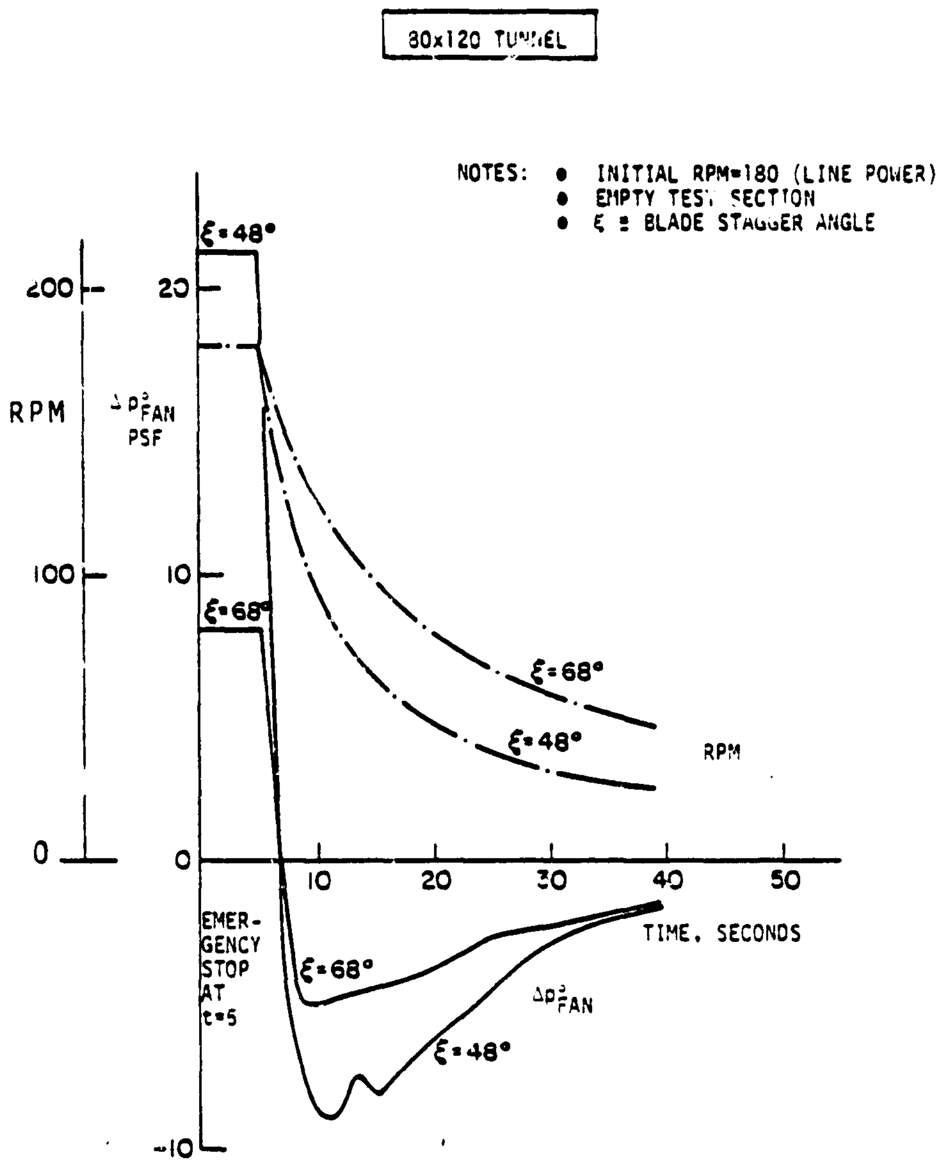


Figure 3.3-15 Fan Pressure Rise and RPM Variations Following Emergency Stop, From Two Operating Conditions, 80 x 120 Tunnel

negative pressure resulting from the q_i = 243 stop is about -6 psf, compared to the initial value of +32 psf; the peak negative pressure is reached about 7 seconds after the stop is initiated.

Fig. 3.3-14 shows the q-decay for the 80 x 120-ft tunnel for the same two operating conditions, and Fig. 3.3-15 shows the fan pressure and RPM variations. Compared to the 40 x 80, these cases show lower drive fan pressures prior to the stop but higher fan negative pressures during the stop, the peak for the high-speed case being about -9 psf and occurring about 5.5 seconds after the stop is initiated. The conclusion is that emergency stops impose higher fan loads during 80 x 120 mode operation.

The fan negative pressure rise data are based on theoretical estimates for the fans in stalled conditions, and should be the object of early revision when new data becomes available. Whatever the magnitudes change, however, the relative severity of the 80 x 120 stops will remain.

3.4 80' x 120' TUNNEL RESPONSE TO EXTERNAL WIND DISTURBANCES

The 80' x 120' tunnel, open to the atmosphere at both ends, is subject to flow velocity changes caused by external winds. The following theoretical analysis was performed to gain an understanding of the expected magnitude of such disturbances and of their controllability by the drive fans. Such an analysis yields more insight into the problem than parametric studies using the simulation math model.

From the dynamical equation for tunnel airflow given in Section 2.2, the following equation may be written for flow acceleration in response to a net pressure differential Δp_g° imposed on the tunnel by external winds:

$$\frac{d}{dt}(\dot{m}) = \frac{A_F}{L_{ref}} \quad \Delta p_g^{\circ} \frac{A_1}{A_F} + \frac{\partial p_{FAN}^{\circ}}{\partial \dot{m}} \Delta\dot{m}$$

from which we obtain the transfer function for $\dot{m}$ to gust pressure:

$$\frac{\Delta\dot{m}(s)}{\Delta p_g^{\circ}(s)} \equiv H_p(s) = \frac{A_1/L_{ref}}{s + \dfrac{A_F}{L_{ref}} \dfrac{\partial p_{FAN}^{\circ}}{\partial \dot{m}}}$$

where A_1 = inlet area = 54439 ft^2, A_F = fan unit area = 7539.82 ft^2, and L_{ref} = 1464 ft (including the pseudo-length increase due to the external air mass). The factor $\partial p_{FAN}^{\circ}/\partial \dot{m}$ is determined by the pressure curves of Section 2.3, and changes slightly according to operating point. Using a nominal value $\partial p_{FAN}^{\circ}/\partial \dot{m}$ = -0.013 psf/slug/sec leads to the transfer function,

$$H_p(s) = \frac{37.19}{s + .066} \quad .$$

The transfer function magnitude is shown in Fig. 3.4-1, illustrating a simple first-order roll-off at $\omega = .066$ rad/sec. It will be noted that this break frequency corresponds to a time constant of 16 sec.

We now wish to determine the response of $\dot{m}$ to an external pressure disturbance with the characteristics of atmospheric turbulence. The tunnel $\dot{m}$ response will be found by power spectral analysis; given the gust disturbance pressure power spectrum, $\Phi_{p^\circ}(\omega)$ the resulting $\dot{m}$ power spectrum is given by

$$\Phi_{\dot{m}}(\omega) = |H_p(\omega)|^2 \; \Phi_{p^\circ}(\omega),$$

indicating those frequencies of $\dot{m}$ response that will be excited by the turbulence.

The atmospheric turbulence power spectrum is a convenient way of representing the statistical characteristics of random gust velocity magnitudes. This subject has been studied extensively for its importance to aircraft safety and handling qualities. Turbulence intensity is found to depend on mean wind speed V_w according to the following relation:

$$\Phi_v(\omega) = \frac{2L}{\pi V} \frac{1}{1 + \omega^2 L^2/V_w^2} \cdot \sigma^2 \qquad \text{(Ref. 10)}$$

where

ω = frequency in radians/sec,

V_w = mean wind speed in ft/sec,

L = characteristic turbulence length = 1000 ft (nominally),

σ = gust rms intensity.

Φ_r = gust velocity power spectral density.

This is the so-called Dryden model of atmospheric turbulence, shown plotted for a V_w = 30 fps condition in Figure 3.4-2.

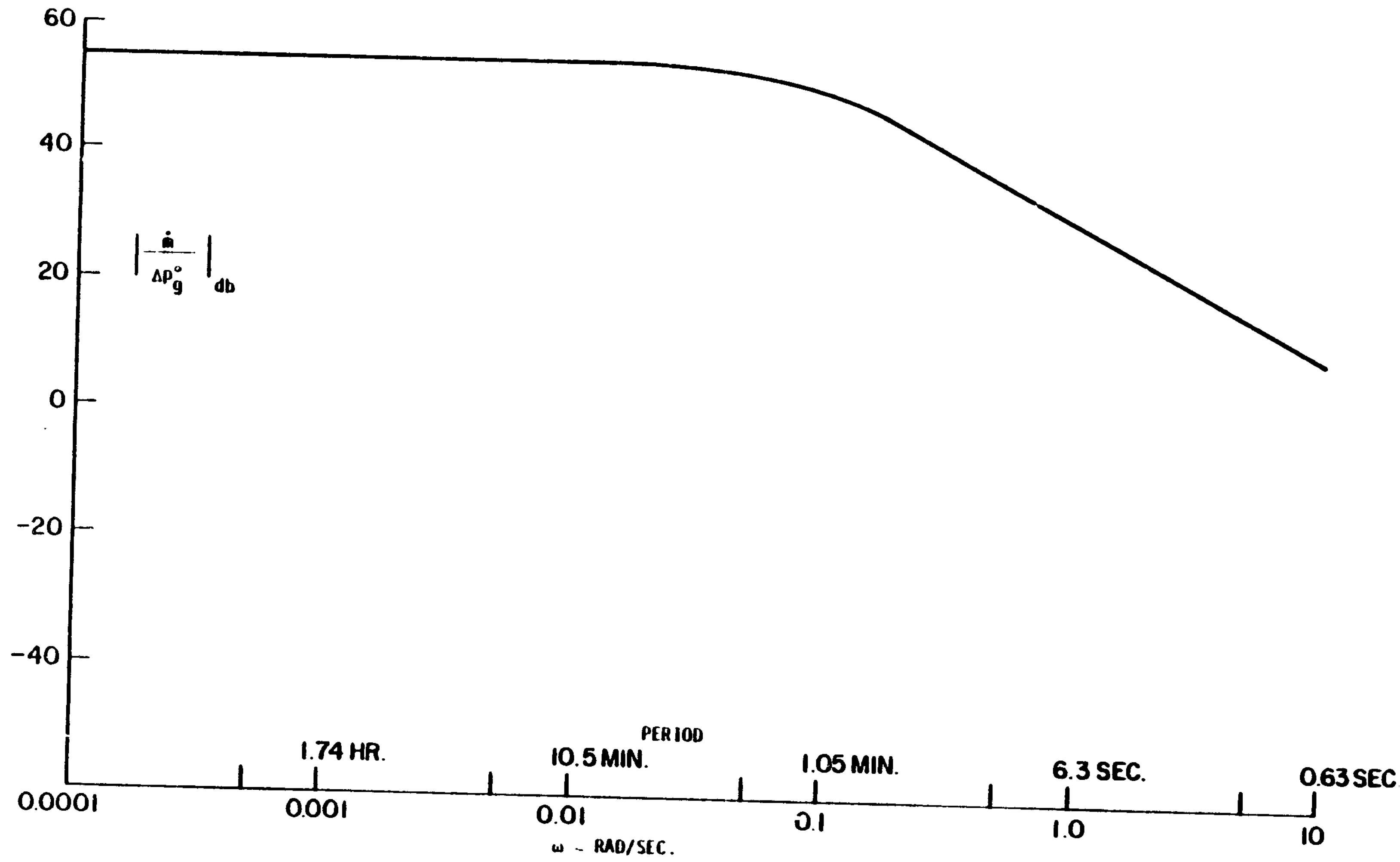


Figure 3.4-1 Tunnel Massflow Response Amplitude

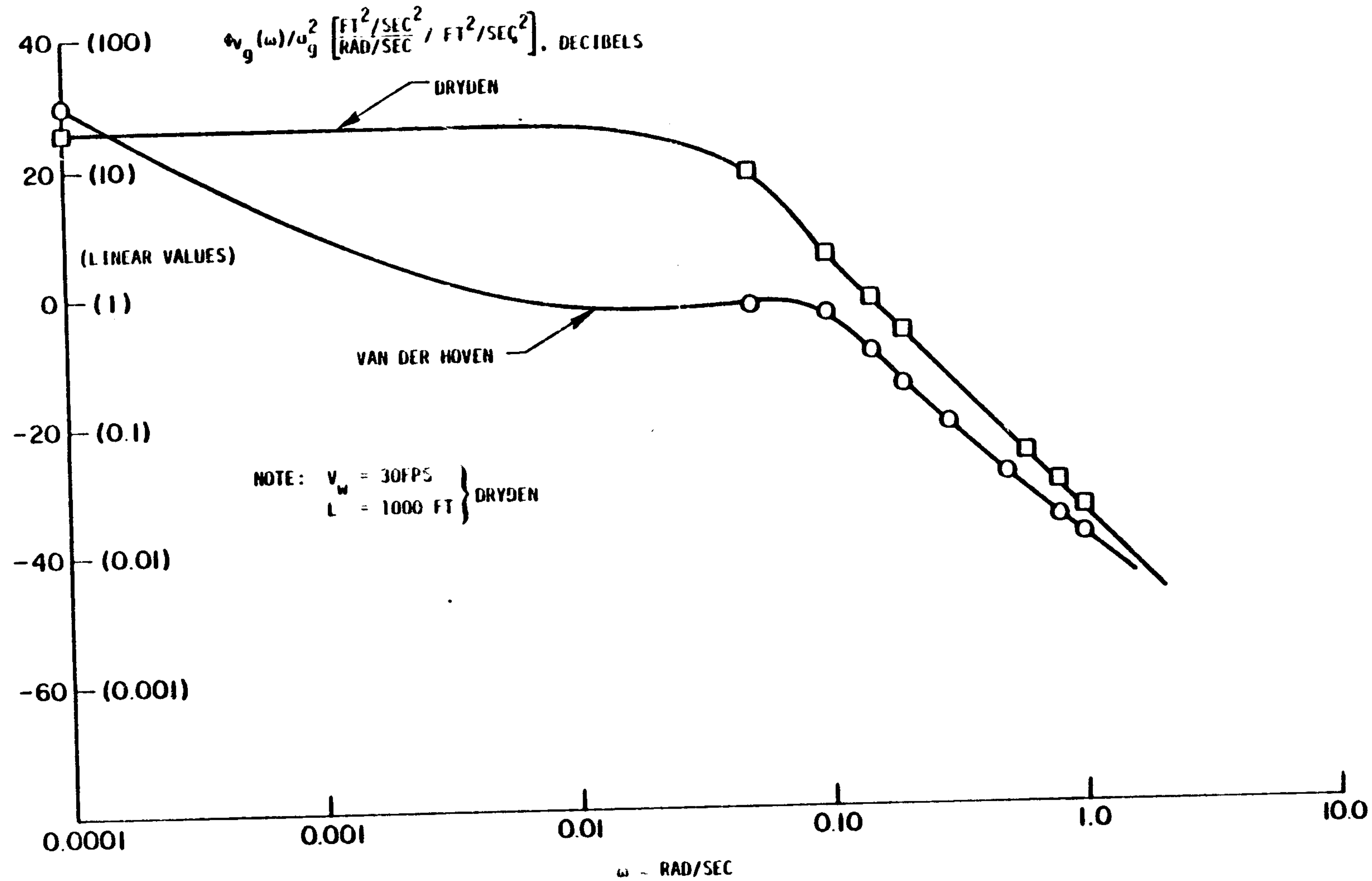


Figure 3.4-2 Atmospheric Turbulence Spectra

Also shown plotted in Figure 3.4-2 is an atmospheric turbulence spectrum determined by VanDerHoven (Ref. 11). It shows general agreement with the Dryden spectrum except that it predicts less intensity in the region of $\omega = .01$ rad/sec.

Note that the vertical scale of these figures is in decibels, where

$$|\Phi|_{db} = 20 \log_{10}|\Phi|,$$

a convenient linear representation of a logarithmic scale.

When the wind tunnel is operating under steady conditions, the velocity of the air at the inlet is proportional to m, at atmospheric total pressure. In this analysis, the effect of a gust striking the face of the tunnel will be viewed as an instantaneous increase of static pressure at the inlet, corresponding to a ram pressure exerted by a jet of ar. This pressure is proportional to the dynamic pressure in the gust; hence,

$$p_g^\circ \propto \frac{1}{2} \; V_g^2$$

where $V_g = V_{TOTAL} - V_{INLET}$. It is assumed that the mean wind speed has previously been trimmed out. It is further assumed that the gust pressure represents the true net pressure force acting on the wind tunnel; if equal and opposite gusts acted on both ends of the tunnel, the effect on m would be greatly reduced. The assumptions thus made, plus the consideration of the higher turbulence levels associated with the larger $V_w = 30$ fps case, result in a "worst case" analysis.

The gust velocity spectrum is transformed to a gust pressure spectrum by the relation

$$\Phi_{\Delta p_g^\circ}(\omega) = (\tfrac{1}{2}\rho)^2 \; \Phi_{V_g^2}(\omega)$$

where

$$\Phi_{V_g^2}(\omega) = \frac{1}{\pi}\left[\Phi_{V_g}(\omega) * \Phi_{V_g}(\omega)\right] \qquad (\omega \neq 0)$$

with "*" denoting the convolution operation. The gust pressure spectrum is plotted in Figure 3.4-3, for gust rms values of 1 and 2 ft/sec.

The tunnel massflow response spectrum is now easily obtained from the relation

$$\Phi_{\dot{m}}(\omega) = |H(\omega)|^2 \, \Phi_{\Delta p}(\omega),$$

as mentioned above. When working with decibel curves,

$$\Phi_{\dot{m}}(\omega)\Big|_{db} = 2|H(\omega)|\Big|_{db} + \Phi_{\Delta p}(\omega)\Big|_{db} \quad .$$

The massflow response power spectrum, plotted in Figure 3.4-4 shows that long-duration disturbances, with periods in excess of 10 minutes, will be transmitted without attenuation through the wind tunnel, resulting in long-period changes in test section speed. As a practical matter, extremely long-period gusts (periods greater than an hour) will probably be masked by diurnal changes of mean wind characteristics. Periods shorter than approximately one minute will be attenuated by fan aerodynamic characteristics. It is clear that very high frequency turbulence does not appear in tunnel speed.

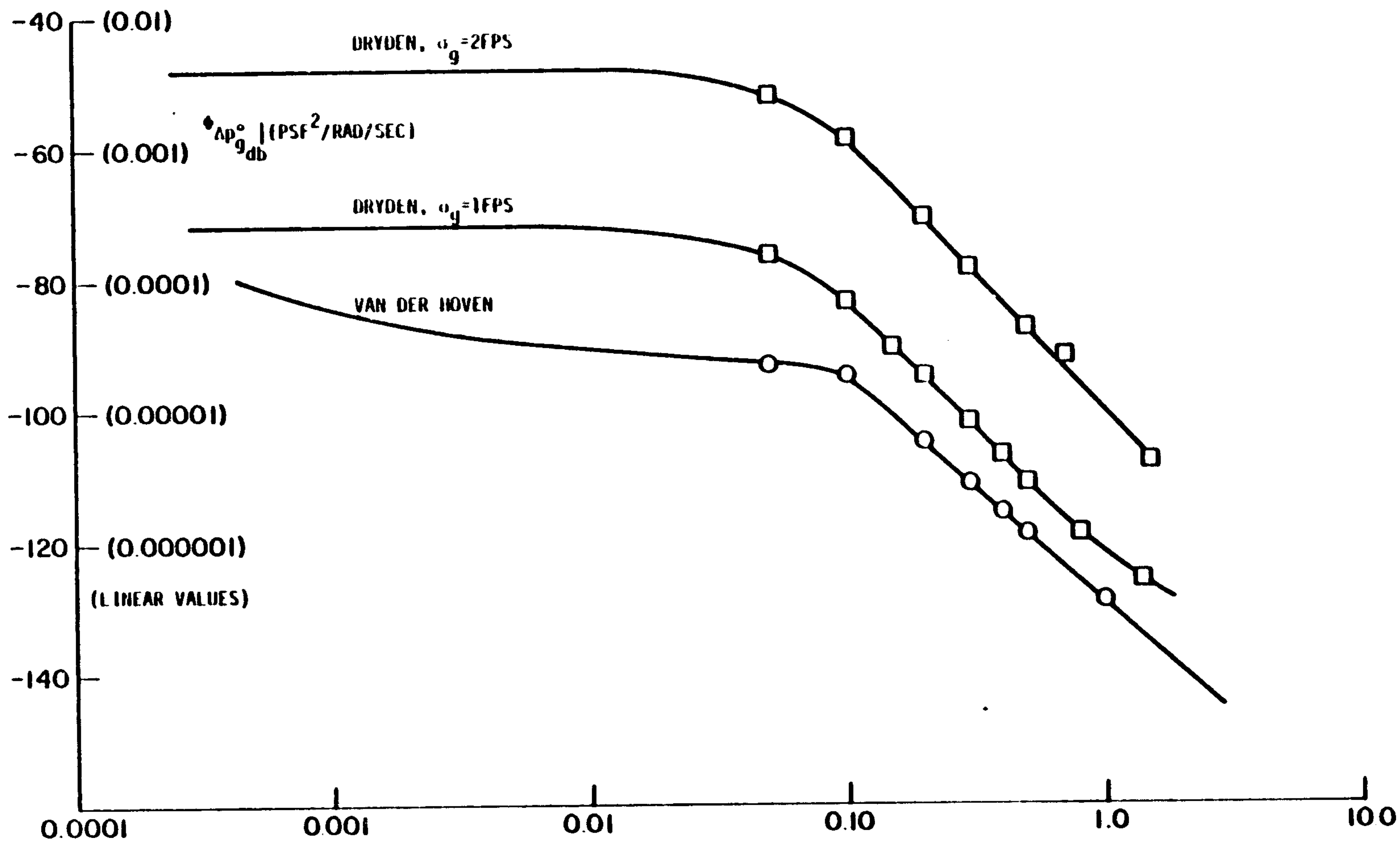


Figure 3.4-3 Gust Pressure Spectra

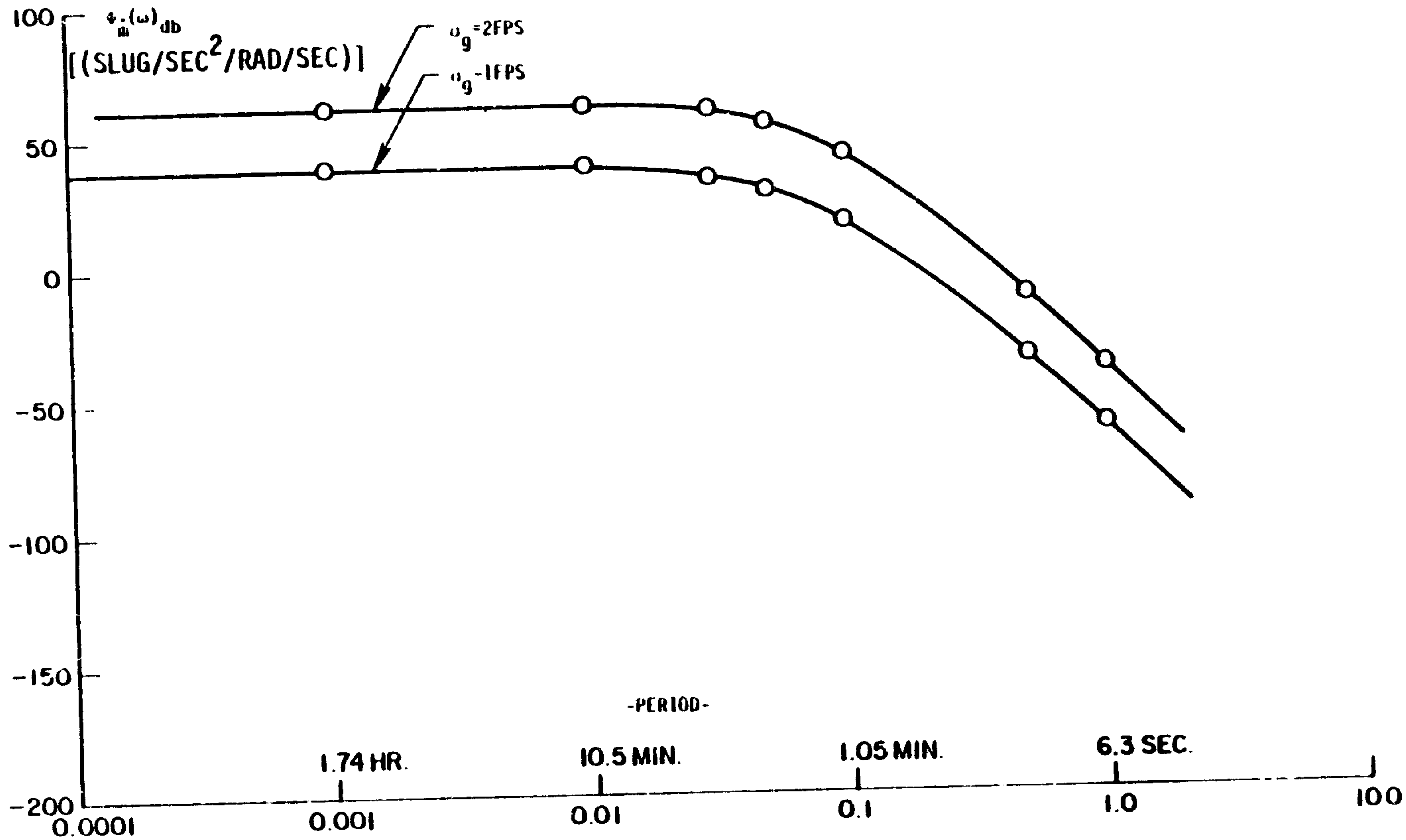


Figure 3.4-4 Tunnel Massflow Response Power Spectrum

The root mean square value of tunnel airspeed disturbance may be computed from the manflow power spectrum. The turbulence is assured to be a Gaussian random variable with zero mean, so that the mean square value of the disturbance is given by:

$$\sigma_{\dot{m}}^2 = \frac{1}{\pi} \int_0^{\infty} \Phi_{\dot{m}}(\omega)\, d\omega$$

Integrating the spectra shown in Figure 3.4-4 gives the rms distrubance value,

$$\sigma_{\dot{m}} = \begin{cases} 1.09 \text{ slug/sec}, & \sigma_g = 1 \text{ fps} \\ 4.55 \text{ slug/sec}, & \sigma_g = 2 \text{ fps} \end{cases}$$

Computing test section velocity from $V_{TS} = \dot{m}/\rho A_{TS}$, it is found that

$$\sigma_{V_{TS}} \begin{cases} .05 \text{ ft/sec}, & \sigma_g = 1 \text{ fps} \\ .20 \text{ ft/sec}, & \sigma_g = 2 \text{ fps} \end{cases}$$

These disturbances are small relative to mean tunnel airflow velocity, and will require special instrumentation to be detected. At $V_{TS} = 150$ ft/sec, a ΔV of 0.2 ft/sec. leads to $\Delta q = 0.076$ psf. The basic tunnel manometric q-measuring system should be augmented by a sensitive airspeed-measuring device, such as a paddle to measure impact pressure or a rotating-arm transducer device such as has been developed for V/STOL aircraft.

Under the assumptions of this analysis, therefore, the effect of random atmospheric turbulence on test section speed is predicted to be small.

If it is desired to attempt to correct for the speed perturbation by varying fan blade pitch, the capability of the fans in this application can be determined from the pressure spectra of Figure 3.4-3. Considering the $\sigma_g = 2$ fps spectrum, it is found by the above method, using

$$\sigma^2_{\Delta p^\circ_g} = \frac{1}{\pi}\int_0^{\infty} \Phi_{\Delta p^\circ_g}(\omega)\, d\omega$$

that

$$^{c}\Delta p^{\circ}_{g} = .0088 \text{ psf, rms, for } \sigma_g = 2 \text{ fps.}$$

From fan performance data, Appendix 1, a nominal variation of head rise coefficient may be determined to be: $\partial K_{T_V}/\partial\xi = .05/$deg, a conservative value. The fan's ability to generate pressure is determined by fan RPM and tunnel speed ($U/\Omega R$ = inflow ratio) and blade pitch angle. From Figure 3.4-3, the fan pressure required as a function of frequency may be determined; then,

$$\Delta p^{\circ}_{FAN_{REQ'D}} = \Delta p^{\circ}_{g} \cdot A_1/A_F$$

The relation

$$\Delta p^{\circ}_{FAN_{REQ'D}} = \Delta K_{T_V} \cdot \frac{1}{2}\rho V^2_{FAN} = \frac{1}{2}\rho V^2_{FAN} \frac{\partial K_{T_V}}{\partial \xi} \Delta\xi$$

shows that a larger $\Delta\xi$ is required at lower tunnel speeds, to obtain a desired Δp°_{FAN}.

The fan pressure requirement is

$$\Delta p^{\circ}_{FAN_{REQ'D}} = \delta_{\Delta p^{\circ}_{g_{rms}}} \sqrt{2} \cdot (A_1/A_{FAN})$$

$$= .090 \text{ psf. (peak-to-peak)}$$

if it is assumed that the full pressure must be generated at a single frequency near the upper limit of the disturbance spectrum, here taken to be ω= 0.1 rad/sec. The blade rate requirement may now be computed for each tunnel speed, knowing the pressure requirement and the frequency at which it is to be generated, since

$$\dot{\xi}_{REQ'D, MAX} = \Delta\xi \cdot \omega = \frac{\Delta p^{\circ}_{FAN_{REQ'D}}}{\frac{1}{2}\rho V^2_{FAN}\ \partial K_{T_V}/\partial\xi} \cdot \omega$$

The results are shown in the following table, for a range of tunnel speeds:

V_{FAN} (fps)	V_{TS} (KTS)	$\dot{\xi}_{REQ'D}$ (deg)
25	11.6	.24
50	23.2	.06
75	34.8	.027
100	46.4	.015
125	58.1	.010

This shows the control of predicted gust effects to be feasible below 20 knots test section speed, using the nominal 0.08%/sec blade rate, if suitable sensors are available to provide data for the blade actuator command. Actuation system time delays, felt to be on the order of one second, do not seriously alter this conclusion, since the periods of the gusts of concern are greater than 30 seconds.

In conclusion, the effects of moderate atmospheric gusts on 80x120 test section velocity are expected to be small, relative to normal test speeds, and to be controllable with the present blade pitch actuation system. Implementation of a gust-control system will require the development of special airspeed sensors and consideration of the possibly detrimental effect on the blade pitch actuation system of continuous, small adjustments in blade pitch. Both of these areas are recommended for further study. An additional conclusion is that turbulence at frequencies sufficient to excite the synchronous motor swinging mode (approximately 7 rad/sec) will be of negligible amplitude.

IV. CONTROL AND MONITORING SYSTEM

4.1 GENERAL SYSTEM STRUCTURE

4.1.1 Overview

This section considers the characteristics of a computer-based system intended to perform monitoring and control augmentation functions to achieve improved overall efficiency and safety in 40' x 80'/80' x 120' tunnel operation. This may be broadly interpreted as achieving savings in both time and energy consumption and providing additional information on tunnel system operational status.

Potential sources of savings in time include:

(1) faster acquisition of tunnel speed setting and efficient compensation for test section flow disturbances;

(2) faster model attitude adjustment between runs;

(3) reduced downtime through improved tunnel and test article status information; and

(4) improved data quality assurance and data display to the test engineer, combined with some level of automatic test point sequencing.

Test sequencing assistance may take the form of either automatic control of test parameters or real-time display of future test points for operator action.

Potential sources of energy savings include:

(1) operation at minimum acceptable tunnel speed or, in IFC mode, minimum fan RPM; and

(2) reduction of run time, as by the above methods.

A principal objective of this investigation was an evaluation of the application of modern computer technology to the wind tunnels to achieve the desired savings in time and energy and improved safety and data quality. It was further desired to explore such computer system application down to the implementation level and specify both its function and interfaces with the wind tunnel and the general requirements covering the procurement of such a system. An additional objective was to design and demonstrate (by simulation) a tunnel speed/q controller that would ultimately reside in part of the computer system to achieve the first goal in improved tunnel operation, that of consistent speed command and control.

This section and the following section (Section V, Specifications) present the results of this evaluation. The remainder of this section is devoted to the discussion of computer subsystem requirements relevant to performing the required functions; the following paragraphs present background material and a summary description of the selected system configuration.

4.1.2 Control Hierarchy and Redundancy

Automatic wind tunnel control is divided into distinct levels, each level characterized by the level of automation present and, by implication, the degree of operator activity required. It is useful to preface computer system discussion with an illustration of the concept of control hierarchy to be followed in this evaluation, shown in Figure 4.1-1. The basic manual control level corresponds to the current method of tunnel and model attitude control, though it may be augmented by more sophisticated displays to give control instructions to the tunnel operator. All control is by the operator at this level, as it is his judgement and observation which "close the loop." The operator receives his instructions from the test engineer.

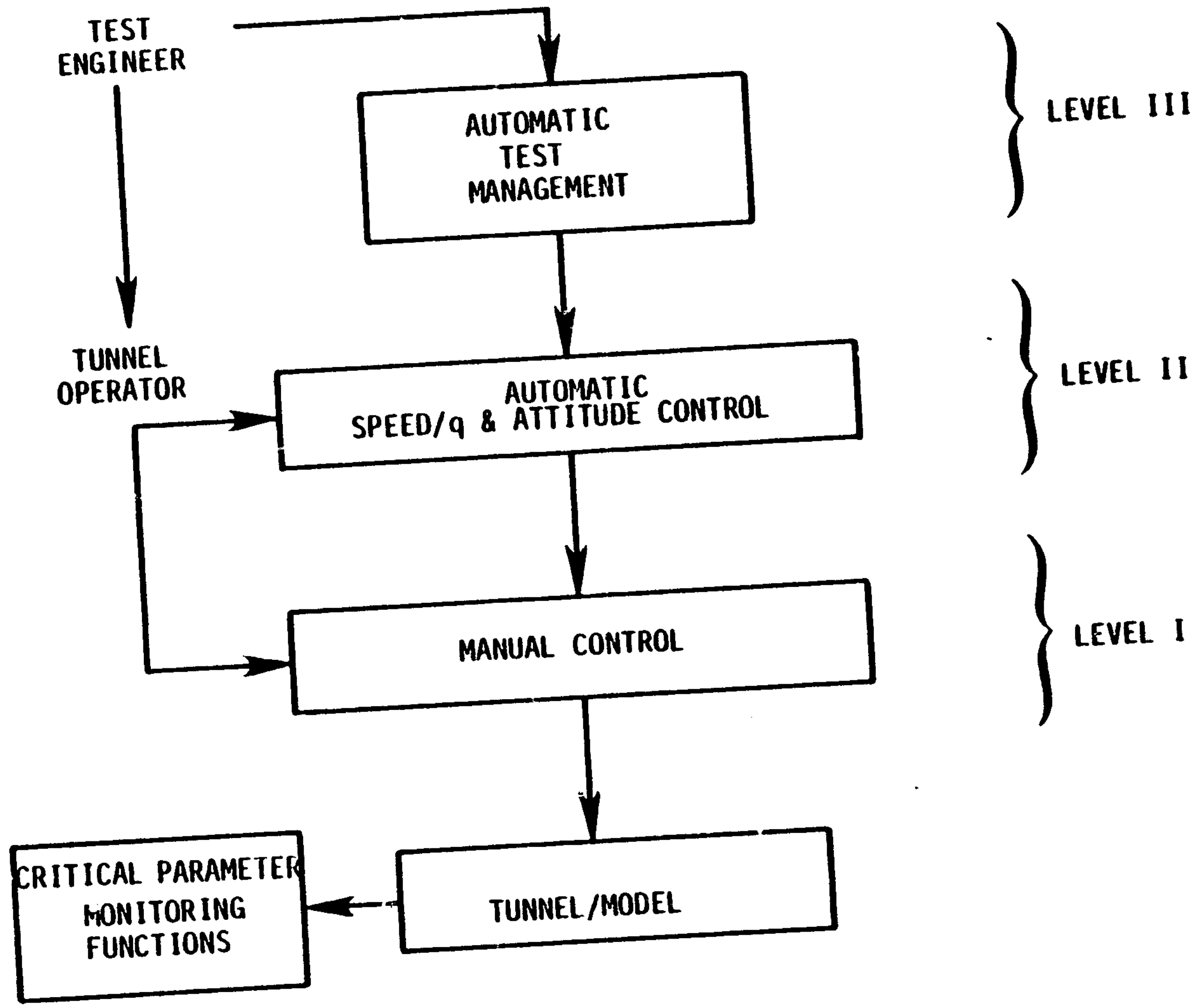


Figure 4.1-1 Definition of Levels of Control

The next level is automatic control of tunnel speed and/or model attitude. This is controlled by the operator as well, but in a different sense: he merely provides the command, while the automatic system "closes the loop" to achieve the command in a (presumably) more rapid and efficient manner.

The third level of control is performed by a system which receives commands from the engineer and translates them into commands to the speed and/or model attitude control systems. This system thus converts test commands from the engineer into tunnel condition commands, automatically: this is test management. As shown in the figure, manual authority still exists from the engineer through the operator to the tunnel using manual controls. This system hierarchy will be referred to in subsequent discussions.

A word concerning system reliability is also pertinent. Table 4.1-1 summarizes four levels of reliability, from the fail-off level of a single-thread system wherein any one failure within the system can disable it with threat of hazard, to fail-safe, fail-operational, and fail-fail-operational. Examples are given in the table.

The level of redundancy desired has a large impact on the configuration of the computer system. Functions for which a high level of reliability is required demand redundant controller units with increased costs for both the computer hardware and the more involved firmware development. This demand may be relaxed if a manual backup is specified, since it may be assumed that the computer system need only be fail-safe, i.e., leave the system in a passive state when it disconnects due to a failure. The availability of a manual backup is made a groundrule in the present study in the cases of the speed/q and model attitude control systems and, as will be seen, appears to be an appropriate basis for the test management system design also.

The degree of flexibility desired of the system also has a large impact on its configuration. The choice is one of placing

Table 4.1-1

Definition of Levels of Reliability

LEVEL OF RELIABILITY	DEFINITION	HOW ACHIEVED
Fail Off	Unsafe after one major component failure	1 Channel
Fail Safe	Safe after one major component failure	2 Channels plus man. backup
Fail Operational	Operational after one major component failure, safe with second different failure	3 Channels plus voting plus man. backup
Fail-Fail Operational	Operational after two major component failures, safe with third	4 Channels plus voting plus man. backup

all computer functions in three large redundant machines, or of providing for the required functions with smaller subsystems whose redundancy (hence, reliability) may vary from one function to another. The former alternative has the disadvantage of possibly requiring a large equipment expenditure to assure one small, but essential function; the latter approach offers much more flexibility but at the expense of higher programming effort. In a developmental system where the initial level of automation is not to be the final level, such flexibility results in a lowering of initial procurement cost.

4.1.3 System Implementation

Determination of the recommended computer system for wind tunnel monitoring and control purposes is made from consideration of such factors as the following:

(1) required functions to be performed;

(2) computer speed requirements;

(3) requirements on size and type of computer memory;

(4) word size requirements;

(5) initial hardware and firmware (program development) costs;

(6) intrinsic reliability considerations; and

(7) compatibility among system elements.

The basic implementation options are:

(1) analog devices;

(2) microprocessor devices and programmable controllers based on them; and

(3) minicomputers.

Typical sources for these devices are shown in Table 4.1-2, with comments on their applicability.

Table 4.1-2

Representative Control System Implementation Hardware

OPTION	SOURCES	FLEXIBILITY	RELIABILITY	COMPONENT COUNT	FIRMWARE COSTS	MAINTENANCE	COMMENTS
Analog	Leeds & Northrup 400 Series Bristol 2000 and CEM Series ACM TA4000 Series	None	Med	High	None	Med	Large Numbers of Arithmetic Elements in System-Extremely Difficult to Aligh and Keep in Adjustment-High Component Count Adversely Affects Reliability
Programmable Controller	Modicon Leeds & Northrup Allen-Bradley	Low	High	Med	Low	Low	Commercially Available Systems do not have the Flexibility to Perform Level 1 Speed Hold Control. Would Have to be Combined with Analog Control Modules - it is a Micro-Processor with Unneeded Overhead.
Micro-Processor	Motorola 6800 Intel 8080 Dec LSI 11	Med	High	Low	Low	Low	Very Flexible with High Reliability and Low Software Costs. Can be Programmed in High Level Language if Desired. Software can be Fixed in Prom.
Mini-Computer	Dec PDP 11-XX Data General Nova MODCOMP 11	High	Med to High	High	Med	Low	Fully Flexible for all Levels of Control-Reliability Quite High with Non-Mechanical Buld Memory-Software Costs Depend Upon Level of Control. High Level Languages Allow use of Structured Programming Techniques Plus Control Languages are Available.

Table 4.1-3 shows the functions considered for computer control in this study and an evaluation of the ability of the various implementation device options to perform them. It is immediately apparent that analog devices are very restrictive, and their functions can be performed equally well with digital devices. No further consideration was therefore given to analog controllers. Upon examination of programmable controllers (PCs) it is found that they contain microprocessor logic devices similar to those that would be used in a special-purpose microprocessor system. The PCs sacrifice some of the capabilities available in microprocessors to obtain push-button programming capability, and force the user to procure dedicated programming hardware that should only be used once, since the functions to be programmed in the computer system are to be permanent. Therefore, programmable controllers were determined inappropriate for purposes of the present task and were eliminated from consideration, in favor of specially programmed microprocessors. These, plus minicomputers, form the basic components from which the tunnel control and monitoring system was developed. With respect to the remainder of the above-mentioned factors, the following describes the general arrangement of the recommended computer system.

4.1.4 Recommended Computer System Configuration

A computer-based system has been developed to fulfill the functional requirements discussed above and shown in Table 4.1-3. The arrangement of this system is shown in Figure 4.1-2. The computer subsystems comprising this system are discussed in detail in the remainder of this section (Section IV).

Each test section is assigned dual-redundant, microprocessor-based subsystems to perform speed/q control and model attitude control. The Speed/q Control Subsystem (SQCS) and Model Attitude Control Subsystem (MACS) interact with their respective wind tunnels and with the common motor-generator drive system, as well as with their peripheral displays and other system elements.

Table 4.1-3
Implementing Options per Function

FUNCTION \ OPTION	ANALOG	PC	MICRO	MINI
Speed Hold	x	x	x	x
Speed Command	x	x	x	x
Auto Power Mode Transition		x	x	x
Power Level Monitoring		x	x	x
Power Level Limiting		x	x	x
Sensed Parameter Monitoring		x	x	x
Estimated Parameter Monitoring				x
Data Interrogation				x
Auto Test Sequencing				x
Model Parameter Operation				x
Signal Select (Redundant)	x	x	x	x
Tolerance Checks		x	x	x
Failure Detection Isolation				x
Model Attitude Control		x	x	x

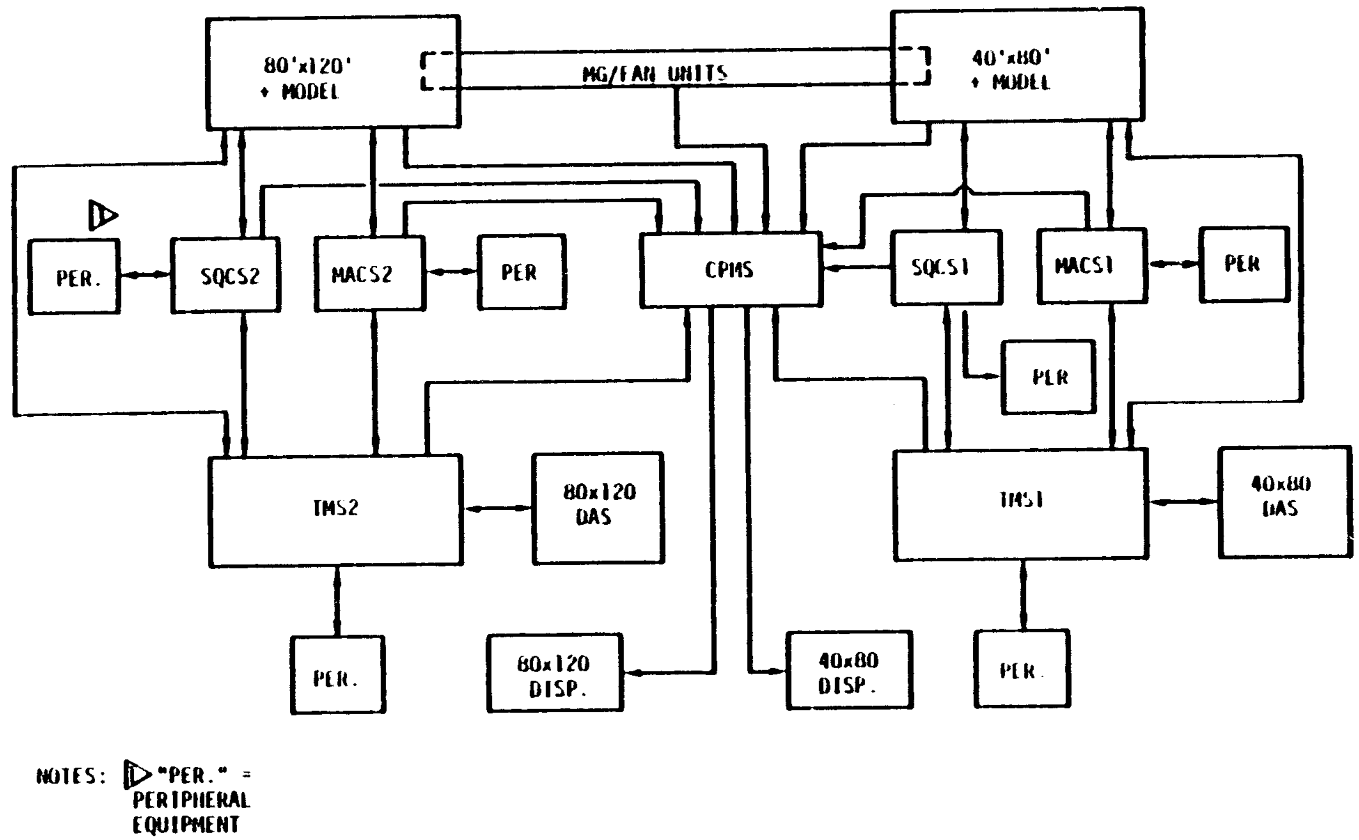


Figure 4.1-2 Wind Tunnel Control and Monitoring System Configuration

The other system elements are a quad-redundant, microprocessor-based Critical Parameter Monitoring Subsystem (CPMS) and a single mini-computer-based Test Management Subsystem (TMS). The CPMS is a central receiver of tunnel and control system status information, and with no manual backup it is designed for high reliability. It interacts actively only with displays and other peripheral devices. The TMS is monitored for failure by the CPMS using special firmware techniques. It gives commands to the SQCS and MACS and interacts actively with the tunnel DAS (Data Acquisition System, existing) and its own peripherals.

The functions contained in these subsystems, and in particular the speed/q control system, are discussed in the remainder of this section.

4.1.5 Cost Estimates

Estimates of the cost of a system such as that described in the preceding subsection have been made and compared to other, alternate systems of varying capabilities. The cost items fall naturally into the areas of hardware and software; in general, the costs associated with the latter are greater and are subject to more uncertainty of estimation. Costs of hardware are falling rapidly with progress in electronics technology; costs of software are rising. The net effect on system costs is uncertain because the availability of higher level languages on new microprocessors results in reduced programming time.

The results of this study of system costs are summarized in Table 4.1-4 and supported by cost breakdown shown in Tables 4.1-5a to 5e. The fact that these are preliminary should be borne in mind; however, they are felt to be "middle-of-the-road" estimates. If a pessimistic view is taken of software development costs, which may not be unrealistic, allowances of 25% or more in software costs should be made.

Table 4.1-4 gives cost estimates for one wind tunnel only. The second wind tunnel system may be assumed to have lower software costs, since it will use computer code already developed, with changes mainly in data values. The exact savings cannot be defined with precision at this time.

The sensor system recommended this time consists of analog sensors for data collecting, with digiting units located in as near proximity as possible to the multiple sensors they monitor. In the interests of minimizing the effects electrical noise, it is strongly recommended that analog data transmission be kept to a minimum. Digitizer output may be called by the CPMS CPU either continuously or only when a change is detected in a monitored parameter; the latter approach is useful if a high overall sampling rate is required. It is not desireable to locate all A/D units adjacent to the CPU, which would require long lines and may encounter equipment volume constraints.

These are three principal types of software structure applcable to a monitoring system such as CPMS, where the objective is a reliable indication of a system fault evidenced through sensor measurements. They are as follows:

Table 4.1-4

Wind Tunnel Control Estimated Cost Summary
(One Wind Tunnel)

	PURE MINICOMPUTER SYSTEMS			PURE MICROPROCESSOR SYSTEMS				MICRO/MINI SYSTEMS		
	1M	2M	3M	1μ	2μ	2μ/3μ	2μ/4μ	1M/2μ	1M/2μ/3μ	(R) 1M/2μ/4μ
SCCS	N/A	N/A	N/A	5295 (15K)	10125 (20K)	10125 (20K)	10125 (20K)	10125 (20K)	10125 (20K)	10125 (20K)
MACS	N/A	N/A	N/A	4830 (10K)	9195 (15K)	9195 (15K)	9195 (15K)	9195 (15K)	9195 (15K)	9195 (15K)
CPMS	N/A	N/A	N/A	6250 (20K)	12500 (25K)	18750 (30K)	25000 (35K)	12500 (25K)	18750 (30K)	25000 (35K)
TMS	N/A	N/A	N/A	N/A	N/A	N/A	N/A	52800 (30K)	52800 (30K)	52800 (30K)
SUBTOTAL	66800 (50K)	133600 (50K)	200400 (50K)	16375 (45K)	31820 (60K)	38070 (65K)	44320 (70K)	84620 (90K)	90870 (95K)	97120 (100K)
CRT-KBD	12400	12400	12400	12400	12400	12400	12400	12400	12400	12400
LINE PRINTER	3500	3500	3500					3500	3500	3500
CARD RDR	6000	6000	6000					6000	6000	6000
SUBTOTAL	21900	21900	21900	12400	12400	12400	12400	21900	21900	21900
REMOTE DATA UNITS	16000	16000	16000	16000	16000	16000	16000	16000	16000	16000
SENSORS	10K	10K	10K	10K	10K	10K	10K	10K	10K	10K
ACTUATORS	3K	3K	3K	3K	3K	3K	3K	3K	3K	3K
MISCELLANEOUS	2K	2K	2K	2K	2K	2K	2K	2K	2K	2K
TOTAL	169700	236500	303300	104775	135220	146470	157720	227520	238770	250020

NOTES:

- (R) SYSTEM RECOMMENDED IN THIS STUDY
- (▷) ALL FOUR FUNCTIONS PERFORMED BY MINICOMPUTER (the 1M, 2M and 3M N/A cells)
- ALL COSTS IN DOLLARS AS OF 5/78
- "K" = 1000
- ( ) DENOTES SOFTWARE/FIRMWARE COSTS

Table 4.1-5.a

Estimated Cost Breakdown for SQCS Subsystem Hardware

SQCS/1	QTY	ITEM	UNIT PRICE	NET
	1	KD11HF CPU	$ 990	$ 990
	1	MRV11AA 4K PROM	175	175
	1	KEV11 Ext. Arith Chip	190	190
	3	DLV11J4-Line Serial	465	1395
	1	KDV11 A Line Clock	290	290
	2	DCK11-AC Bus Foundation	175	350
	1	KD11HF 4kRAM	--	--
	1	TEV11 Bus Terminator	110	110
	1	H9281-AC 12x12 Backplane	145	145
	1	Power Supply	650	650
	1	Power Supply Cables, Misc.	1000	1000
				$5295
SQCS/2	1	KD11HF CPU	$ 990	$ 990
	1	MRV11AA 4k PROM	175	175
	1	KEV11 Ext Arith	190	190
	2	DLV11J 4-Line Serial	465	930
	1	KPV11 A Line Clock	290	290
	1	KD11HF 4kRAM	--	--
	2	DCK11-AC Bus Foundation	175	350
	1	TEV11 Bus Terminator	110	110
	1	Power Supply	650	650
	1	H9281-AC 12x12 Backplane	145	145
			1000	1000
				$ 4830

Table 4.1-5.b

Estimated Cost Breakdown for MACS Subsystem Hardware

MACS/1	QTY	ITEM	UNIT PRICE	NET
	1	KD11HF CPU	$ 990	$ 990
	1	MRV11AA 4kPROM	175	175
	1	KEV11 Ext. Arith Chip	190	190
	2	DLV11J 4-Line Serial	465	190
	1	KPV11A Line Clock	290	290
	2	DCK11-AC Bus Foundation	175	350
	1	KD11HF 4kRAM	--	--
	1	TEV11 Bus Terminator	110	110
	1	H9231AC 12x12 Backplane	145	145
	1	Power Supply	650	650
		Cables, Misc.	1000	1000
				$4830
MACS/2	1	KD11HF CPU	$ 990	$ 990
	1	MRV11AA 4kPROM	175	175
	1	KEV11 Ext. Arith Chip	190	190
	1	DLV11J 4-Line Serial	465	465
	1	KPV11A Line Clock	290	290
	2	DCK11-AC Bus Foundation	175	350
	1	KD11 HF 4kRAM	--	--
	1	TEV11 Bus Terminator	110	110
	1	H9281AC 12x12 Backplane	145	145
	1	Power Supply	650	650
		Cables, Misc.	1000	1000
				$4365

Table 4.1-5.c

Estimated Cost Breakdown for CPMS Subsystem Hardware

CPMS/1,2,3,4	QTY	ITEM	UNIT PRICE	NET
	1	KD11 F PCU+4kRAM(4)	$ 990	$ 990
	1	MRV11AA 4kPROM(2)	175	175
	1	KEV11 Ext. Arith Chip	190	190
	4	DLV11J4-Line Serial(2)	465	1860
	1	KWV11 Prog. Clock (4)	600	600
	1	DRV11-P Bus Foundation(4)	275	275
	1	TEV11 Bus Terminator(2)	110	110
	1	Power Supply	650	650
	1	DDV11B 6x9 Backplane	400	400
		Cables, Misc.	100	1000
				$ 6250

Table 4.1-5.d

Estimated Cost Breakdown for TMS Subsystem Hardware

	QTY	ITEM	UNIT PRICE	NET
Basic TMS	1	PDP 11/34 Processor-Package incl. Man Frame with 64K Bytes RK11J 2.5 MB Disk with Controller RK05F 5.0MB Disk LA 36 Terminal RSX11 M Software Racks, Cables, Cabinets	$ 28900	$ 28900
	1	LA180 Printer	3500	3500
	1	CR11 Card Reader	6000	6000
	2	8001 Intecolor Terminals with options @ 6200	6250	12400
	1	DX11 8-Line Serial Interface, Misc.	2000	2000
				$ 52800
Remote Data Units	16	16-Line Remote Data Processors @ 1000	1000	16000
		Misc. Support		2000
				$ 18000

Table 4.1-5.e

Estimated Minicomputer System Cost Breakdown

QTY	ITEM	NET PRICE
	MINICOMPUTER SYSTEM	
1	PDP11/60 Main Frame Pkg., incl. PDP11 160 Main Frame with 64K Bytes RK11-J 2.5Ub Disk with Controller RK05-F 5.0 Ub Disk LA36 Terminal RSX11 M Software	$ 40000
1	FP11E Floating Pt. Unit	5600
1	KWIP Programmable Clock	2000
2	DR11K Bus Foundation Module @ 700	1400
	FORTRAN 4 + Software	3300
5	DZ11 Serial Interface @ 2310	11500
	Cables, Parts, Misc.	3000
		$ 66800
	MINICOMPUTER SUMMARY (Hardware)	
3	Minicomputer Systems	$ 200400
	Remote Data Units	18000
1	LA180 Line Printer	3500
1	CR11 Card Reader	6000
2	8001 Intecolor Terminals with Options @ 6200	12400
		$ 240300

(1) modular-redundant -- the CPU outputs are voted and channels are eliminated if they differ from the mean, until two channels remain; failure of one of the last two channels fails the system; commonly referred to as a "brickwall" system;

(2) modular-redundant monitored -- each CPU monitors its own operation, in addition to output voting; this allows degredation to, and operation on, one remaining channel, if it is possible to develop reliable monitoring software; it is considerably more reliable than (1);

(3) sensor-voted -- each CPU monitors its own sensor and the sensors of the other channels, and exchanges data with other CPU's; finally, the outputs are voted.

These systems are presented in the order of increasing reliability and increasing complexity. Greater complexity results in the ability to minimize nuisance failures and their effects, detect latent sensor failures and improve failure isolation, but appears in the form of a large increase in the amount of signal processing (reduced cycle time) and the requirement to synchronize several CPU's for data exchange and intercommunication.

It is concluded that the CPMS presents the most difficult system development problem of the subsystems studied in this effort, and will require the most careful definition in terms of requirements and objectives. On the microprocessor level, its functions, as they should be performed, are not appropriate to the SQCS and MACS computer systems.

Finally, it should be noted that these cost estimates are based on the use of hardware determined to be suitable for the tasks. It is felt that, in particular, floating-point capability is required of the micro-processors to obtain the desired cycle rates. Hardware compromises may be offset by more programming effort, in general, but this tradeoff has not been evaluated, as it is recommended that consideration be given to preparing for long-term expansion of the original systems in the initial equipment purchase. Factors significant in this regard include:

(1) commonality between minicomputer and microprocessor hardware and software;

(2) adequate keyboard and display capability; and

(3) preparation of software codes for later expansion to more units to achieve increased redundancy.

The remainder of Section IV considers the functions of the computer subsystems, in particulary the speed/q control subsystem, SQCS.

4.2 SPEED/DYNAMIC PRESSURE CONTROL SUBSYSTEM (SQCS)

4.2.1 Overview

Automatic regulation of tunnel test section speed or dynamic pressure is a requisite for increased test efficiency in the new and modified full-scale wind tunnels. Ease of operation afforded by a speed/q-command feature and rapid reaction to disturbances imposed by changes in model drag are two principal benefits. With increasing levels of computer authority the goal of optimally efficient test conduct is approached.

The requirements imposed on the control system in this study include:

(1) fail-safe operation, reverting to manual control in the failed state;

(2) convenient interfacing with a human operator; and

(3) accurate setting of speed or dynamic pressure within limitations imposed by sensor accuracies and mechanical linkage nonlinearities (such as deadzone).

In general, a controller was sought that would provide good regulation of dynamic pressure, featuring small overshoot or undershoot of q during q changes, rapid response to q-change commands, and rapid compensation of test-article-induced disturbances.

4.2.2 Speed/q Control Function Analysis

The functions performed by the speed/q control subsystem (SQCS) fall into three categories:

(1) information acquisition;
(2) computation and logic; and
(3) signal output.

These functions are as follows:

(1) Information Acquisition Functions

a. Sensor select. Based on the last computed value of dynamic pressure, select one of several transducer outputs to be read to update the computation of q or speed.

b. Receive q command. The commanded q is to be set either by the tunnel operator or by the test management subsystem computer. The SQCS computer receives this command and, upon receipt of an activation command (discrete) from either source, energizes the motor generator and/or blade pitch control actuator. (If V is commanded, a switch so indicating causes an alternate algorithm to be used.)

c. Sense tunnel status. Pressure and temperature transducers; set inputs; all inputs required by RPM and blade pitch control algorithms.

d. Sense discrete inputs. Operating mode switches, engage/disengage switches.

e. Sense subsystem status. Monitor selected outputs and inputs of the redundant elements of the SQCS to detect discrepancies indicating errors.

f. Data retrieval. Obtain control law stored in computer memory: gains, constants, table lookup values.

(2) Computation and Logic Functions

a. Control laws. Compute all quantities and perform all logical branching required by the V-q control algorithms, including data retrieval from memory.

b. Command logic. Select functions to be performed on basis of operator input through switches.

c. Self-monitoring computation and logic. Perform comparative tests on other elements of the SQCS.

(3) Signal Output Functions

a. Control actuation. Activate motors or drivers in RPM and/or blade pitch control systems.

b. Operator information. Operate control panel displays.

c. SQCS data exchange. Provide data to other elements of the SQCS for their self-monitoring functions.

d. Test management data. Provide data to the test management minicomputer.

4.2.3 Speed/q Control Law Development

The term "control law" refers to the sequence of equations and logical branches by which the control objective is accomplished. In this application, the inputs to the control system are commanded and measured values of dynamic pressure. An error signal is computed as the difference of these two quantities, and a corrective command signal determined from the error signal value is sent to the control actuators in the RPM and blade pitch system

Speed/q control law development consists of two steps:

(1) The generation of a desired feedback loop based on the control requirements and on the characteristics of the wind tunnel parameters to be controlled, in this case the pitch of the fan blades and, in the IFC mode, the RPM of the fans; and

(2) The translation of the analytical results of this procedure into interconnected components for subsequent implementation and reliability studies.

Figure 4.2-1 shows the intended relationship of the automatic speed/q control system to the existing (and planned) manual system. Comparing measurements of q to a desired reference, an adjustment to RPM and/or blade pitch angle is commanded. Whereas in the manual mode the operator controls Ω and ξ, in the automatic mode h controls q through one controller which adjusts both Ω and ξ to provide the desired q.

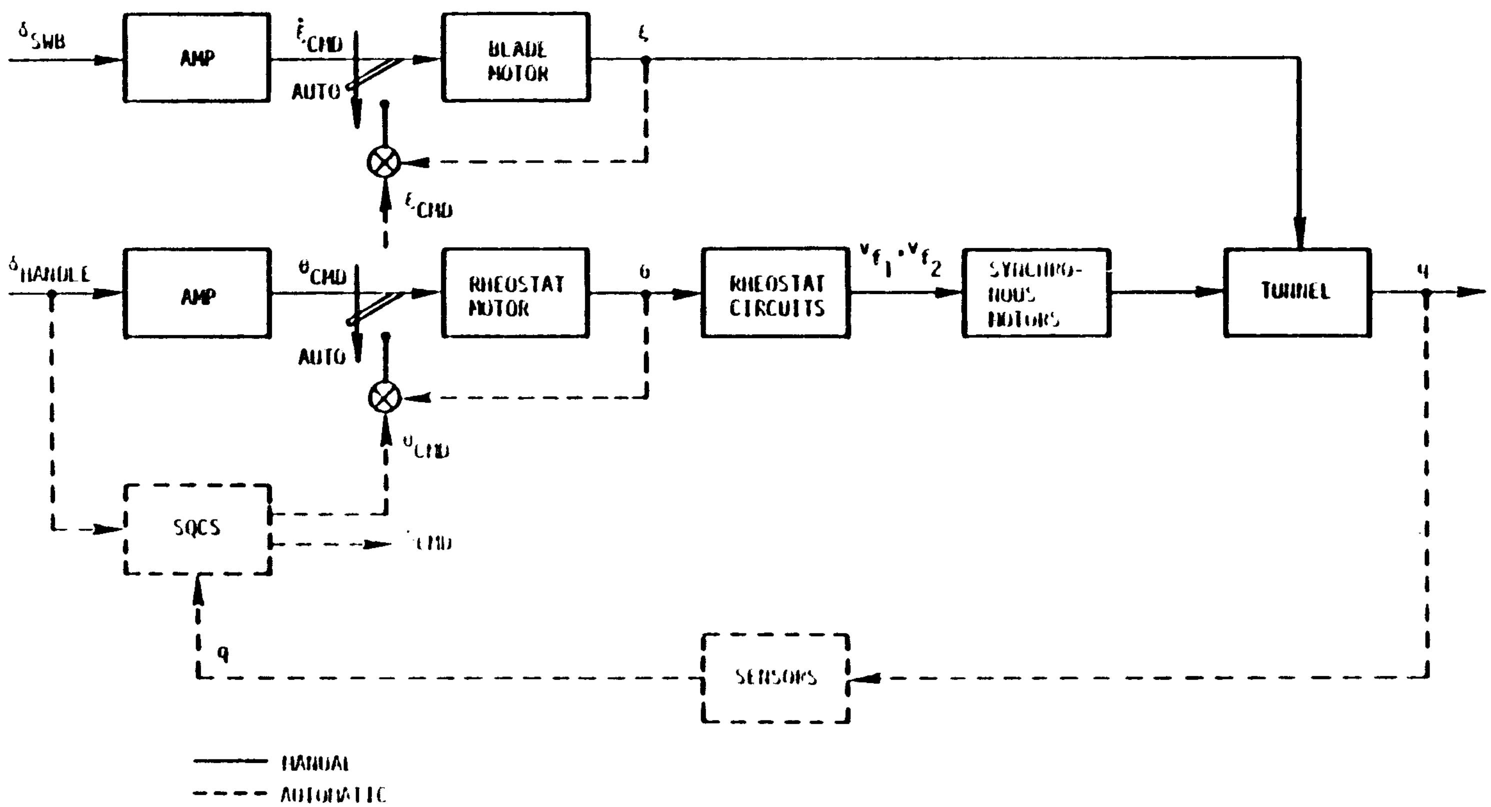


Figure 4.2-1 Relation of Speed/q Control System to Manual Control System

The basic function of the speed/q controller is to maintain a reference, commanded setting and compensate for errors due to test section disturbances. Figure 4.2-2 shows schematically the establishment of motor speed and blade pitch settings, corresponding to a commanded dynamic pressure, using a feed-forward path; this is the same as the unaugmented, manual control method and serves to establish the required conditions of fan blade pitch and fan RPM through commands to the blade pitch actuator motors and motor generator system controls (in the IFC mode), respectively. The combination of fan RPM and blade pitch chosen to provide a required fan pressure rise, hence sustain a required tunnel dynamic pressure, may be chosen from an infinite number of possible values, but of the three variables (RPM, blade pitch, and tunnel q), once two are specified, the third is determined. The feed-forward control path thus acts as would a human operator in establishing values of RPM and blade pitch that he "knows" will bring him "close to" the desired tunnel q.

The use of the feed-forward paths for RPM and blade pitch angle control is important and has been recommended for several reasons:

(1) it provides for separation of the control of large and small disturbances or command changes; this prevents the saturation of tracking loops during large, non-tracking condition changes;

(2) it prevents possible conflict between RPM and ξ controls;

(3) it allows the flexibility of choosing known relationships between ξ and RPM to minimize power, noise, vibration, etc., as may be determined to be significant when the tunnel is operational.

This control path requires the addition of a position or output controller to the motor-generator exciter fields in the existing system.

Speed control is accomplished by converting the speed command to a q command and controlling on q as before. This reduces

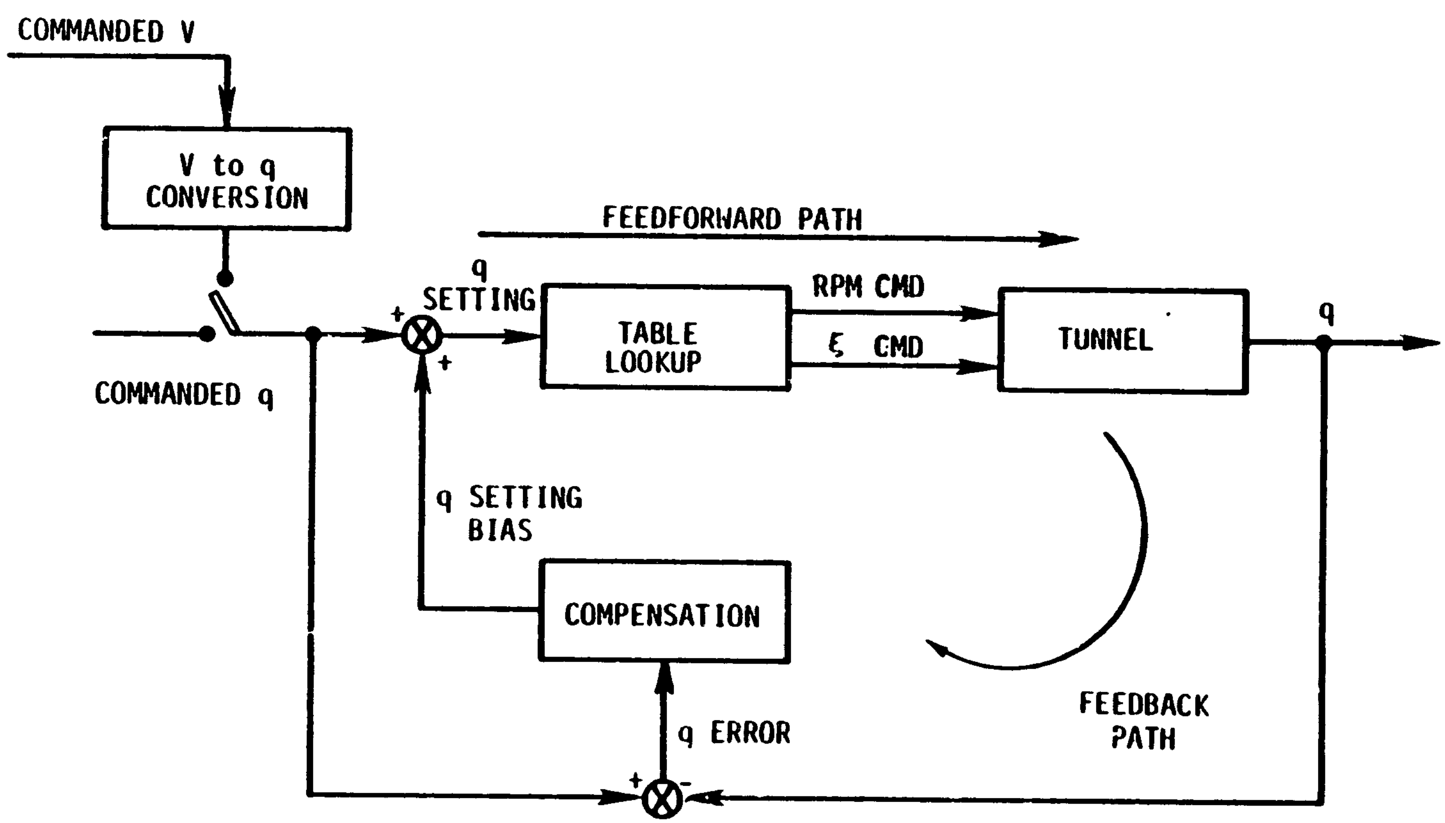


Figure 4.2-2 Control System Methodology - Schematic

the number of control loops required. The V-q conversion requires knowledge of tunnel stagnation conditions; the conversion equations are shown in Figure 4.2-8. In the following, "q control" will refer to either V or q control.

To obtain precise control of q, the open-loop, feed-forward RPM and blade pitch settings are biased to offset errors in the q setting; this is the closed-loop, feedback path shown in Figure 4.2-2. If q is too large, for example, a negative q setting bias is generated to alter the feed-forward command in the negative direction, effectively commanding a lower value of q until it is back to within a selected tolerance about the desired value.

The q error signal is modified through proportional-integral-derivative (PID) compensation to improve the response of the controller. If q_e is the error in q from the commanded value, a q setting bias is generated of the form

$$\Delta q_{set} = K_p\, q_e + K_I \cdot \int q_e\, dt + K_D \cdot \frac{d}{dt}(q_e)$$

The basic proportional feedback is augmented by integral feedback to null steady-state error, and derivative feedback to quicken the response. Derivative feedback is generally undesirable because it magnifies the effects of system noise and is hampered by rate limits of other parts of the system, such as blade pitch actuators. The basic control design task is to determine the "best" values of the gains K_I, K_D, and K_p.

The recommended speed/q control law is shown in block diagram form in Figure 4.2-3. This control law was modeled and added to the math model as shown in Figure 4.2-4. Figure 4.2-4 references other figures in which elements of the system or model are defined.

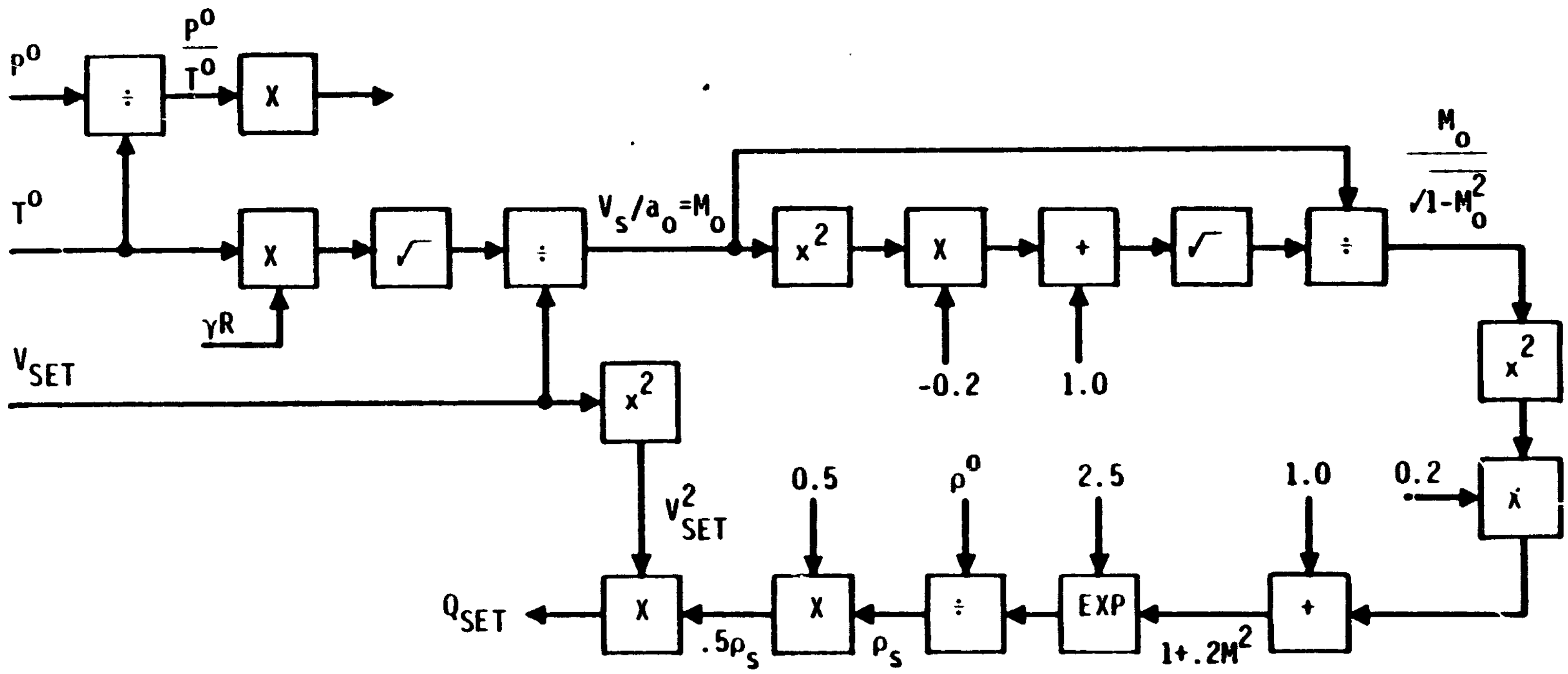


Figure 4.2-8 V_{SET} - q_{SET} Conversion Computation: Operational Sequence

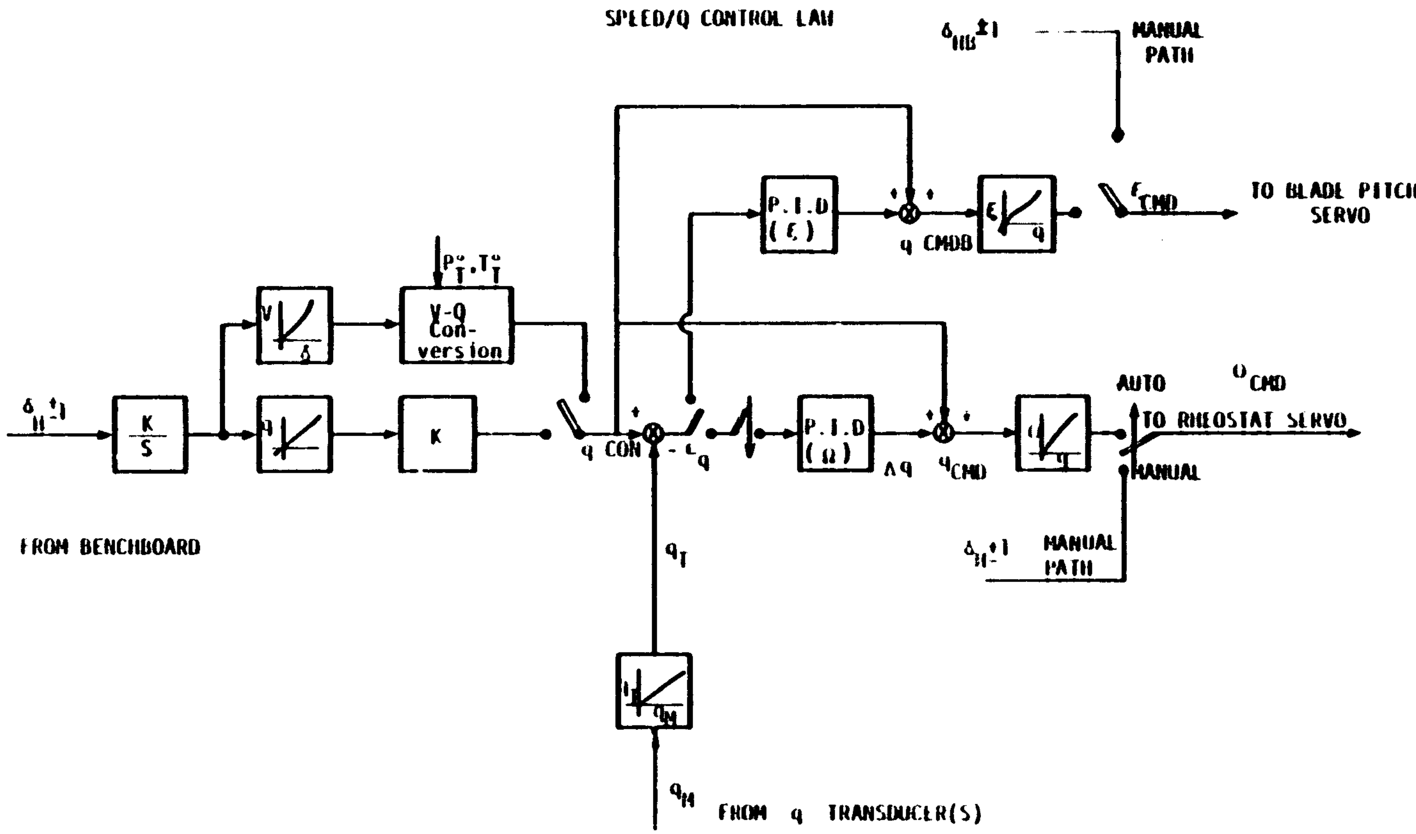


Figure 4.2-3 Speed/q Control System Block Diagram

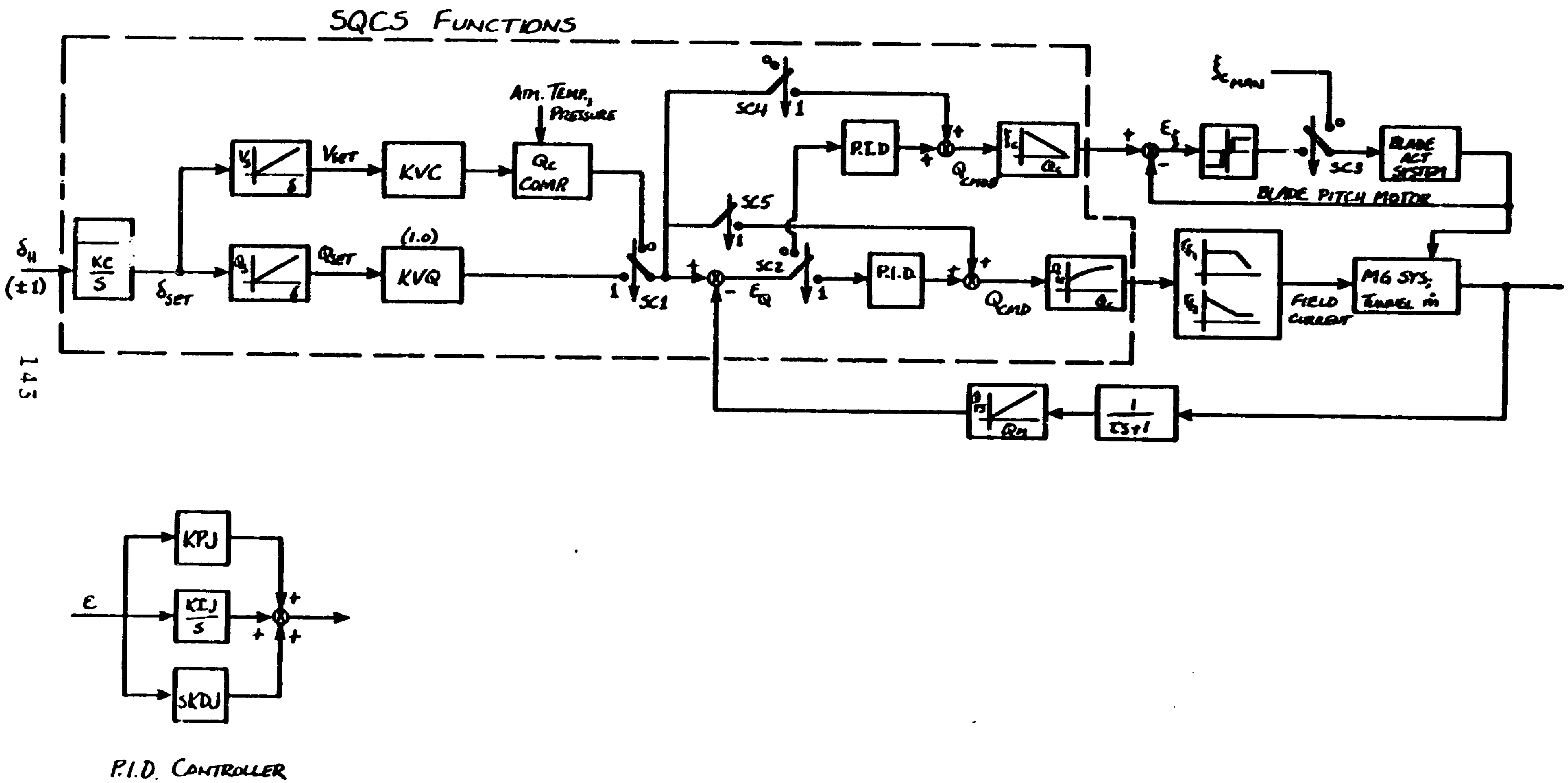


Figure 4.2-4 Control System Structure and Modeling

The several switches shown in Figures 4.2-3 and 4.2-4 enable the selection of different operating modes in different test conditions. Definition of functions is given in Section 4.2.6.

4.2.4 SQCS Algorithms

The algorithms of the SQCS consist of the block diagram controller operations and the logic required to execute them. The logical functions of the SQCS are shown in Figures 4.2-5 and 4.2-6 and refer to the control law functions shown in Figure 4.2-3 which are discussed in the previous subsection. The logical functions are particularly important because they determine how and when the functions of the contol law are performed and also how the operator and the SQCS interact through benchboard displays.

It is recommended that full use of the control capabilities of the digital microprocessor-based SQCS be made. The use of the feed-forward, condition-setting control method makes possible large control commands while achieving q- or speed-hold at each operating point. Accordingly, complete control logic for this level of operation is shown.

The most difficult automatic control function is transition between line and IFC electric power modes. The SQCS must perform the following logical functions:

(1) determine if the commanded speed/q condition requires transition from line to IFC or vice versa;

(2) initiate the electromechanical sequencing operation (analogous to the operator throwing the IFC transition switch);

(3) monitor the status of the transition: indicate its successful completion to the tunnel operator and continue in the speed/q command function, or indicate a fault if transition has not occurred in a prescribed period of time.

A logic diagram of the IFC transition sequence is shown in Fig. 4.2-7.

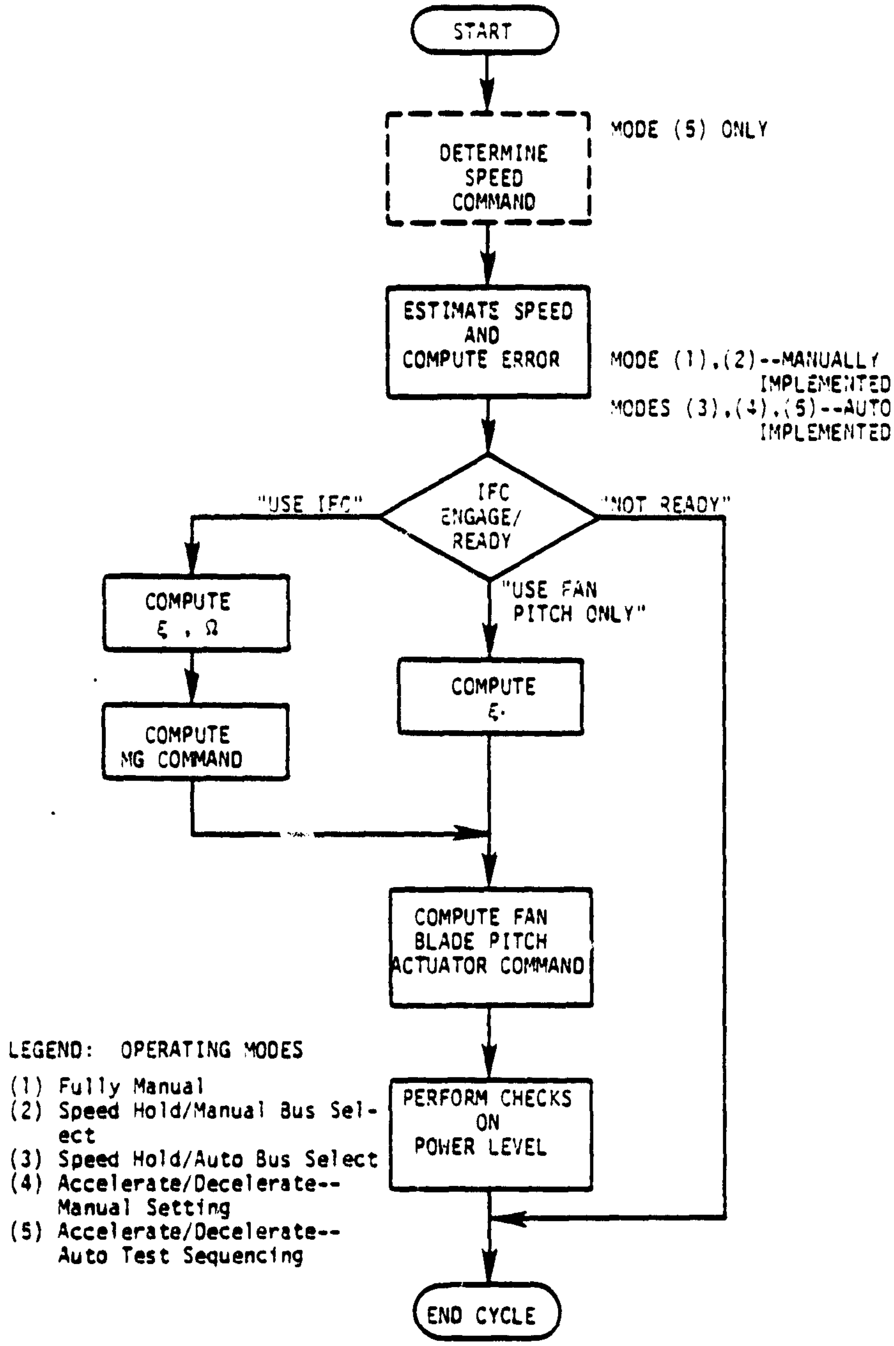


Figure 4.2-5 Speed Control Function Logic Diagram (1 of 2)

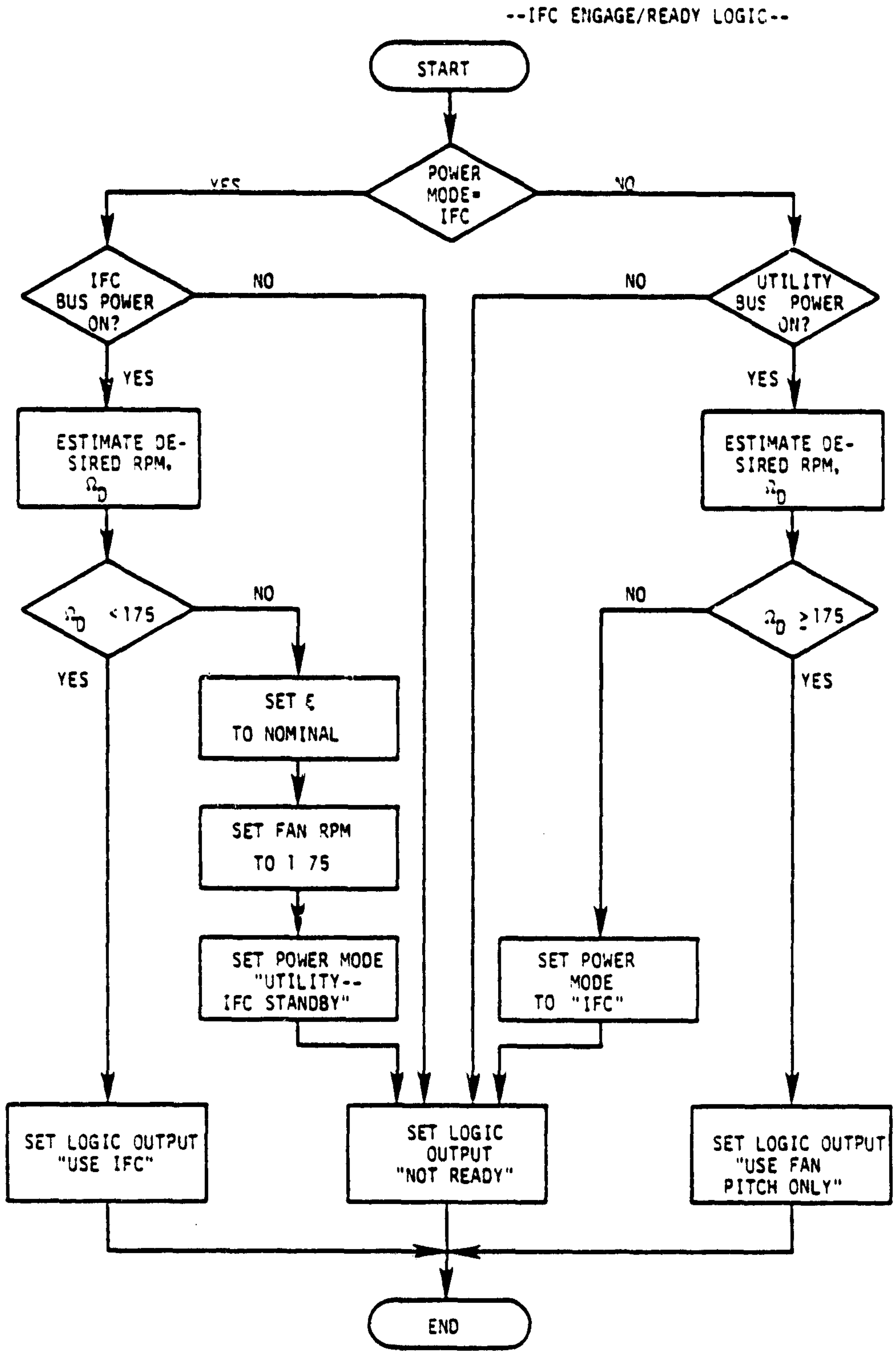


Figure 4.2-6 Speed Control Function Logic Diagram (2 of 2)

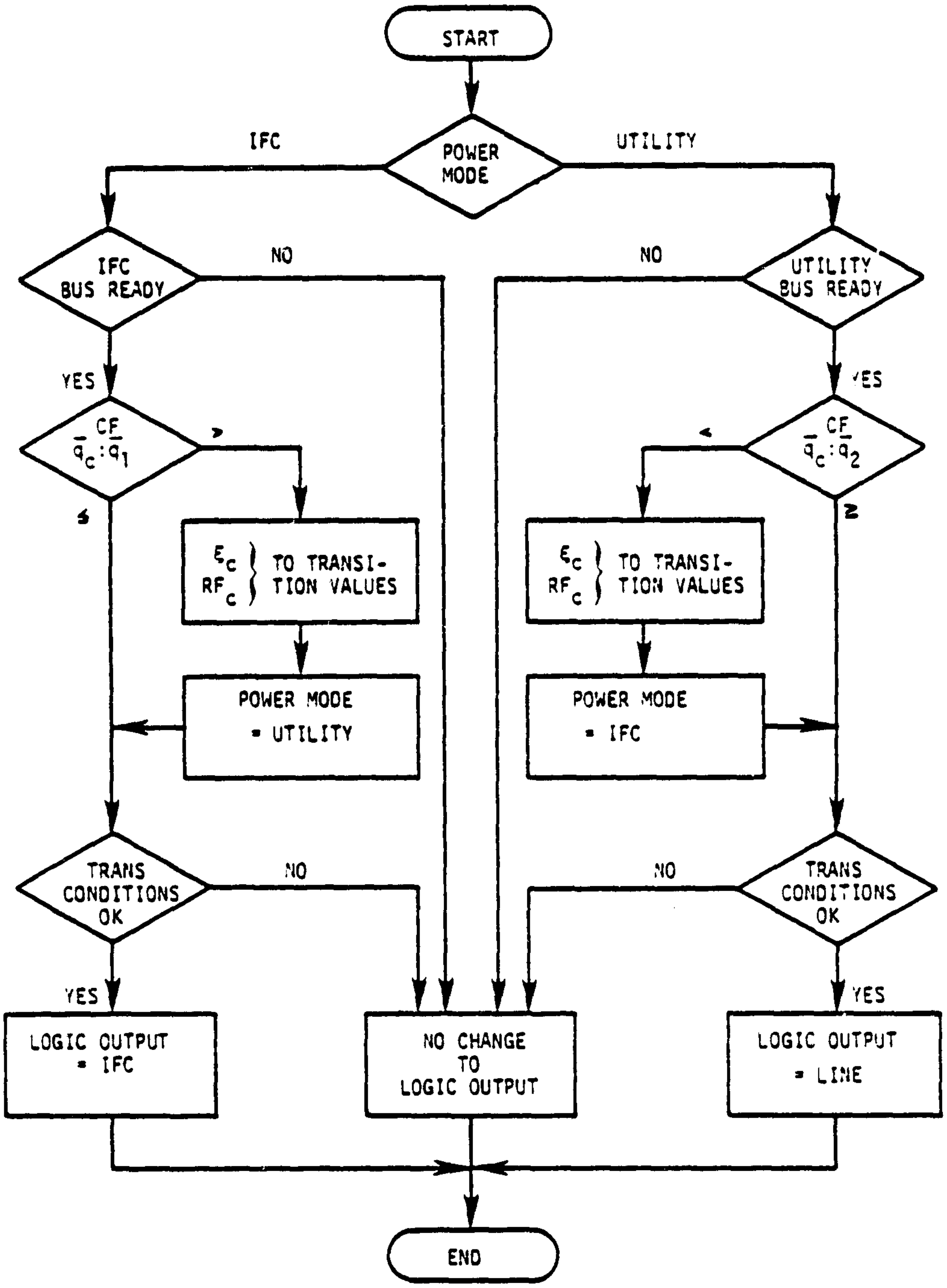


Figure 4.2-7 Automatic IFC Mode Transition Logic

It is recommended that the decision for automatic transition between the IFC and LINE power modes be made on the basis of commanded tunnel q rather than on fan motor power consumption, to prevent frequent and probably unnecessary transitions when operating near the normal transition point. If the tunnel is initially operating in IFC mode near the power limit, and model drag increases cause the IFC power limit to be reached while attempting to hold q, the controller should allow q to depart from the commanded value rather than initiate IFC transition. In all likelihood, a reverse transition would be required moments later when the model is repositioned for another run. An amber caution light should illuminate to inform the operator when the drive system is in this power-limited situation.

The q-setting corresponding to a desired speed is computed using isentropic flow relations from measurements of tunnel flow stagnation temperature and pressure. The equation is simply

$$q = \frac{1}{2} \rho V^2$$

with

$$\rho = \frac{p^o}{RT^o(1+.2M^2)^{2.5}}$$

$$M = M_o/(1-.2M_o{}^2)^{\frac{1}{2}} \quad \text{where } M_o = \sqrt{\gamma RT^o}$$

A computational algorithm to compute q is shown in Fig. 4.2-8.

4.2.5 SQCS Reliability

The speed/q control system is to be a fail-safe system; i.e. loss of the system leaves the tunnel under manual operator control. It is recommended that this be achieved through dual-redundant microprocessors performing identical operations on input data and sending identical outputs to actuator units. The two processors each perform comparisons on the data of itself and of the other processor. If a discrepancy outside the range of allowable values is detected, the system goes to an idle state, returns control of RPM, blade pitch, and IFC transition to the operator, and provides indication of this status change to the operator and engineer.

A failure in the test management system (TMS) is not to impair the operation of the SQCS. Data and input commands are input to the SQCS (and MACS) computers through dedicated peripheral equipment as well as through the TMS. During a run, the data in the SQCS cannot be altered. Hence, the TMS may be received to change test plans without disturbing the automatic control of speed or q. This follows the desire for a dedicated, single-purpose speed/q control system.

The capability of the TMS may be used to expand the reliability of the SQCS microprocessor system if it is used in a monitoring and voting role to isolate a faulty microprocessor. The faulty M/P removed, the remaining single M/P could continue to provide automatic speed/q control with the TMS minicomputer monitoring it (through independent sensor inputs to the TMS), thus achieving higher SQCS reliability without adding a third redundant SQCS channel. This is not recommended at present, however, because of desire to maintain distinct separation between SQCS and TMS functions.

4.2.6 SQCS Implementation

This section presents detailed SQCS implementation recommendations in accordance with the discussions in the above subsections. The information presented in the following includes:

Table 4.2-1, I/O and Function Distribution
Figure 4.2-9, Structural Subsystem Arrangement
Table 4.2-2, I/O Itemization
Table 4.2-3, Performance
Figure 4.2-10, Control Panel Layout

Table 4.2-1
I/O and Function Distribution,
SQCS1 and SQCS2

INPUT/OUTPUT DISTRIBUTION	
INPUTS	
SQCS1/1 SQCS1/2	Receive identical inputs from all sources (40 x 80)
SQCS2/1 SQCS2/2	Receive identical inputs from all sources (80 x 120)
OUTPUTS	
SQCS1/2	Outputs to SQCS1/1
SQCS1/1	Outputs to 40 x 80 tunnel, 40 x 80 operator displays, CPMS and TMS1
FUNCTION DISTRIBUTION	
SQCS1/1; SQCS2/1	Basic functions plus output management.
SQCS1/2; SQCS2/2	Basic functions plus crosscheck management.

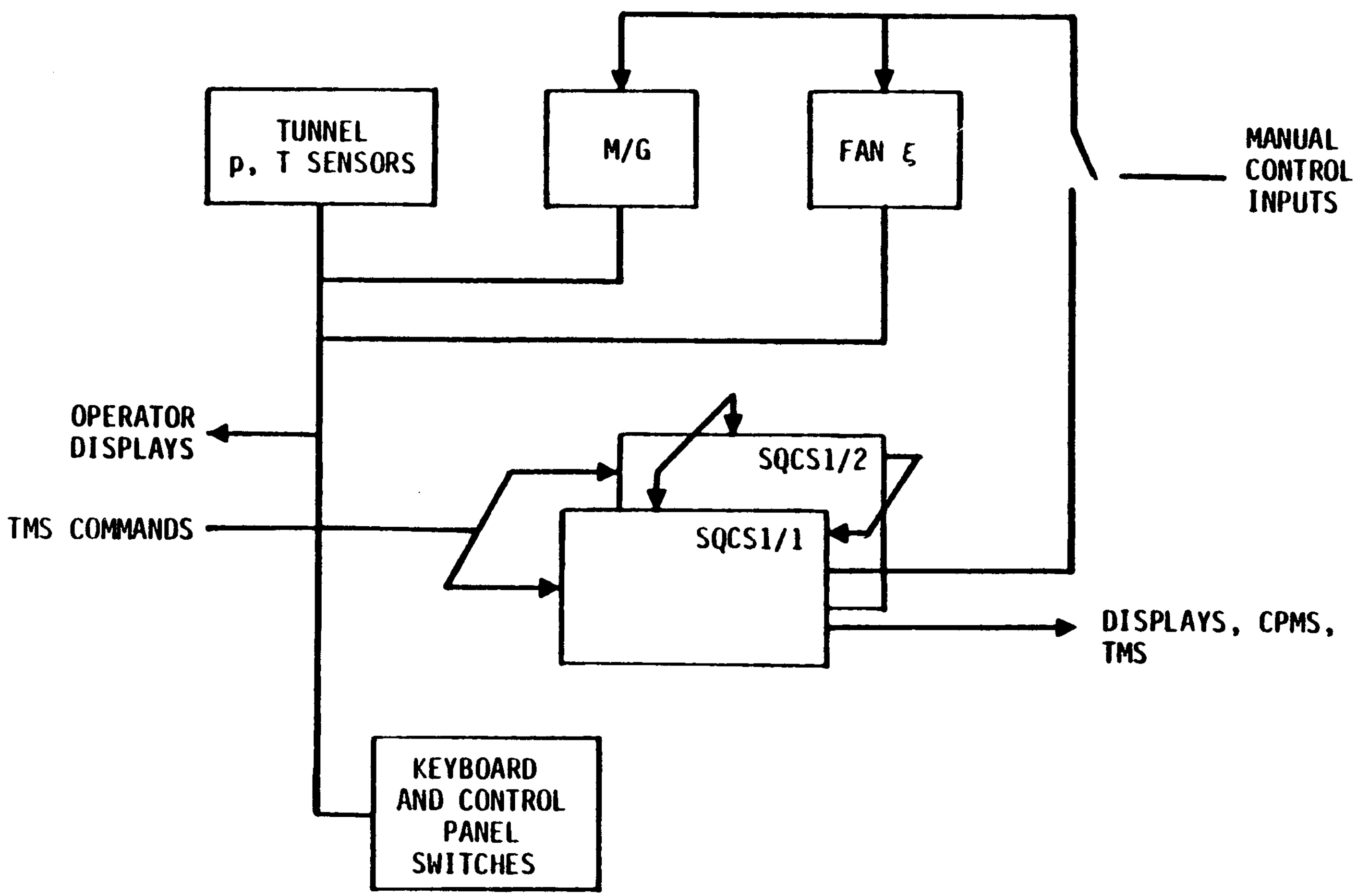


Figure 4.2-9 General Arrangement of Subsystems SQCS1 and SQCS2

Table 4.2-2

Input/Output Itemization, SQCS1 and SQCS2

INPUTS	FORM	REMARKS
1. Pressure transducers	Digitized, 12-bit	- Must select appropriate transducer based on q
2. Tunnel stagnation conditions	Digitized, from transducer or thumbwheel or from TMS	- Required for V-q conversion
3. Speed/q command	Digitized voltage corresponding to desired value	- Origin either operator handle or TMS computer
4. Mode switches V-q select IFC manual/auto V-q command or Engage/disengage		
OUTPUTS	**FORM**	**REMARKS**
1. M/G rheostat actuator command	Digitized	- D/A may be required
2. Blade pitch motors command	Discrete	- D/A may be required; goes to SCR driver
3. Microprocessor data	Digital	- For monitoring
4. Minicomputer data (TMS)	Digital	- For monitoring
5. Displays	Digital, D/A	- Operator information.
6. CPMS data	Digital	

Table 4.2-3

Performance Requirements: SQCS1 and SQCS2

ITERATION RATE (1) All functions except those itemized in (2) shall be accomplished every 0.1 second. Tolerance on the cycle-to-cycle variation in the time at which the q-pressure transducer is interrogated is 0.025 seconds. (2) Functions exempt from the iteration rate requirement (1) shall be accomplished no less frequently than every 0.5 second. For the SQCS, these exempt functions are: (a) Recognition of operator discrete inputs and reconfiguration of the control laws on their basis, (b) Conversion of speed/q handle deflection (δ_H) to q_{CON}, the control command to the inner loop (see Figure 4.2-3), (c) Transition between line and IFC electric power modes.
DATA ENTRY Positive verification of data entry is a requirement. The length of time from the operator's "enter" request to data storage to positive verification by the SQCS shall not exceed 1.0 second.
MEMORY RETENTION Memory shall be retained following a power supply failure for a minimum of 72 hours.

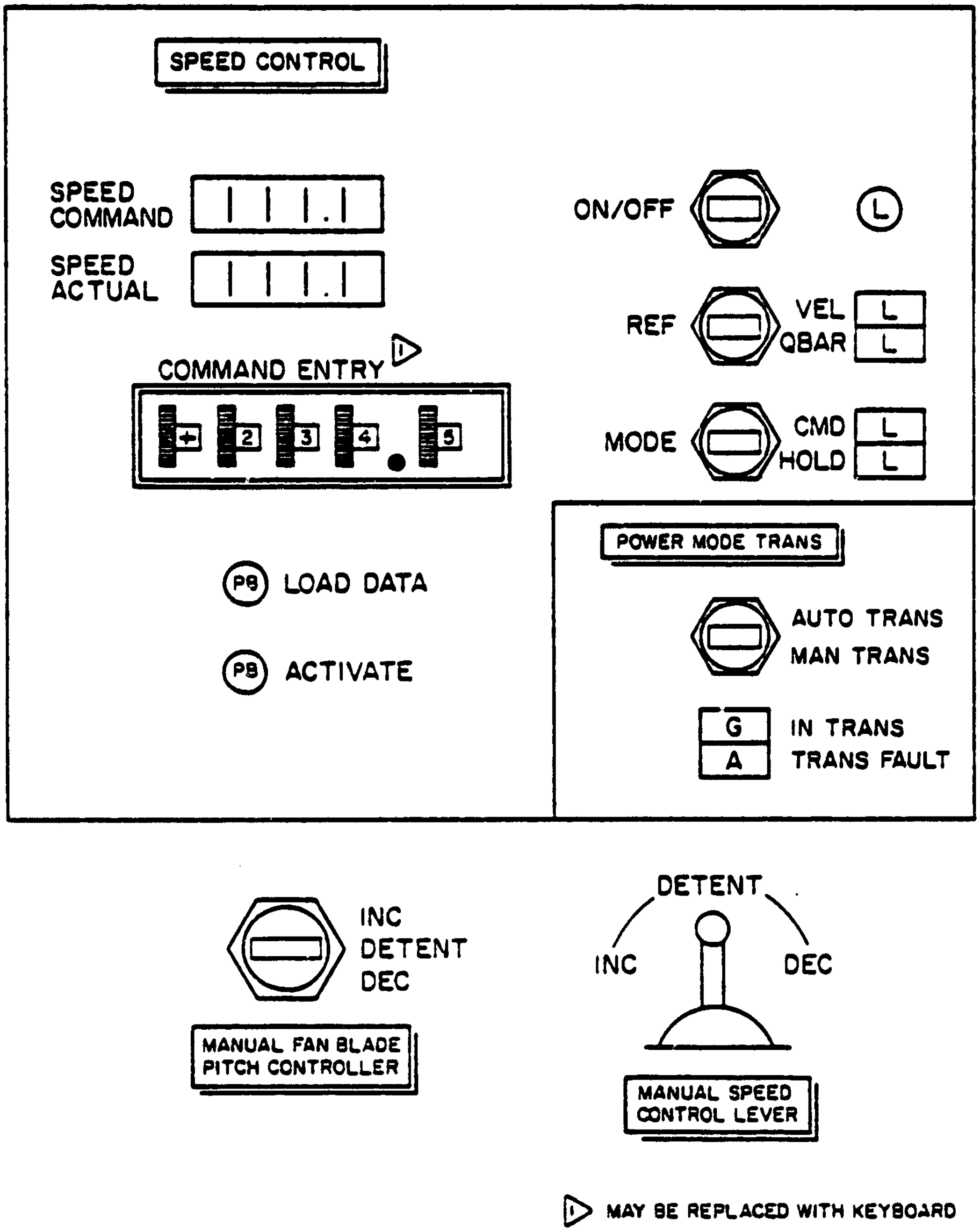


Figure 4.2-10 Proposed Speed/q Control Panel Layout

4.2.7 Sensor Analysis

The most direct limitations on the accuracy of the wind tunnel automatic speed controller are imposed by the sensors that provide data to the computational algorithms resident in the controller software. As seen in the controller description above (Section 4.2.2), the two critical sensing requirements are

(1) the sensing of test section dynamic pressure, the principal controlled variable; and

(2) the sensing of stagnation pressure and temperature as required in the calculation of the dynamic pressure corresponding to a desired test section velocity.

This section considers the limitations likely to be presented by realistic constraints on accuracy, noise sensitivity, response characteristics, and the failure characteristics of the pressure and temperature transducers to be employed in the speed/q control system. The impact of error bounds, the significant factors of implementation, and integration with the computer system are discussed.

The two types of instruments to be considered are differential and absolute pressure transducers.

4.2.7.1 Description of the Tunnel q-Measuring System

The wind tunnel q-measuring system operates on the simple principal of treating the wind tunnel as a venturi, and derives dynamic pressure as the differential between the approximately stagnation pressure in the large settling chamger and the approximately static pressure at the entrance to the test section. A calibration correction is applied to this differential to make it experimentally accurate.

The pressure differential is measured by means of 1-1/2" diameter tubes manifolded around the tunnel periphery and connected to opposite sides of a diaphragm. The diaphragm is linked mechanically to a scale, yielding direct readout of differential pressure. This forms the basic q-measuring system of both the 40' x 80' and 80' x 120' tunnels.

The q-measuring transducers of the q-control system are to tap the lines of this existing (40' x 80') system. The output of this transducer will be corrected to true dynamic pressure within the control computer and used as the feedback signal in the control system.

4.2.7.2 Accuracy Considerations

Transducer accuracy limits the ultimate q-measuring capability available to the control designer. The principal requirement is the test section dynamic pressure be accurately known. Assuming that the measured-to-actual correction is accurate, the sources of error in the q measurement will be:

(1) transducer error; and
(2) digitization error in the control computer.

Transducer error is assumed to be inclusive of all of the normally contributive factors, including:

(1) linearity
(2) repeatability
(3) hysteresis
(4) resolution
(5) input voltage variation
(6) long-term stability
(7) environmental effects: temperature, humidity, vibration, acceleration.

All these factors comprise the operating error band of the transducers. A typical value of accuracy for a high-quality, commercially available differential pressure transducer is $\pm 0.3\%$ of span; that is, at any measured pressure, the reading may differ from the true value by ±0.3% of the full design pressure range of the transducers. The implications of this in the q-control system are explored below. Transducers with higher accuracy will often be certified by the manufacturer if the user can demonstrate environmental conditions less extreme than assumed by the manufacturer in the standard specifications.

Digitization of the analog transducer output introduces a granularity into the pressure measurement because the A-D converter has a finite word size, generally 8 or 12 bits in length. If the transducer range is 100 psf, for example, the limit of accuracy using an 8-bit word is

$$\frac{100}{2^8} = \frac{100}{256} = .391 \text{ psf,}$$

and using a 12-bit word it is

$$\frac{100}{2^{12}} \quad \frac{100}{4096} = .024 \text{ psf.}$$

The 8-bit word here is seen to yield an unacceptably large resolution interval, and the 12-bit word is required. This points out the importance of considering computer word size in making computer hardware selection.

The level of precision obtained with a given transducer is dependent on the design pressure range of the instrument, since the operating error band is given in percent of range. Typical differential pressure transducers have ranges of ±0.05, ±.10, ±.40, or ±1.0 psi or greater. Absolute pressure transducers are generally higher in rating, having ranges of 0-1 psi, 0-2, 0-10, up to very high pressures.

Applying the representative 0.3% full-scale error band to these ratings yields a linear plot of dynamic pressure error versus instrument range, as shown in Figure 4.2-11. For very high accuracy, a transducer of small range is required, but the q range of the wind tunnel sets the minimum range of the pressure-measuring system. The design process is one of resolving these conflicting requirements.

In test situations in which test section velocity is of interest, an error in q-setting results in an error in velocity setting, and because of the quadratic variation of q with V, the error in speed due to a given error in q is larger at lower speeds. Speed errors resulting from q errors of different-range transducers are shown in Figure 4.2-12, in knots. Figures 4.2-11 and -12 show the best error bounds that can be obtained with given transducers at a given speed, with an instrument of 0.3% accuracy. For both absolute and differential transducers, improved accuracy can be obtained by lowering the range or performing a special calibration, should conditions permit.

Note on Figure 4.2-12 the speeds at which the differential transducers "bottom out" and begin to overpressure.

Speed control is as important as q-control in the testing of rotary-wing models, because of the dependence of rotor aerodynamics on advance ratio. Speed and q must be considered simultaneously in error analyses of transducer q-measuring systems.

The principal alternative to a transducer system for speed/q-control is a modification to the existing mechanical q-scale to generate an electrical signal that can be read by the control microprocessor. This has the possible advantage of improved accuracy, particularly at the highest q's in the 40' x 80' test envelope; however, it has the disadvantages that:

(1) it would require a custom modification of the existing equipment, and

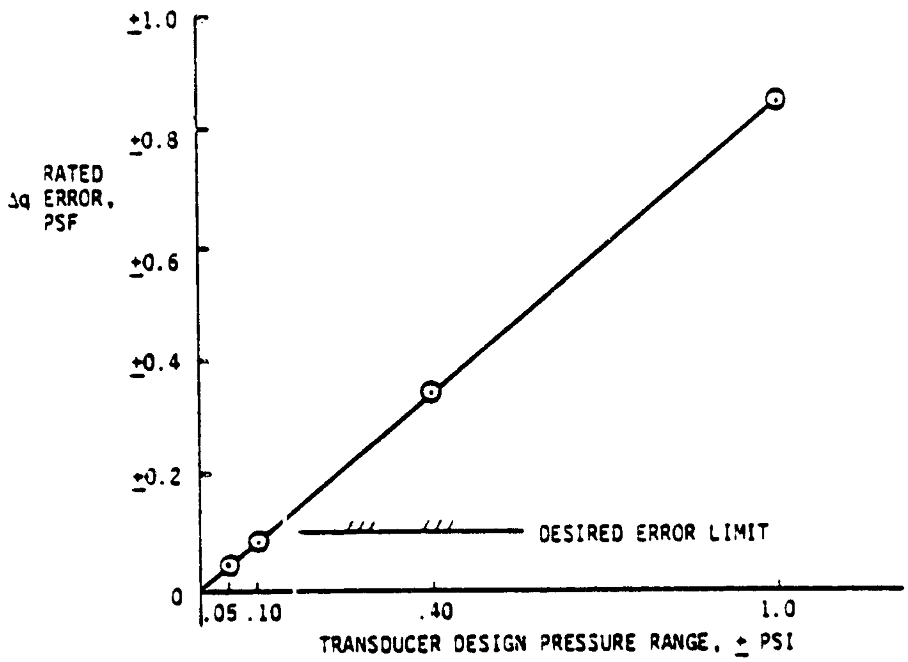


Figure 4.2-11 Representative q-Measuring Error Limits

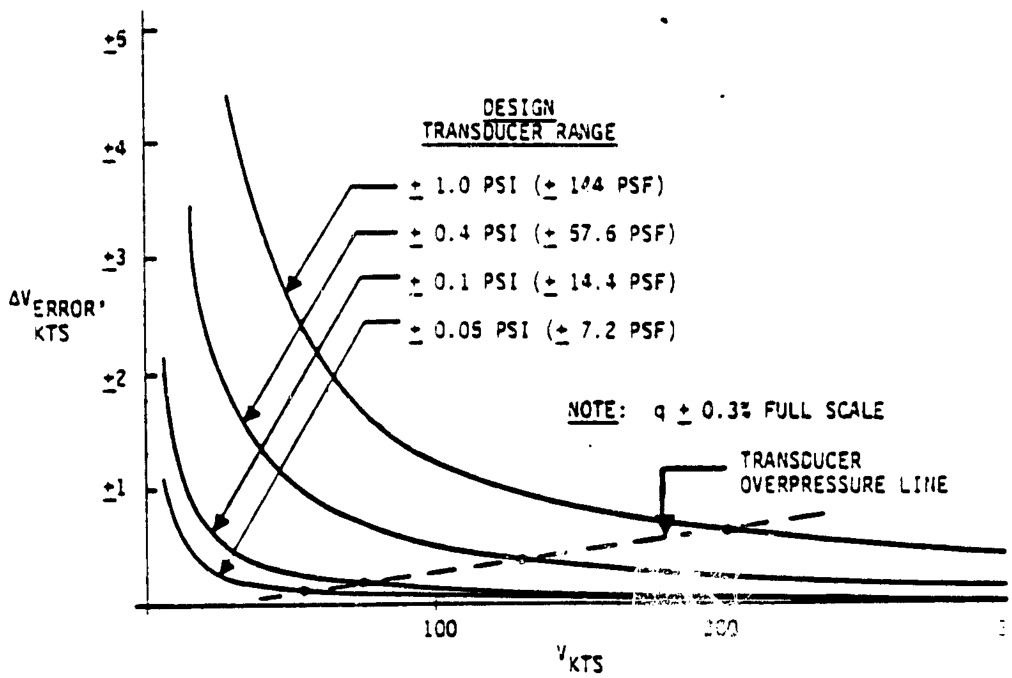


Figure 4.2-12 Velocity Error Resulting from $\pm 0.3\%$ q Error

(2) it places the control system in direct contact with the data acquisition system, an action violating the basic groundrules of this study.

Thus, while the method should be considered as an alternative to the transducer system, it will not be further considered here.

Finally, it should be noted that only half the range of a differential transducer is needed since the stagnation and static sides never interchange, even in reverse tunnel flow. This may enable the transducer manufacturer to rate the instrument at higher-than-normal accuracy, i.e., perform a special calibration.

Differential pressure transducers rated at 0.03% accuracy are available, though the constraints on their operating condition should be carefully considered relative to the wind tunnel control system environment. It is essential that transducers of the best obtainable accuracy be used in order to attain accurate speed settings at low tunnel dyanmic pressures.

4.2.7.3 Representative Implementation Schemes

Based on the error characteristics and transducer types discussed above, several transducer systems are shown to illustrate ways in which accuracies and ranges may be traded off to obtain good accuracy across the tunnel q range. The performance of the transducer systems is shown by plotting the error in airspeed resulting from q measurement error, versus airspeed, as in Figure 4.2.12; q error is constant over speed for a given transducer, of course, since it is based on instrument range only.

In these systems, multiple transducers are used, the control microprocessor selecting the signal from the proper transducer at a given tunnel speed.

Figure 4.2-13 shows the performance obtained with three differential transducers used in parallel. They are, from the high-speed end,

(1) a ±2.5 psi differential transducer with a special calibration to give ±.12% accuracy; this instrument gives a q accuracy of

$$(.0012)(144)(2.5)(2) = \pm 0.86 \text{ psf}$$

and a resulting speed accuracy better than ±1 knot down to 110 knots tunnel speed;

(2) A ±0.4 psi differential transducer rated at ±0.3%, giving ±0.35 psf q accuracy and a resulting speed accuracy better than ±1 knot down to 50 knots; this transducer "bottoms out" at 130 knots, by intention;

(3) a ±0.1 psi differential transducer rated at ±0.3%, giving ±.09 psf q accuracy and a resulting speed accuracy better than ±1 knot down to a speed of ~20 knots; this transducer is allowed to "bottom out" at 65 knots.

It will be noted that the high-q error of ±.86 psf is larger than desired. It will also be noted that the middle transducer could be eliminated if the speed error is allowed to exceed 1 knot between 65 and 110 knots; this is not recommended, however, as it is a prime rotorcraft testing speed range.

An example of the interconnection of these transducers is shown in Figure 4.2-14.

For the 80' x 120' tunnel, with its maximum q of 50 psf, a performance such as shown in Figure 4.2-15 can be obtained using two differential transducers.

(1) A ±0.4 psi instrument rated at ±0.15%, giving a ±.17 psf q accuracy and better than a ±1 knot speed accuracy down to a speed of 35 knots; and,

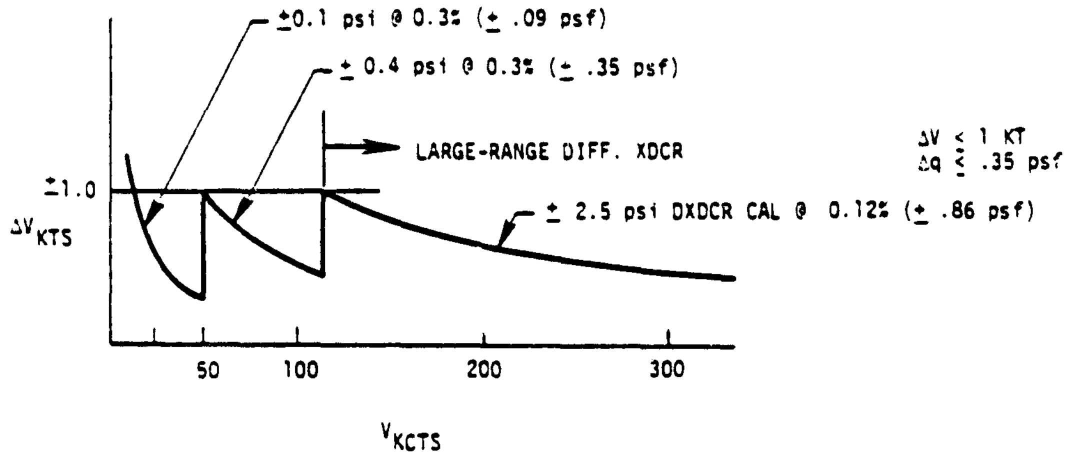


Figure 4.2-13 Three-Differential Transducer System for 40' x 80' Tunnel

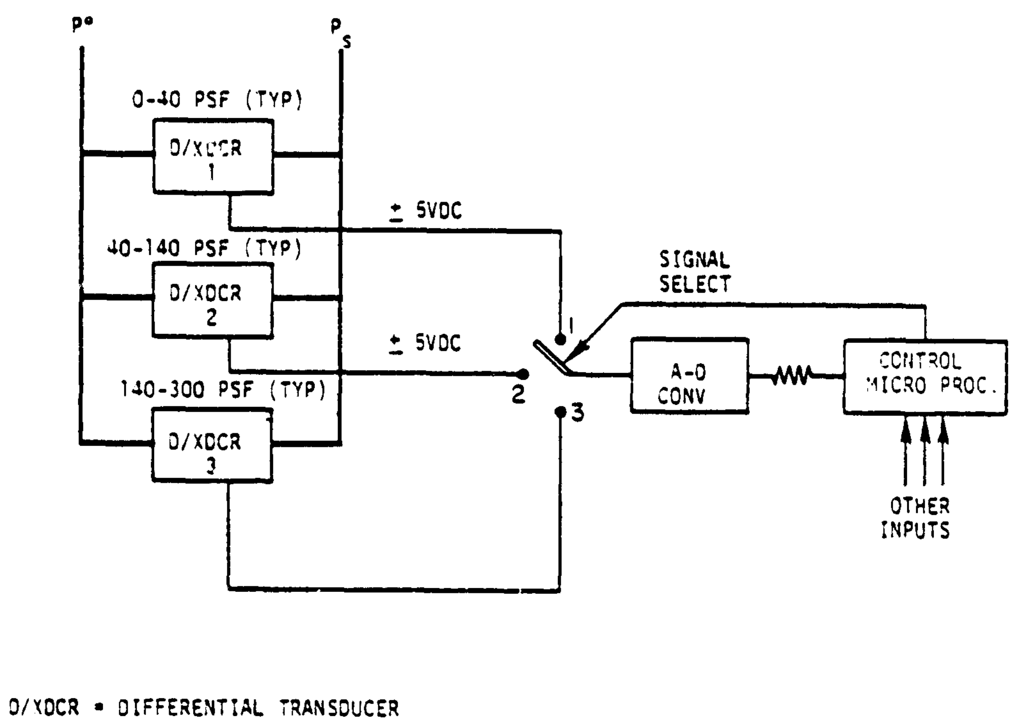


Figure 4.2-14 Typical Differential Transducer Arrangement

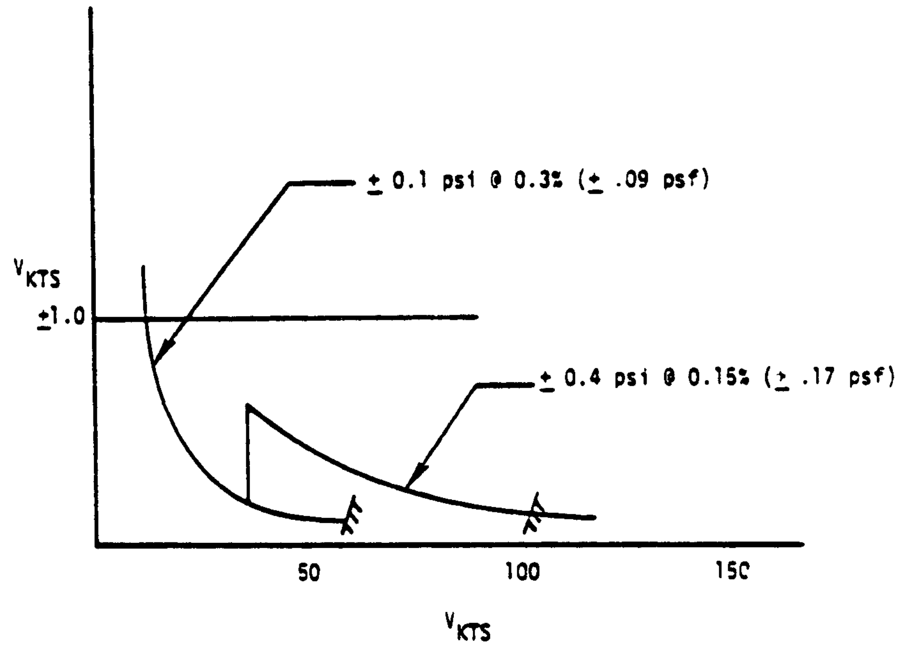


Figure 4.2-15 Two-Differential-Transducer System for 80' x 120' Tunnel

(2) A ±0.1 psi instrument rated at ±.3% giving ±.9 psf q accuracy and better than ± knot speed accuracy down to a speed of 6 knots.

Note that the high-speed transducer(s) continues to function for low-speed operation, giving a reference for failure detection and hence fail-safe reliability. At the high-speed end, an additional transducer is required if the operation is to be proven fail-safe.

4.2.7.4 Additional Implementation Considerations

Response Time

Modern capacitive pressure transducers respond on the order of milliseconds, a rate far beyond imposing limitations on a tunnel speed regulating system. For the 40' x 80'/80' x 120' speed-measuring system, a more important consideration is the transmission of pressure signals to the transducers through the several hundred feet of ducting involved in the q-system. Theoretical and experimental results such as those of Ref. 13 show that, for a 1-1/2" I.D. tube 200 feet long, less than 10% attenuation of the pressure amplitude would be observed at a frequency of 20 cycles per minute, at a phase lag of about 40 degrees (i.e. a 0.3-second time lag) indicative that the pressure pulse travels at approximately the speed of sound through the tube. For tubes of the length used here, pressure resonances are not anticipated. Pressure signal attenuation is less than half, however, at frequencies on the order of 1 Hz, which indicates that pressure disturbances caused by random tunnel turbulence may be sensed and input to the speed/q controller if the transducer signal is not filtered. This would tend to overwork the speed/q controller, leading to increased hardware maintenance requirements. It is recommended that the degree of turbulence be examined in the operational wind tunnels, and that a signal filter be installed if necessary. The filter may be one of the following:

(1) an acoustic impedance inserted in the pressure lines;

(2) an analog bandpass filter on analog transducer output (prior to A/D conversion) set nominally at 0.25 Hz rolloff frequency; or

(3) a digital filter providing an optimal estimate of mean pressure level in the pressures of random disturbances (optimal estimator or Kalman filter).

Installation Factors

Several factors of concern in the installation of high quality transducers are as follows:

(1) Electrical noise - The operating principal of many of the most accurate transducers is based on electrical capacitance. Therefore, adequate electrical shielding of the transducers is required.

(2) Power supply - A separate, regulated power supply, noise free, is recommended for the transducer system. Typically, ±15 VDC is required. Deviations in input voltage from nominal cause changes in transducer output; a typical value is ±0.3% of reading per 0.1 input volt charge.

(3) Vibration and acceleration - The transducer(s) should be mounted such that the axis of the diaphragm is oriented in the direction of least acceleration or vibration. Sensitivities to vibration range from 0.03% to 0.25% per g, depending on the range of the instrument.

(4) Temperature - Temperature variations impose the most severe transducer accuracy limits. Installing the transducer(s) in a controlled-temperature environment is likely to allow significant improvements in certified accuracies.

(5) Additional instrument factors - Absolute pressure transducers contain a scaled vacuum for reference, that is subject to long-term degradation due to leakage, although recent instruments show reliabilities up to 25,000 hours. The use of an absolute transducer does, however, introduce a maintenance item, though its cost may be warranted by the improved accuracy it can provide. Initial check calibrations will be required to evaluate system drift and overpressure effects, if any.

In conclusion, the balance room environment of the 40' x 80' tunnel may be an acceptable environment, though the presence of vibration and proximity to electrical equipment imply that better accuracy would be possible if the transducer system were mounted on a building foundation.

Each transducer should have its own amplifier for signal output to reduce electrical noise effects, and the use of individual, 12-bit A/D converters is recommended.

4.2.7.5 Secondary Pressure and Temperature Measurement Requirements

Given a commanded test section velocity, the corresponding dynamic pressure setting is computed (see Figure 4.2-8) from

$$q = \frac{1}{2} \rho V^2 = \frac{1}{2} \frac{p}{RT} V^2$$

where p and T are test section static conditions. Errors in the computation of p and T therefore affect the accuracy of the q-setting and, hence, affect the resulting V.

In the algorithm discussed previously (Section 4.2.4), p and T are computed from measured stagnation pressure and temperature of the tunnel airflow, just upstream of the test section. Partial differentiation of the above expression for q gives

$$\left.\frac{\partial q}{\partial p}\right|_T = \frac{V_{FPS}^2}{2RT} \doteq 5.662 \times 10^{-7} V_{FPS}^2 \text{ [psf/psf]; } T = 518.6°R$$

and

$$\left.\frac{\partial q}{\partial T}\right|_p = \frac{-p\ V_{FPS}^2}{2RT^2} \doteq -2.294 \times 10^{-6} V^2 \text{ [psf/°R]; } p = 2116 \text{ psf}$$

The variation of these derivatives over the 40' x 80' tunnel speed range is shown in Table 4.2-4.

Table 4.2-4

Q-Setting Sensitivity to p° and T° Measurements in 40x80 Tunnel

V_{KTS}	∂q/∂p (psf/psf)	∂q/∂T (psf/°R)
30	.0014	.0057
59	.0056	.023
89	.013	.052
118	.022	.092
178	.051	.206
237	.090	.367
296	.141	.574

As can be seen from this table, the effects of errors in tunnel condition measurements can exceed the effects of errors in the transducer q-system. A T° error of 1°F at top speed will result in a q-setting error of .57 psf and an accompanying speed error of .28 knots. A p° error of 0.01" Hg (.00491 psi) corresponds to a q error of .71 psf. These are errors in the q commanded to achieve a desired speed, and hence are independent of the q-sensing system and the action of the control system.

This phenomenon would seem to put a practical limit on wind tunnel speed setting accuracy. Temperature variation across the tunnel section may greatly exceed 1°F, and the variation of atmospheric pressure in the settling chamber exceeds .08 psi = 12 psf from floor to ceiling. To achieve more precise speed and q control at all speeds will require added instrumentation, in the form of pressure and temperature transducers and associated software, to determine tunnel flow properties.

4.2.8 Closed-Loop Wind Tunnel Control Studies

The wind tunnel math model described in Sections II and III was utilized in control studies to determine:

(1) the basic characteristics of the proposed speed/q-control system and appropriate loop gains for that system;

(2) the extent of limitations imposed on tunnel control by irregularities and nonlinearities likely to be present in the actual facility.

This subsection presents results of the following investigations:

(1) speed/q-command and hold effectiveness; and

(2) the effect of specific system nonlinearities on q-control.

Closed-loop control requires definition of the elements shown in the block diagrams above: feedback gains and schedules for the setting of commanded q through RPM and blade pitch angle specification must be provided.

RPM and blade pitch angle schedules were defined for low-speed (IFC-mode) and high-speed (line power mode) 40 x 80 tunnel operation, and are shown in Figures 4.2-16 and -17, respectively. The IFC-mode schedule follows the nominal RPM-ξ schedule shown in Figure 3.2-3. Various other schedules are feasible. The line-power blade pitch schedule is unique, however, since RPM is fixed at 180. Figure 4.2-17 shows the blade pitch schedule for the full operating envelope of the 40 x 80 tunnel. It will be noted that an alternate, slewing schedule in the IFC-mode may be desireable if the only purpose is to transition quickly to line power, to eliminate the blade pitch changes present in the schedule selected here. Such alternate schedules may be stored in SQCS memory and selected at will, yielding time and power savings.

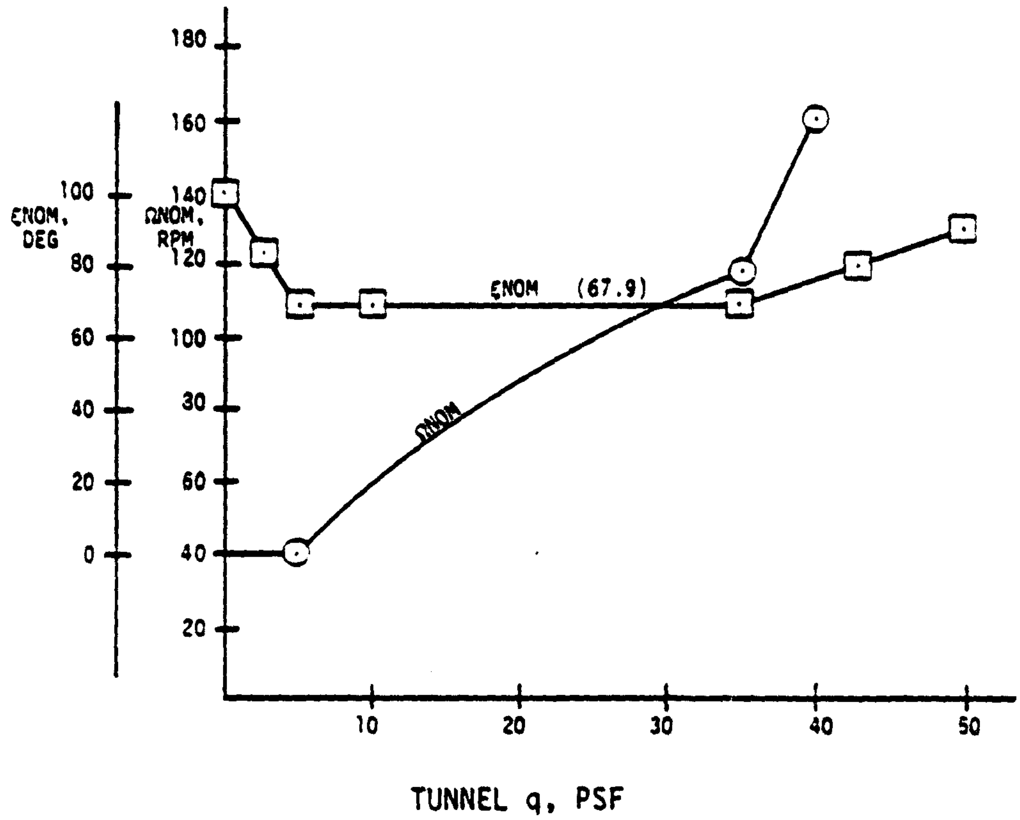


Figure 4.2-16 Preliminary IFC-Mode, RPM-Stagger Angle Schedule

Closed-loop runs examined here utilized blade pitch switch at high speeds and RPM control with constant blade pitch angles at low speeds. Combined RPM-ξ control at low speed may be desireable if blade rates can be made high enough. Control feedback gains were set empirically to give good response following a step q disturbance; tunnel and control nonlinearty effects are thus implicitly accounted for. Optimal control design techniques yield more exact feedback gain specifications, but the effect of system nonlinearities requires careful, explicit consideration. This technique is reserved for future work.

Experiments with derivative compensation in the feedback loop showed unsatisfactory response; hence, proportional plus integral compensation was used. The K_p and K_I gains selected for RPM and ξ control are shown in Figures 4.2-18; they must be scheduled to vary with operating condition.

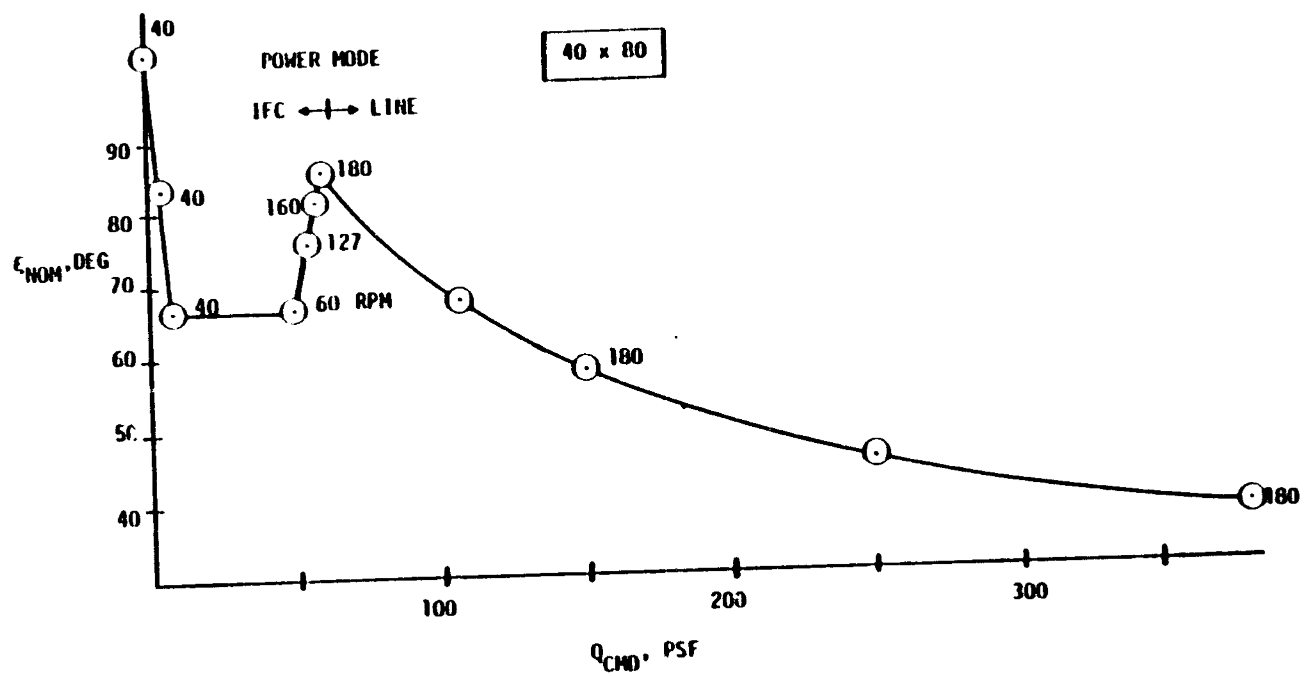


Figure 4.2-17 Full Envelope 40x80 Blade Stagger Angle Schedule

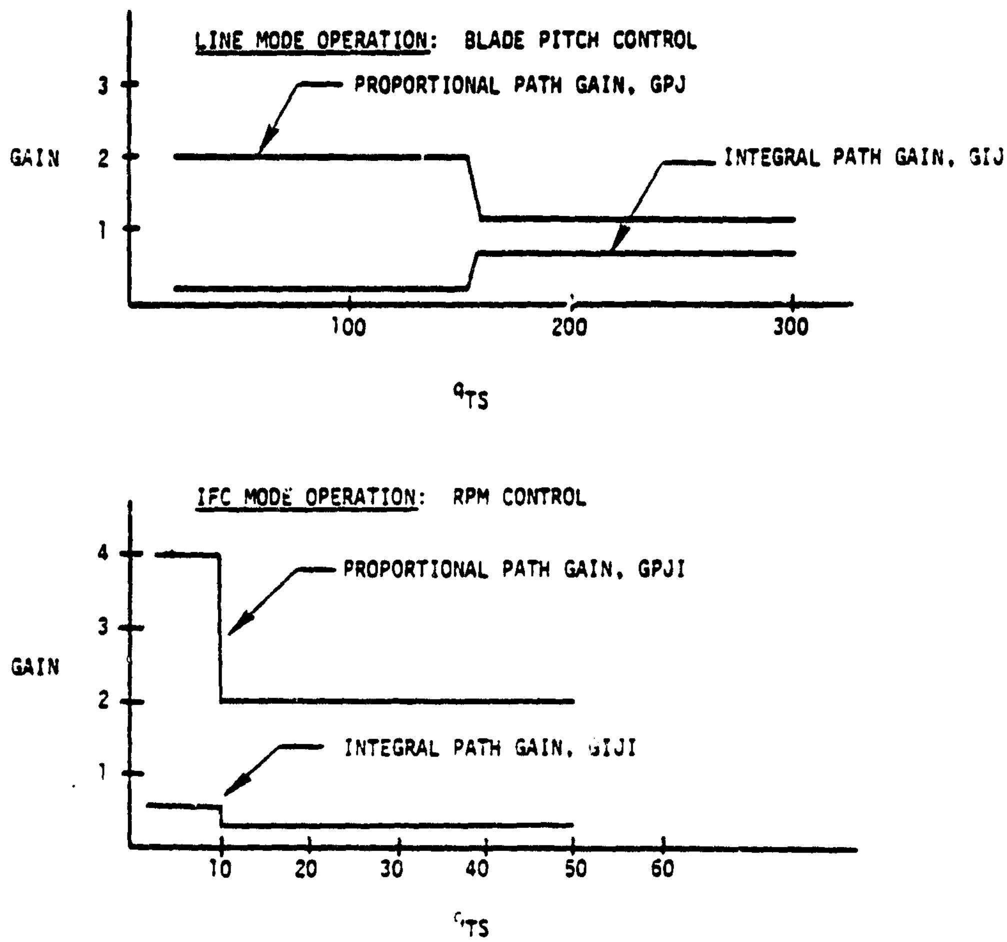


Figure 4.2-18 Preliminary Controller Gains for Closed-Loop Operation

The effectiveness of this baseline controller is shown by the representative closed-loop response in Figures 4.2-19 and -20. Figure 4.2-19 shows closed-loop, q-hold response following a test section drag input step of 5000 lb. at three operating conditions: q_i = 243, 151, and 55 psf, corresponding to Ω = 180 and ξ = 48°, 58°, and 85°, respectively. The blade pitch actuator is assumed to be "perfect" - no hysteresis or deadzone in blade pitch setting. The first two cases show the set q to be regional and hold with high accuracy after about 20 seconds; the third case requires around 30 seconds because more blade pitch change is required at lower tunnel dynamic pressures, and the blade pitch rate is limited in this study to a nominal value of 0.08°/sec. The performance of the controller in each of these cases is satisfactory.

Figure 4.2-20 shows two IFC-mode cases in which the controller is to hold q following a 2000 test section drag input, using RPM as the control. The controller is seen to be quite effective and provide satisfactory control; improved knowledge of MG system characteristics and careful gain selection will permit reduction of the oscillation in q as the set value is required. If particular interest in these cases is the variation of DC armature current within the MG system, which according to the machine constants assumed in this study are seen to undergo large excursion beyond the steady-state values.

The effects of blade pitch actuator hysteresis and deadzone were studied for a typical line-power-mode case, ξ = 48°. The results are shown in Figure 4.2-21. Deadzone is seen to cause a slight offset in desired q and a resulting "hunting" oscillation, but is not serious. Hysteresis, however, which is present to some extent in all mechanical linkages, is seen to be capable of causing a limit cycle in tunnel q, as the controller can never quite null out the q error by making just the right adjustment to ξ. This behavior is unacceptable, as it is a disturbance to data acquisition and a possible

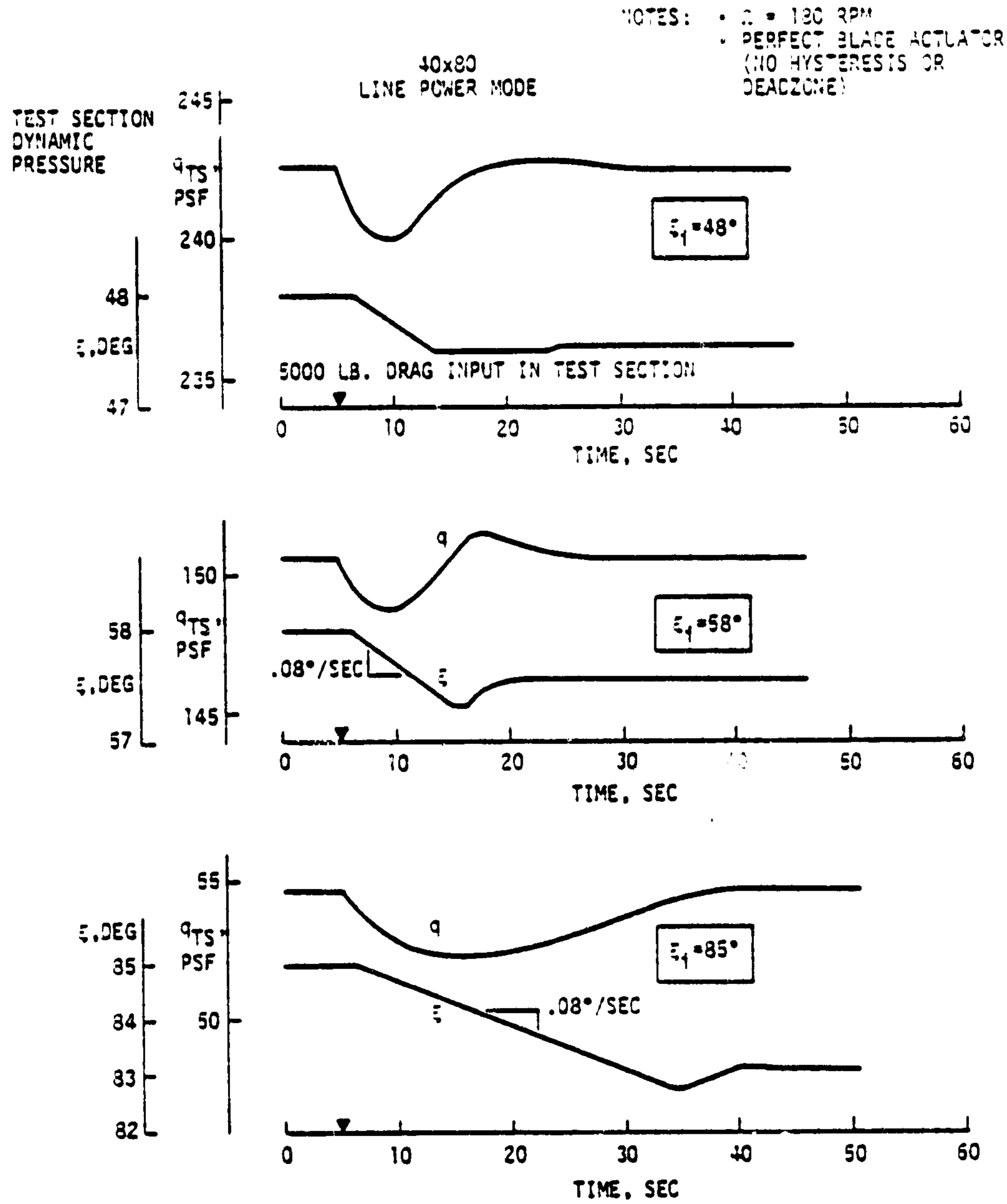
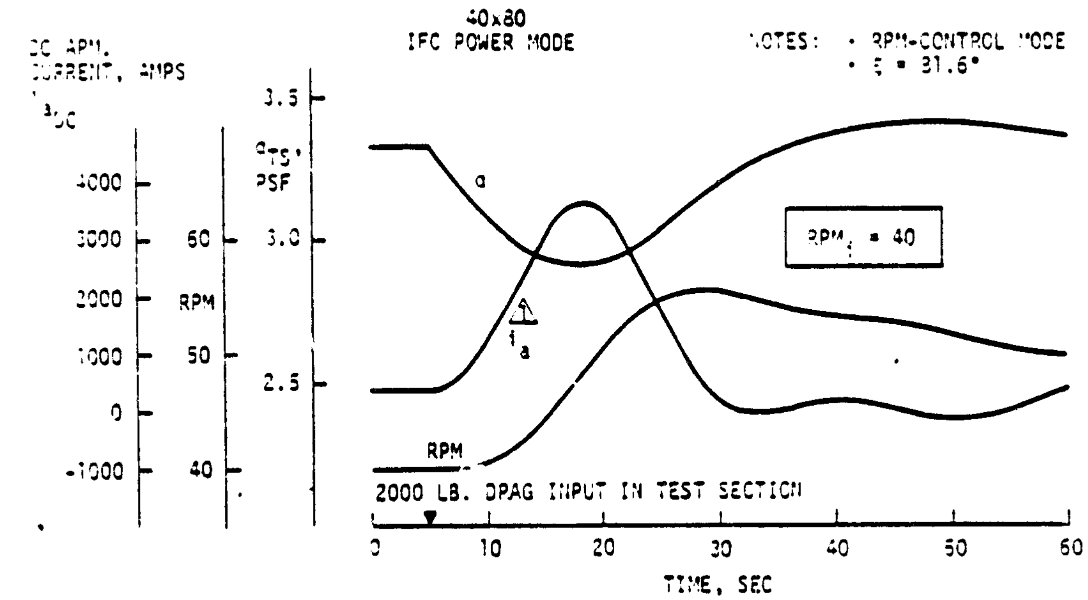
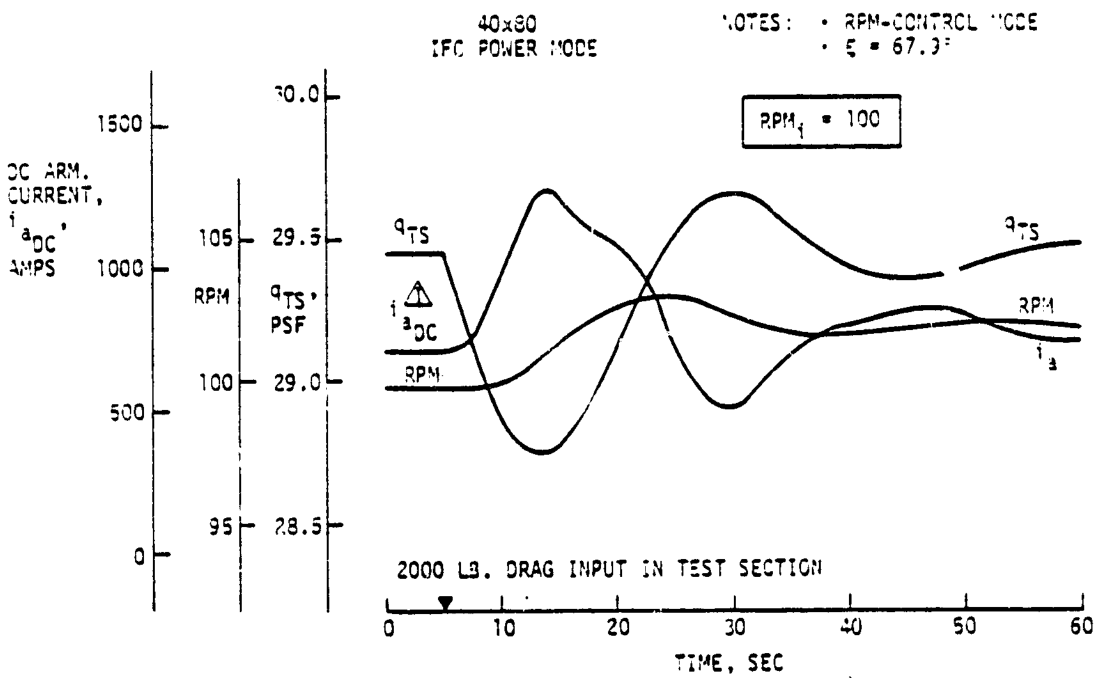


Figure 4.2-19 Closed-Loop Response to a Step Drag Input at Three Operating Conditions; Line Power Mode; Perfect Blade Actuator



⚠ MAGNITUDE OF i_a VARIATION IS BASED ON PRELIMINARY ESTIMATES OF IFC CHARACTERISTICS



⚠ MAGNITUDE OF i_a VARIATION IS BASED ON PRELIMINARY ESTIMATES OF IFC CHARACTERISTICS

Figure 4.2-20 Closed-Loop Response to Drag Input at Two Operating Conditions: IFC Mode, ξ-Fixed

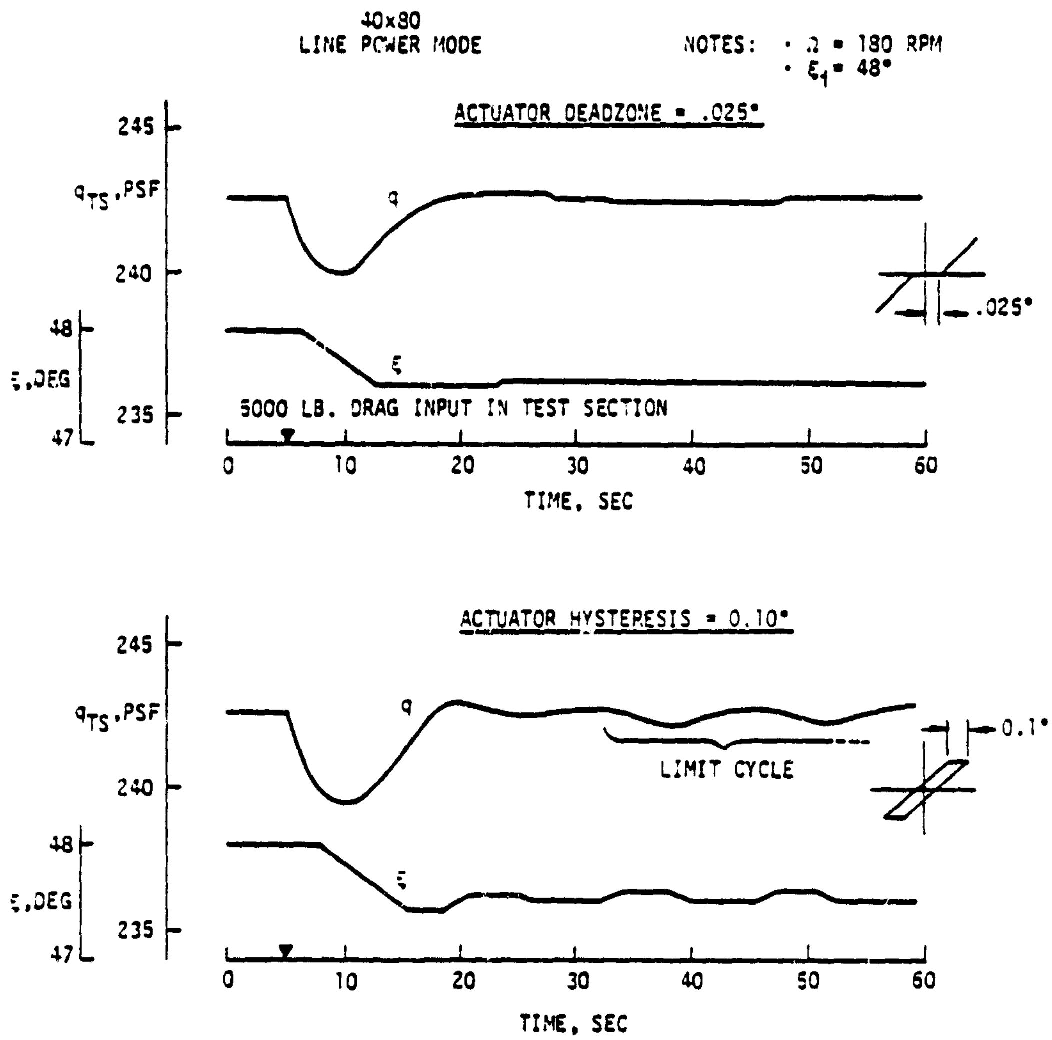


Figure 4.2-21 Closed-Loop Response to a Step Drag Input in the Presence of Actuator Non-linearities; Line Power Mode

divergent instability. It can be lessened by increasing blade pitch setting tolerance, but can only be eliminated by disengaging the q-hold system or at least the integral feedback path, after q is first within tolerance. This can be accomplished by the addition of appropriate logical functions to the SQCS control law.

The cases described above demonstrate the feasibility of the proposed speed/q control law over the 40 x 80 tunnel operating envelope and establish a baseline controller for the development of more optimal control laws. With the provision of new controller gains and operating schedules, control of the 80 x 120 tunnel is effected similarly.

4.3 MODEL ATTITUDE CONTROL SUBSYSTEM (MACS)

4.3.1 Overview

Models will be supported in both the 40' x 80' and the new 80' x 120' test sections using the three-strut plus turntable system now used in the 40' x 80'. Model pitch attitude is varied by changing the length of the tail support strut; model yaw angle is varied by rotating the turntable that carries all three struts. A schematic of this system is shown in Figure 4.3-1.

The function of the automatic model attitude control system is to relieve the tunnel operator of the task of manually setting individual pitch and yaw attitudes and to permit actual attitudes to be commanded instead of arbitrary meter counts. It is further to provide the capability to employ different model rates at different points in the test sequence, within safety constraints, and to enable model attitudes to be commanded by a remote computer under the test management function described in Section 4.3.3.

4.3.2 Control Function Analysis

The overall objective is more effective control of model pitch and yaw attitudes through automatic calculation of attitudes from turntable and tail strut position sensors, selection and control attitude rates, and sequencing of attitude changes by a test management computer. Specific requirements on the automatic system include the following:

(1) fail-safe operation, reverting to manual control in case of controller error;

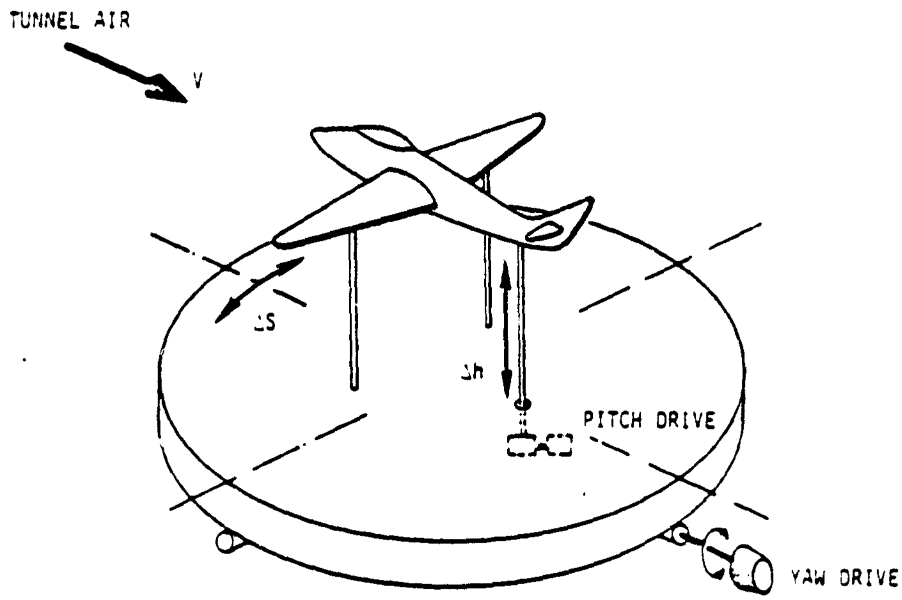


Figure 4.3-1 Model Support and Positioning System

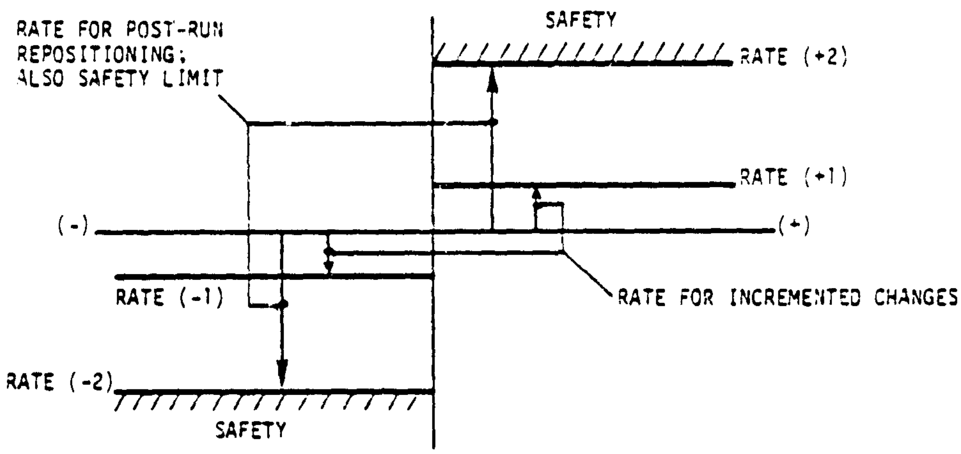


Figure 4.3-2 Proposed Model Attitude Rates

(2) variable rate limits, variable tail strut height-pitch angle calibrations;

(3) model attitude and attitude command displayed to the tunnel operator and test engineer and available to the test management computer;

(4) manual entry of geometric data for model attitude computation;

(5) non-interruptible power supply for both computers and model attitude drive motors.

The selection of model attitude rates involves consideration of the following factors:

(1) the desire for the fastest feasible re-positioning of the model from one run to the next, consistent with adjustment of tunnel q to test conditions, as in the most sophisticated control system the test management computer commands both tunnel q and model attitude sequencing;

(2) the requirement for a rate limit such that the rate of increase or decrease of angle of attack or yaw or of aerodynamic loads can be monitored by the test engineer;

(3) improvement in accuracy of small position changes by using a reduced rate that results in smaller offset errors due to motor inertia, leading to an overall reduction in the number of motor cycles.

At present, a two-rate attitude drive is envisioned, providing a compomise between the lower, precise rate best for attitude sweeps, and the higher rate desired for post-run model repositioning. This is shown schematically in Figure 4.3-2. This may be accomplished, for example, by providing two power leads of different voltages for the driver motors, a scheme suitable if dc motors are used.

The use of an infinitely variable rate drive would provide further versatility by permitting the rate to be varied continuously by the control system depending on attitude error and attitude command. Some time savings in model positioning may be realized if the inertial characteristics of the drive system require the desired attitude to be approached slowly to avoid overshoot.

For yaw angle positioning, direct measurement of angle as movement at the turntable edge necessitates less computation, but again, sensor and microprocessor resolution must be considered.

The use of an automatic positioning system enables simultaneous attitude changes in pitch and yaw. The desirability of utilizing this system capability must be determined by the user.

4.3.3 Model Attitude Control Laws

The model attitude control loop is a position control system shown schematically in Figure 4.3-3. Receiving model attitude commands from the tunnel operator or test management computer, the computer algorithms convert the attitude command to the corresponding tail strut extension and/or turntable rotation and send drive signals to activate tail strut and turntable motors until the commanded extensions and rotations have been obtained.

4.3.4 Model Attitude Control Algorithms

A key function in the MACS is the conversion of attitude command to tail strut extension. This may be done in one of two ways:

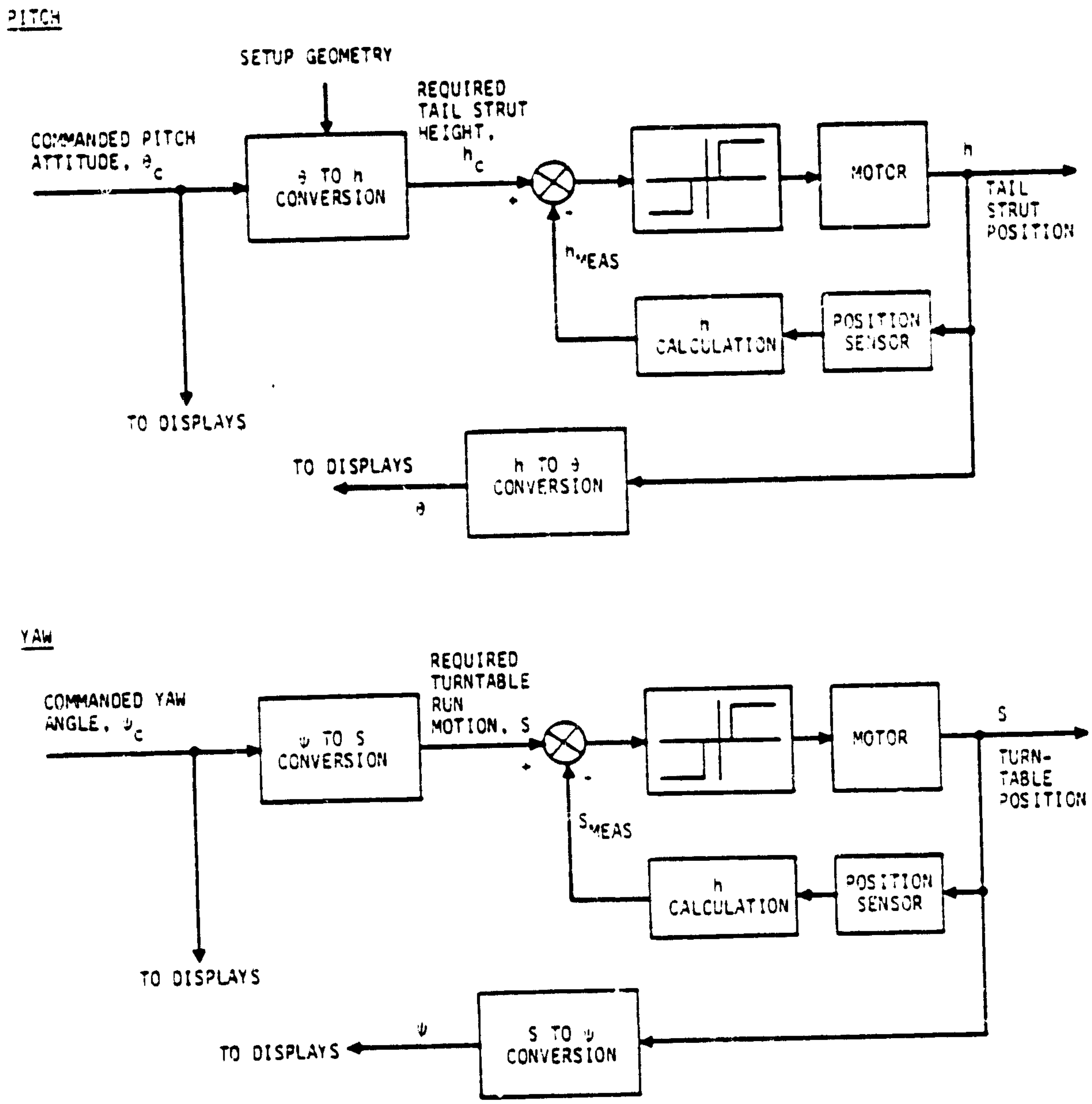


Figure 4.3-3 Model Attitude Control System (MACS) Control Laws

(1) by measuring tail strut extension at various calibrated model attitudes, storing these pairs of values in controller memory, and performing a linear interpolation to obtain h from Θ;

(2) by a trigonometric calculation based on model position measurements.

In method (2), tail strut extension can be calculated from the expression:

$$h = [(Z_m - \ell'_{TS} \sin(\Theta - \xi)]^2 + (X_{TS} - \ell'_{TS} \cos(\Theta - \xi))^2]^{1/2}$$

where, as illustrated in Figure 4.3-4,

Z_m = main model pivot height above tail strut pivot;

ℓTS = tail socket length, from main pivot;

Z_T = tail pivot height above main pivot;

$\ell'_{TS} = (\ell^2_{TS} + Z^2_T)^{1/2}$;

$\xi = \tan^{-1}(Z_T/\ell_{TS})$;

θ = model attitude from horizontal;

h = tail strut length from tail strut pivot to tail strut ball center.

Only four dimensions are required: Z_m and X_{TS}, which are model-support-dependent, and ℓ_{TS} and Z_T, which are model dependent. The above equation is exact, and if the struts do not deflect significantly under model load, a point-by-point attitude calibration is not required.

Aside from the conversion of attitude command to tail strut or turntable position, the principal operations of the MACS computers are logical in nature. The system must:

(1) correlate position to command;

(2) guard position limits; and

(3) select drive rates.

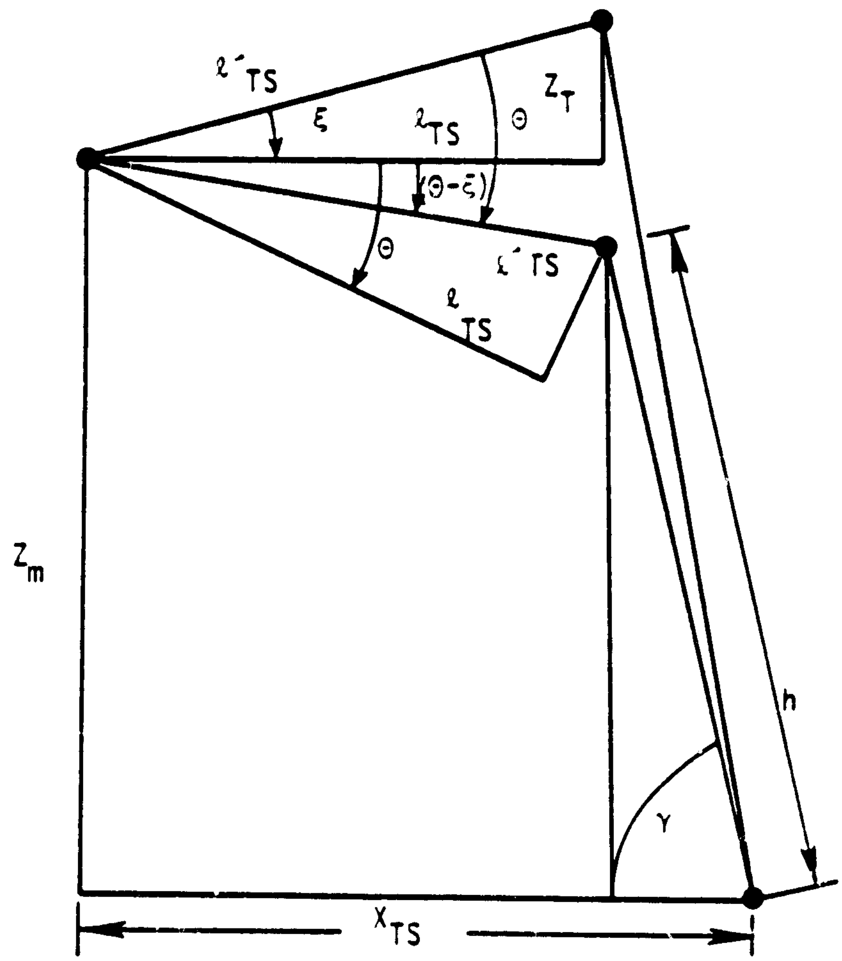


Figure 4.3-4 Tail Strut Geometry

The essential logical functions to be performed in the MACS software to control pitch and yaw attitude are shown in the flowcharts if Figures 4.3-5 and 4.3-6. The functions are largely ones of performing tests on system status and activating or deactivating output commands based on that status. The inputs and outputs are discussed more fully in Section 4.3.6, below. Such functional blocks as "Engage Tail Strut Lock," which refers to turning off tail strut air to engage the spring-loaded fairing locks, may be expanded to show more detailed activation logic when the system design is finalized.

4.3.5 MACS Reliability

The model attitude control system is to have fail-safe reliability with manual backup. It will always be acceptable to control the model by manual operations, and although automatic operation is desirable the loss of the automatic system is not cause for halting testing.

It is recommended that the desired fail-safe reliability of the MACS be obtained with dual-redundant, dedicated microprocessors performing both input/output and cross-monitoring functions and disengaging themselves in the event of disagreement in input or output or internal computations. In this structure it is similar to the SQCS discussed above.

As noted in Section 4.3.2, the difficulties of installing and controlling an infinitely-variable-rate attitude drive imply that a two-speed, fast/slow rate be employed. The slow rate is to be used for small, point-to-point attitude changes and near the high-force, limiting attitudes of models to improve setting precision. The fast rate is to be used for resetting

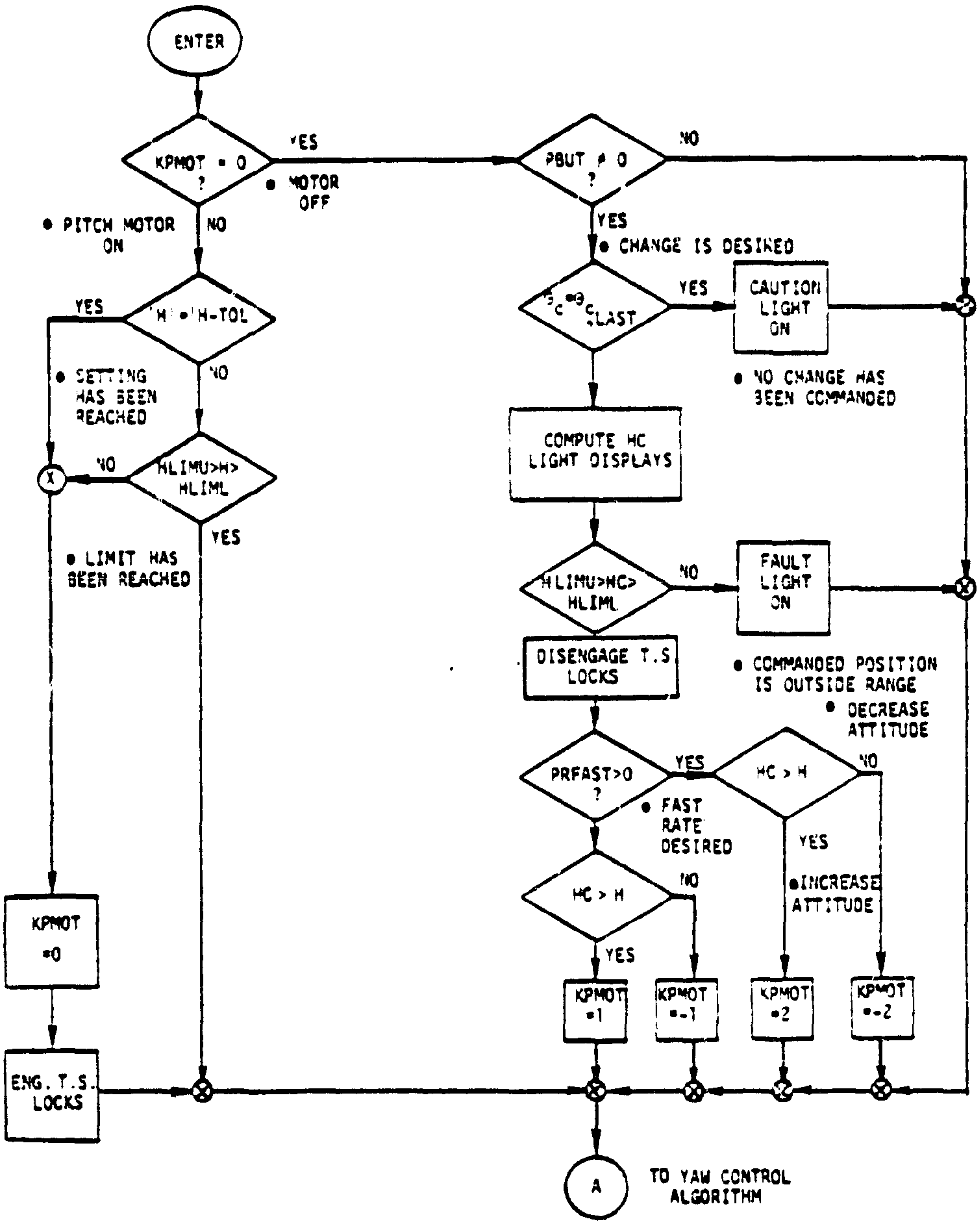


Figure 4.3-5 Model Pitch Attitude Control Logic - 2 Speed Drive

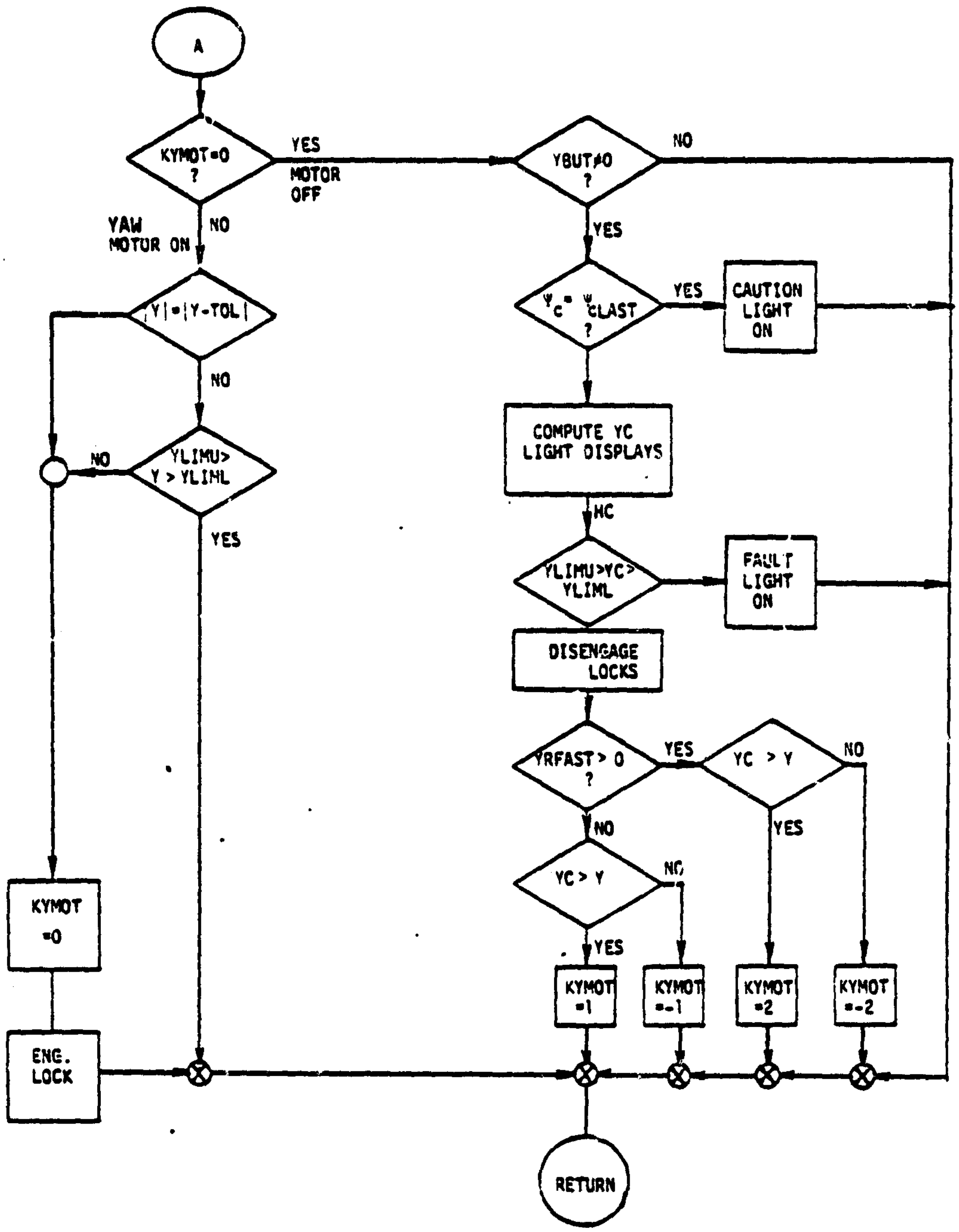


Figure 4.3-6
Model Yaw Attitude Control Logic - 2 Speed Drive

C-3

between runs. This selection of rates can be effected with ease by the tunnel operator, hence the principal loss in test efficiency would be in adjusting for a precise attitude or a reluctance to reposition simultaneously in two axes. The MACS provides, however, the capability for multi-speed attitude control if desired and feasible.

4.3.6 Model Attitude Control Subsystem Implementation

This section presents detailed MACS implementation recommendations summarizing the functions and requirements discussed above. A system schematic drawing is shown in Figure 4.3-7. The system achieves fail-safe operation through dual redundancy: monitoring functions within the two separate computers will shut the MACS off if discrepancies are detected in input or output data, and control reverts to manual. Computer or operator generated signals activate a motor controller on each axis, which in turn starts the drive motor. Position pickoffs on the tail strut and turntable are scaled and compared to position commands computed from attitude commands.

Tables 4.3-1 and 4.3-2 itemize the distribution of control functions between the dual processors and the specific inputs and outputs identified for this system. Table 4.3-3 gives performance requirements considered necessary in an attitude control system.

A representative control panel layout for the model attitude control subsystem is shown in Figure 4.3-8. It features:

(1) thumbwheels for positive-indication attitude selection;

(2) lighted displays, computer-controlled, of actual and commanded attitude;

(3) a pushbutton to activate the system toward seeking the commanded model attitudes;

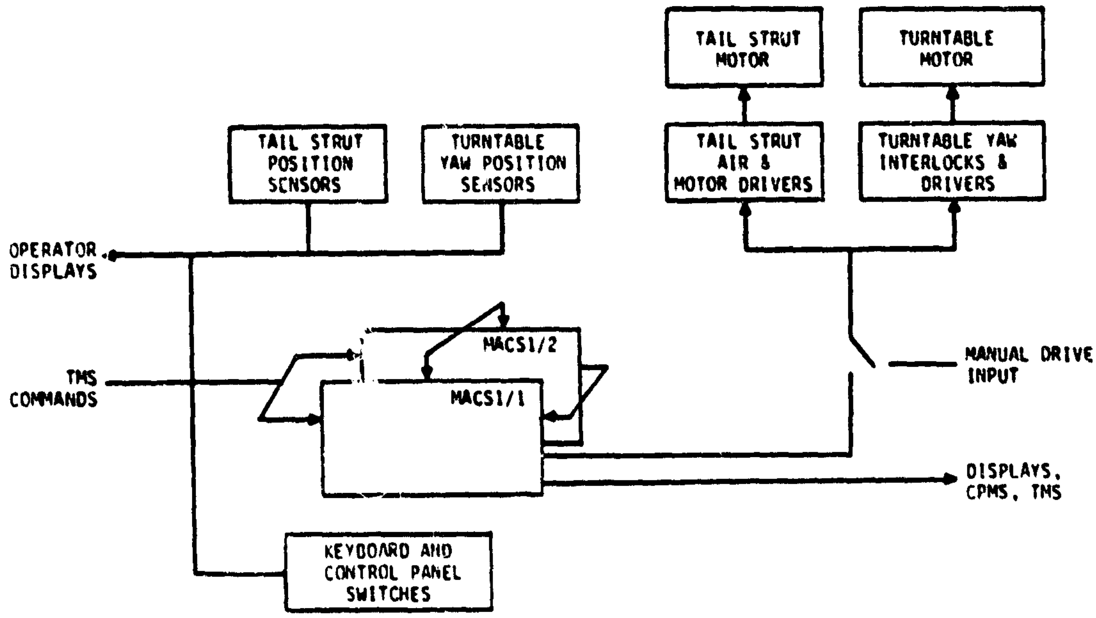


Figure 4.3-7 General Arrangement of Subsystems, MACS1 and MACS2

Table 4.3-3

Performance Requirements: MACS1 and MACS2

ITERATION RATE All functions shall be accomplished every 0.1 seconds. Tolerance on the cycle-to-cycle variation in the time at which the tail-strut position and yaw angle sensors are interrogated is 0.02 seconds.

Table 4.3-1

I/O and Function Distribution MACS1 and MACS2

INPUT/OUTPUT DISTRIBUTION

INPUTS

MACS1/1 MACS1/2	Receive identical inputs from all sources (40x80)
MACS2/1 MACS2/2	Receive identical inputs from all sources (80x120)

OUTPUTS

MACS 1/2	Outputs to MACS 1/1
MACS 1/1	Outputs to 40x80 and desired 40x80 operator displays, CPMS and TMS1
MACS 2/2	Outputs to MACS 2/1
MACS 2/1	Outputs to 80x120 and desired 80x120 operator displays, CPMS and TMS2:

FUNCTION DISTRIBUTION

MACS 1/1; MACS 2/1	Basic functions plus output management
MACS 1/2; MACS 2/2	Basic functions plus crosscheck management

Table 4.3-2

Input/Output Itemization MACS1 and MACS2

INPUTS	FORM	REMARKS
1. Tail strut position sensors	Digitized	• must resolve 0.1" tail strut extension over 20'
2. Yaw angle position sensors	Digitized	• must resolve 0.25" turntable motion at periphery over ± 90°
3. Commanded pitch and yaw attitudes	Digitized voltage corresponding to desired settings	• origin thumbwheels, keyboard, or TMS computer
4. Set-up geometric information	Digitized	• from keyboard
5. Activation command	Discrete	• control panel pushbutton
6. Attitude rate manual select	Discrete	• for use in manual operation only
7. System engage/disengage	Discrete	• disengage to revert to manual control
OUTPUTS		
1. Activation signals to pitch and yaw motor devices and interlocks	Digital	• switch on motors, disengage tail strut air and yaw locks to move model.
2. Control panel attitude displays	Digital analog (D/A)	
3. Pitch and yaw data to TMS		• for monitoring
4. CPMS data		
5. Data for other micro-processor		• for monitoring

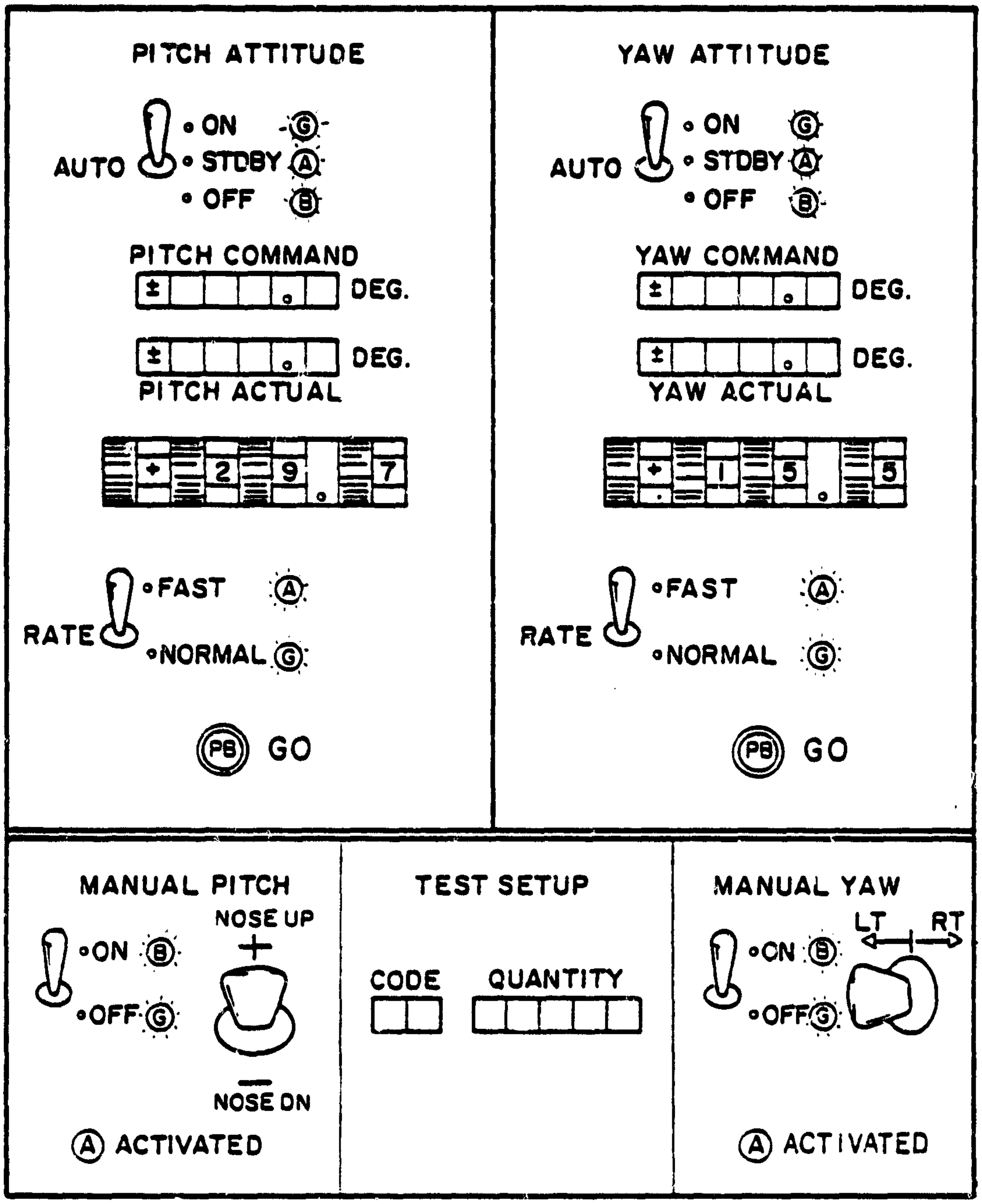


Figure 4.3-8 Proposed MACS Control Panel

(4) a fast/slow rate select switch; and

(5) manual-control jogging switches: switch deflection engages a drive motor, releasing it stops the motor.

A peripheral keyboard is required to input model and support system geometric data.

A mechanical display of model attitude, in raw count form, is also required to support manual operation, since under the present implementation scheme the lighted display of model attitude will be lost if a computer shutdown occurs.

The data stored in computer memory is protected by software to prevent its inadvertent alteration during a run.

4.4 CRITICAL PARAMETER MONITORING SUBSYSTEM (CPMS)

4.4.1 Overview

This section discusses a control subsystem to monitor the status of operationally significant parameters of the wind tunnel system. These parameters represent measurements taken in the test section, on tunnel structure, in the drive system, in the other control subsystems, and on the models. This is a passive control system in that it outputs no commands to change model or test conditions, but rather tests parameter values against predetermined values and activates visual and/or aural warnings if discrepancies are detected. It was found in consideration of this subsystem that its role is independent of those of the other control subsystems and critical to either manual or automatic control, as out-of-tolerance conditions could exist in either case in elements such as the fans or the model. Therefore, somewhat higher reliability is recommended in this system, since it represents a large improvement in capability and versatility over existing and planned electromechanical status annunciating systems.

4.4.2 Control Function Analysis

The CPMS has the following principal functions to perform:

(1) receive sensor data, convert to engineering units, and compare to predetermined, reference values stored in computer memory;

(2) perform pre-comparison computation and/or filtering on certain selected parameters to monitor quantities not directly measurable; for example, combine fan RPM, blade pitch angle, and tunnel speed measurements to compute fan stall margin;

(3) perform comparisons among various input signals; for example, vote the redundant blade pitch angle measurements on a given fan, or compute the mean blade angle setting of all six fans;

(4) perform integrations and/or differentiations to obtain parameter rates of change or mean values;

(5) based on preselected criteria, activate the appropriate warning or caution lights, perhaps with aural warning, if out-of-tolerance conditions are detected;

(6) reset a failure alarm when the fault is cleared, or hold until it is; master alarm lights are resettable for most failures, annunciator lights remain on until fault is cleared (as discussed in Section 4.4.5, below); and

(7) perform integrity checks on sensors using available sensor redundancy.

Secondary functions of the CPMS are:

(1) coordinate of the functions of the redundant, independent CPMS microprocessors to be used;

(2) provide hard-copy system status information, and store selected monitoring data--both critical and non-critical--for a post-run dump;

(3) manage operator input discretes;

(4) manage data inputs from SQCS and MACS microprocessors and TMS minicomputer; and

(5) manage operator input of parameter reference values; some reference values are in permanent memory while others are to be changeable from the operator keyboard.

The selected annunciation system has two levels of warning authority in announcing out-of-tolerance parameters:

(1) CAUTION - an indication that an out-of-tolerance situation exists somewhere in the system, that must be acknowledged by the operator in clearing the alarm; it represents a degradation of the test effectiveness of the system; no other operator action is required.

(2) WARNING - an indication that a dangerous fault has been detected that requires operator action to avoid possible damage to facility or model; the operator consults a display panel to determine the exact nature of the fault.

In certain critical parameters an aural warning may be added to the WARNING-level alarm to further alert the tunnel operator and engineer to a hazardous situation.

The logic controlling the illumination and extinction of lights, activation of aural warning, and resetting of alarms is all controlled by firmware in the CPMS computers.

The sequence of warning annunciation is as follows:

- CAUTION light or WARNING light calls operator's attention to annunciator panel, also indicating seriousness of problem; with WARNING light, test must be halted.
- ANNUNCIATOR light, one of many grouped according to system, informs operator of exact location of fault.
- ANNUNCIATOR light remains on until fault is corrected, though CAUTION light may be reset for another indication. WARNING light is generally not resettable.

4.4.3 CPMS Algorithms

Two types of algorithm are required to perform the parameter monitoring function:

(1) parameter selection, scaling, computation and comparison, and

(2) fault annunciation management.

A typical logic flow chart for these algorithms is shown in Fig. 4.4-1. The operations performed within the CPMS computers are as follows:

(1) select a parameter as directed by the executive program;

(2) convert to engineering units and combine with other parameter measurements (if necessary) to compute net parameter value;

(3) compare to reference parameters;

(4) if out of tolerance, illuminate appropriate warning/ caution and annunciation lights, and aural warning if desired;

(5) return to select a new parameter, and repeat.

The equations used in scaling and in the computation of abstract parameters must be stored and called as required for each parameter. Similar parameters should be grouped in time to minimize cycle time.

Parameter limits set in the computer must be wide enough to avoid nuisance trips from noise or sensor drift; periodic recalibrations of some sensors (i.e., the insertion of revised limits) should be planned.

Variable sampling rates are desirable so that high rates can be maintained on the most critical parameters while a larger number of parameters are sampled at lower rates. This must be selectable if data channels are to be added or deleted.

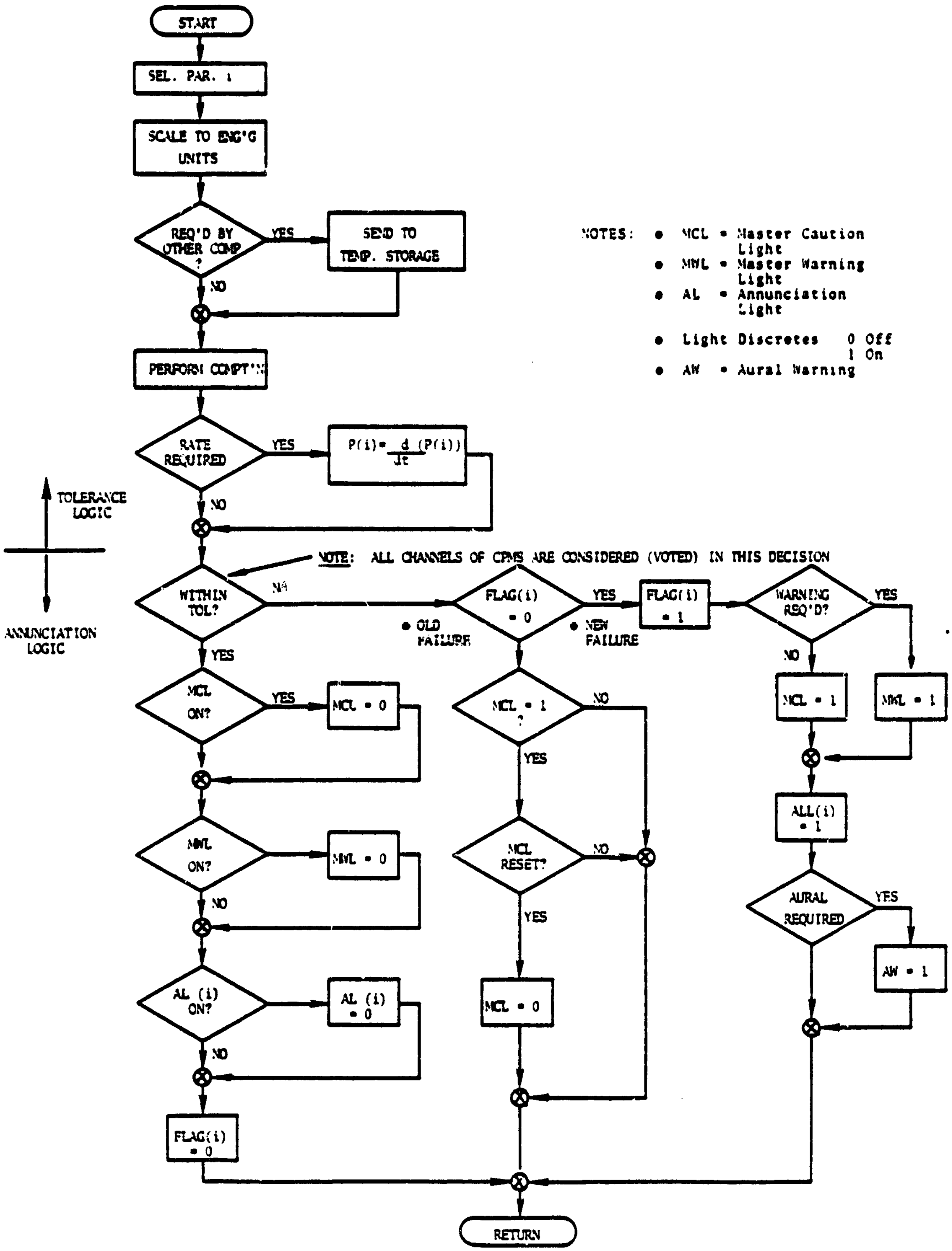


Figure 4.4-1 Critical Parameter Monitoring Subsystem Tolerance Check and Annunciation Logic

4.4.4 CPMS Reliability Requirements

Because of its importance to all modes of wind tunnel operation, it is recommended that the critical parameter monitoring subsystem be fail-operational in reliability. If this is achieved, no single monitoring subsystem failure will result in loss of monitoring of a critical tunnel parameter, and the ability to detect and compensate for sensor errors is improved.

The recommended subsystem thus consists of four redundant microprocessor units. Most CPMS functions are performed simultaneously in the units, though some unique pairing of operations may be made in the interests of improved cycle time for less critical ("caution"-type) parameters. A voting system is to be used to detect processor malfunctions arising from the units themselves or from their input data. Should a disagreement be detected, the signal from the outlier will be discounted; should a disagreement between the remaining signals be detected, it will be treated as if the fault or voted, depending on how the voting logic has been programmed to test this parameter. This required consideration of the redundancy on the sensor level. This methodology is shown in Figure 4.4-2. Unlike the SQCS and MACS units, however, the CPMS does not remove itself from operation following a failure or several failures, since it can still provide some useful information as long as even one unit is functioning. Until a WARNING is declared, the tunnel may be operated with any number of CAUTION annunciations, real or erroneous. The probability of erroneous signals, with a quad-redundant system, is very low.

CPMS SIGNAL VOTING LOGIC (3 UNIT VOTING)

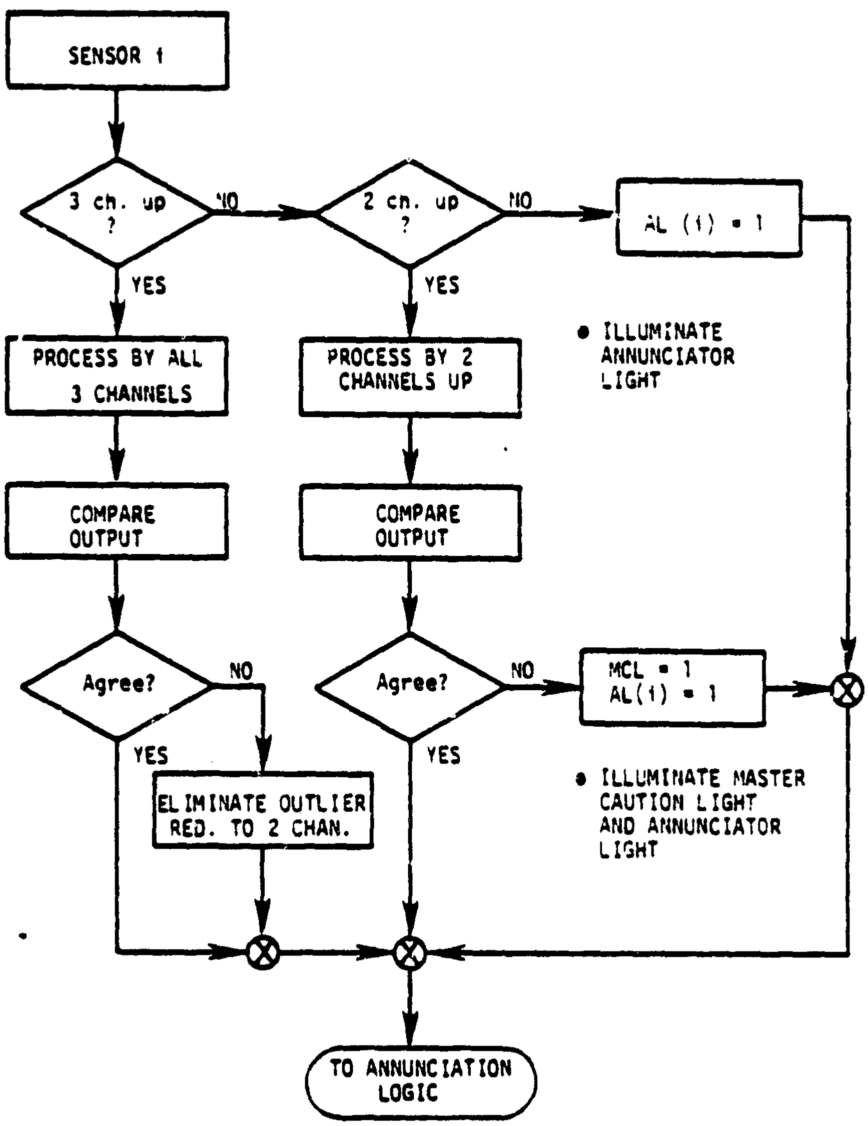


Figure 4.4-2 CPMS Signal Voting Logic

The reliability of this system will be determined in large part by the number and expected reliability of sensors and by the method through which the computers monitor themselves and each other, i.e., how the voting logic is programmed. Very high levels of reliability may be obtained from a triply-redundant system if sensor inputs as well as computer outputs are voted, but the development of such software is a major undertaking, particularly in a case such as this in which different levels of sensor redundancy may be desired due to equipment cost consideration versus failure impact. A simpler, quad-redundant system may be more cost effective. A detailed analysis of the CPMS is required before further design decisions can be made.

4.4.5 CPMS Implementation

The CPMS should be regarded as a central coordinating unit for tunnel parameter monitoring, receiving data from both test sections, both models, and the fans and M-G system. Duplicate multiple redundancy is thereby avoided, and a single quad-redundant system created to monitor tunnel parameters.

The general arrangement of the CPMS is shown in Figure 4.4-3. Tables 4.4-1 and 4.4-2 present input itemization and function districution, respectively.

Figure 4.4-4 shows a suggested fault annunciator panel for the CPMS. Master CAUTION and WARNING lights should be located near the SQCS control panel for maximum visibility by the tunnel operator. A large number of annunciator lights, grouped according to system, are located on a panel to the side of the operator's control panel. These lights indicate the number and extent of the faults detected, and are controlled

Table 4.4-1
Input/Output Itemization CPMS

INPUTS PARAMETER	SENSED	COMPUTED	SENSOR(S)	EST. NO.	SCAN RATE	CAU-TION	WARNING
TUNNEL PARAMETERS							
• Blade pitch mismatch	✓		Pos.	18	H		✓
• Fan stall		✓	Press.RPM	13	H		✓
• Loss of V/q auto.	✓		-	-	H		✓
• Loss of mod. att. auto	✓		-	-	H		✓
• MG sys. fault (elec)	✓	✓	-	-	H		✓
• Fan bearing temp.	✓		Temp.	12+	L		✓
• Fan oil temp.	✓		Temp.	12+	L		✓
• Fan vibration	✓		Vib.	6	L		✓
• Louver interlocks	✓		Discrete	40	L		✓
• Blade pitch motors	✓		Temp.RPM	24	H		✓
• Instr. failure	✓						
• Fouling	✓		Voltage	1	L	✓	
• Data system error	✓	✓	-	-	H	✓	
• Improper control input	✓		-	-	H	✓	
• Power rate excess	✓	✓	Wattmeter	6+	H	✓	
• IFC trans. failure	✓		Switch	1	H	✓	
• Mod. att. con. fault	✓		Pos'n.	2	H	✓	
• Control authority limit reached		✓	-	-	H	✓	
• Wall pressures	✓		Press.	20	L	✓	
• High T_T	✓		Temp.	1	L	✓	
MODEL PARAMETERS							
• Engine RPM	✓		RPM	4	H		✓
• Engine oil temp.	✓		Temp.	4	H		✓
• Engine press.	✓		Press.	4	H		✓
• Engine vibration	✓		Vib.	2	H		✓
• Hydraulic press.	✓		Press.	2	H		✓
• Pneu. press.	✓		Press.	2+	H		✓
• Engine EPR	✓		Press.	2	L		✓
• Engine EGT	✓		Temp.	2	L		✓
• Engine Surge	✓	✓	Press.RPM	4	L	✓	
• Attitude error	✓		Pos.	2	L	✓	
• Loss of data chan.		✓	-	-	H	✓	

Table 4.4-2

I/O and Function Distribution

INPUT: ALL CPMS COMPUTERS
Fan motors Blade position sensors 40x80 model parameters 80x120 model parameters Blade actuation system parameters Tunnel physical parameters SQCS1 SQCS2 MACS1 MACS2 Voting from other CPMS elements
OUTPUT:
Light and aural warning discretes Voting signals TMS inputs
FUNCTIONS:
Parameter monitoring Display management Redundancy management System management

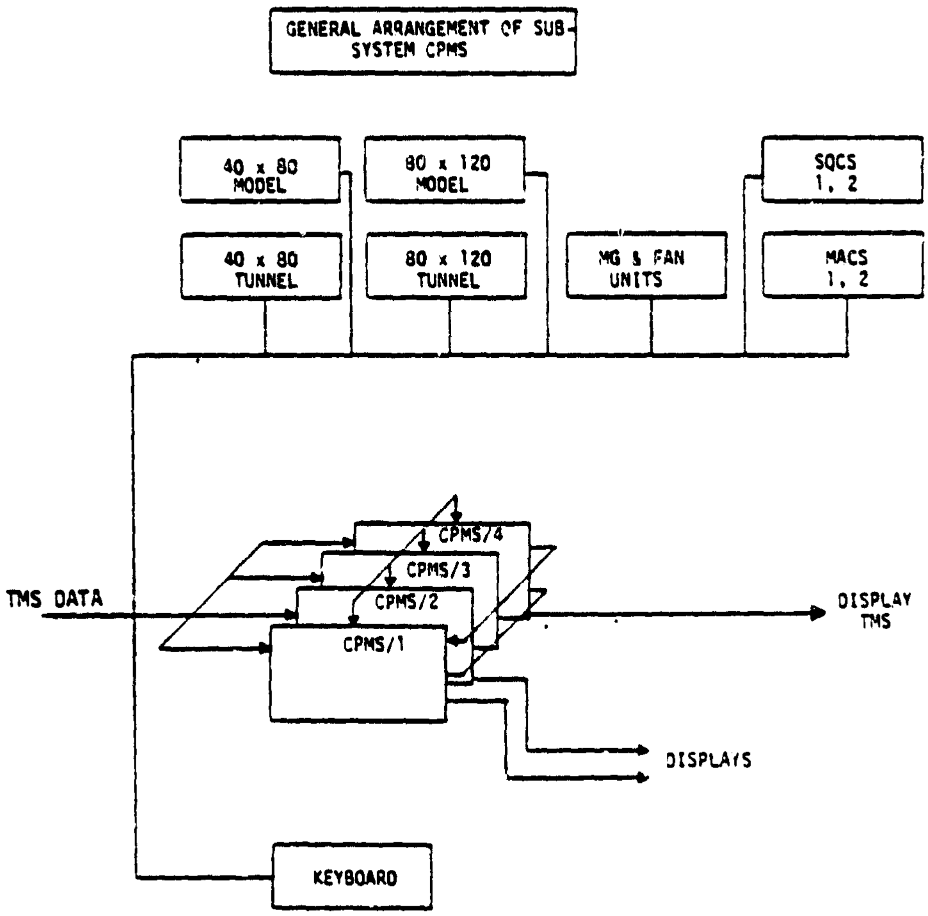


Figure 4.4-3 CPMS General Arrangement

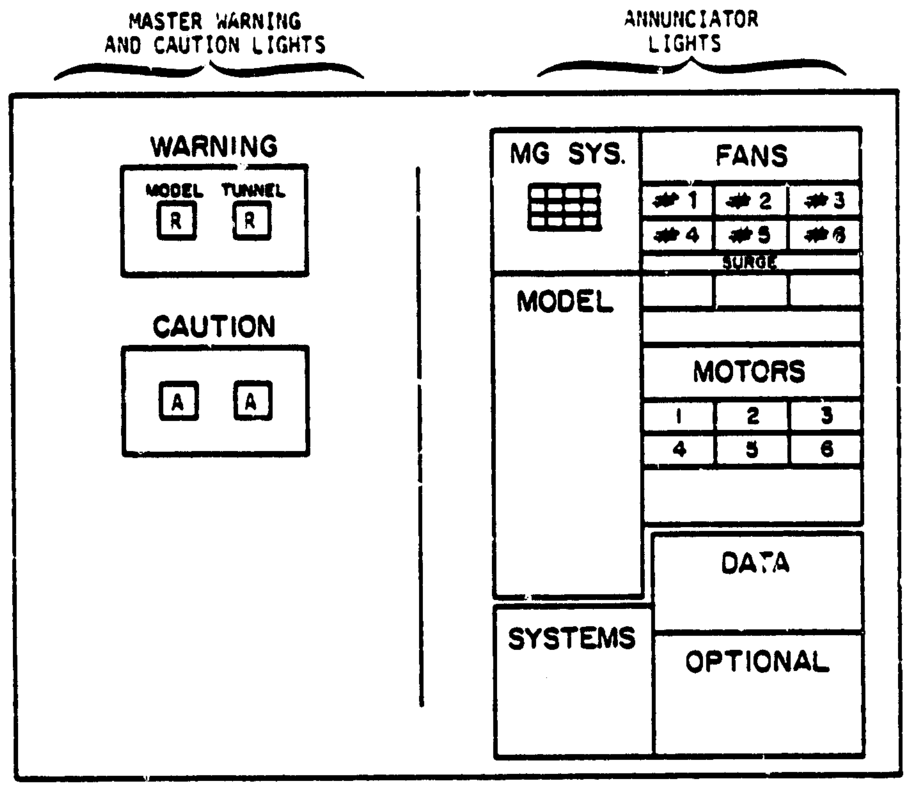


Figure 4.4-4 Proposed Fault Annunciator Panel

by logic within the CPMS computers. Implementation of the CPMS requires treatment of two major design areas:

(1) the design of the sensor system providing data to the CPU; and

(2) the design of the software to provide a flexible, self-monitoring computer system achieving the maximum level of reliability given constraints on the type and location of hardware devices and available sensor inputs, both in number and type.

4.5 TEST MANAGEMENT SUBSYSTEM (TMS)

4.5.1 Overview

The test management subsystem is conceived to fill the role of interface between the test engineer, the existing tunnel data acquisition system, and the previously-dicussed control subsystems, and to perform the sophisticated numerical operations required to evaluate data quality. While TMS may provide information to the SQCS and MACS, those subsystems retain final control over their respective functions.

With the test management subsystem, the level of automatic conduct of a wind tunnel test is reached. Under automatic control, the test engineer would be relieved of the necessity to monitor the operation of the facility itself and could instead direct more attention to significant characteristics of the data being collected. Certain key requirements and considerations resulting from this role are discussed below.

4.5.2 Test Management Subsystem Function Analysis

The test management subsystem has broad functional requirements including the following:

(1) store and execute model attitude/test condition requirements;

(2) interact with speed control and model attitude control systems;

(3) draw real-time data from the tunnel data system and perform statistical and comparative tests to ascertain data quality;

(4) interact with test monitoring displays to show test conditions and real-time model data;

(5) control model parameters, such as control surface deflections and flap settings;

(6) execute energy-minimization algorithms or follow trajectories of minimum-energy operating points, to be implemented through the tunnel speed/q control system;

(7) input pre-test setup data to the SQCS and MACS subsystems.

To evaluate the quality of data in an on-line mode -- the data interrogation function -- the TMS must perform statistical tests of data characteristics against known or estimated statistical parameters. Such parameters include mean, standard deviation, and rms value. Departure of these data parameters from known, nominal values may be taken as indicative of a system fault. For example, the increased noise level in the signal from a suddenly-damaged strain gage will show up as an increase in the standard deviation of the signal. The data may appear random under normal operating conditions, but its statistical properties may be very well-defined, and reveal significant changes in the nature of the data not at all apparent in a visual record. The TMS may also have the authority to take an increased number of sample points if this is necessary to raise the statistical data confidence level to a desired value. This is one of the most demanding modes of real-time data analysis.

A number of sources of data error lie in test condition settings. The TMS may monitor and display the status of:

(1) model fouling detection (which may also be detectable through statistical monitoring of scale measurements);

(2) off-nominal test conditions; and

(3) model parameter settings inconsistent with the test plan.

The impact of the fault, and recommended action, may also be displayed.

Control of model attitude, model configuration, and test condition are complex, interrelated functions consisting of numerous, sequenced steps. They are critical in the sense that certain combinations of model attitudes and tunnel q may be prohibited due to model loads limitation; hence, the limits guarded in these algorithms plus those in the model attitude control system must ensure fail-safe operation in the event of a failure in either the TMS or the attitude control system.

Control of model parameters such as RPM or thrust involves the dynamics of the plant (device) generating the measured output, hence closed-loop system instabilities can occur if real-time automatic control of these parameters is attempted. Careful consideration of control algorithms to be used is needed in this case. The alternative of open-loop control, in which throttle setting is controlled, for example, is simple and safer in a research environment, though of somewhat less usefulness since, when the independent variable is indeed throttle setting, inconsistent thrust levels could occur. In general, dynamic model parameters will require pre-test evaluation of the stability of their response to commands if automatic regulation is desired. Dynamic parameters may include: RPM (propeller, rotor, turbojet, or electric motor), airflow (pneumatic systems) model force or moment, hydraulic flow rate, or engine thrust. Sensor requirements are also more critical for these parameters. Static parameters amendable to straightforward regulation include (relative to the above): throttle or rheostat setting, air valve opening, model attitude, or throttle position and fuel flow.

4.5.3 Test Management Subsystem Reliability

Most of the functions of the TMS are to provide support to the engineer in the form of data quality assurance and test sequencing. At the point at which speed and model attitude commands are transmitted to the SQCS and MACS for execution, however, protection against TMS error must be provided, i.e., it must be fail-safe. This protection may be built into the SQCS and MACS in the form of pre-determined command schedule bounds and allowing these fail-safe systems to guard the tunnel and model. The incorporation of such "reasonableness checks" in computer software is a standard technique. This, however, will not protect the model parameter settings.

An alternative method is to have the TMS computer perform some isolated operation monitored by the CPMS. Failure of the TMS to perform the operation at the required time will be detected by the CPMS and construed as indication of a TMS failure, and TMS may be taken off line. This protects the model parameter settings also, and is a reasonable method in light of the tendency of computers to fail as a whole rather than in one particular area.

A third method is to back up the TMS computer with a duplicate, achieving fail-safe status through dual redundancy. This may be quite expensive and even if a second computer is available in the control room not in use, duplication of software and data transmission over long lines may prove infeasible.

While resolution of this problem is not practical at present, the second of these three approaches, utilizing the fail-operational reliability of the CPMS, appears the most attractive.

4.5.4 Test Management Subsystem Implementation

The input/output requirements of the TMS are shown in Table 5-1 and general layout is shown in Figure 5-1. to -4 show functional step sequences for test condition (tunnel speed) management, model attitude management, and model configuration management.

The use of a minicomputer system is recommended due to the requirements for high level interaction with the test engineer and the need to process large amounts of numerical data.

Table 4.5-1

Test Management Subsystem Input/Output Requirements Summary

INPUTS	OUTPUTS
1. Time history data from tunnel data acquisition system;	1. Line printer output of test status, progress, and faults;
2. Discrete data from tunnel data acquisition system;	2. Command signals to speed/q and model attitude control microprocessors;
3. Model parameter data;	3. Actuation signals to model activators;
4. Test plan: model configuration sequence, test speed sequence, model attitude sequence, data channels required, failure mode actions;	4. Initial test set-up parameters sent to speed/q, model attitude, and critical parameter monitoring microprocessors. ▷
5. Data from microprocessors on speed/q control, attitude control, tunnel status.	
	▷ After this, the M/P computers are completely independent of TMS computer activity; the TMS may only request speed/q or model attitude changes of the M/P system.

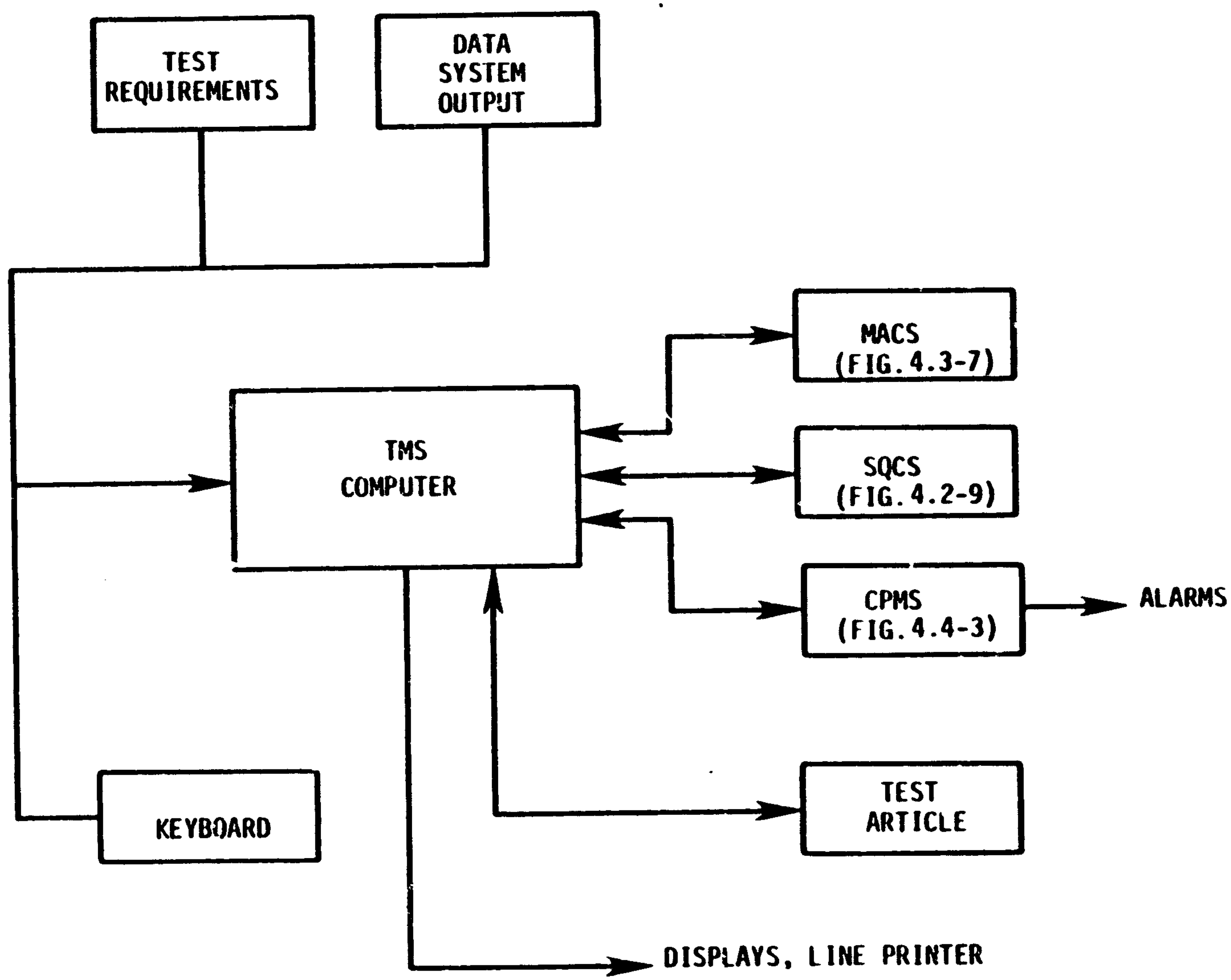


Figure 4.5-1 Test Management Subsystem Schematic

Table 4.5-2

Step Sequence for Test Condition Management

(1) Receive condition command from test/run sequences.

(2) Perform safety check.

(3) Transmit V/q command to speed/q control system (SQCS).

(4) Activate SQCS

(5) Receive indication of completed transmition from SQCS.

(6) Compare to command from test/run sequences.

Table 4.5-3

Step Sequence for Model Attitude Management

(1) Receive attitude command from test/run sequences.

(2) Perform safety check (attitude vs. q).

(3) Transmit attitude command to model attitude control system (MACS).
(pause during model motion.)

(4) Activate MACS.

(5) Receive final attitude from MACS.

(6) Compare to command from test/run sequences.

Table 4.5-4

Step Sequences for Model Configuration Management

(1) Receive model configuration vector from test/run sequences.

Run Pt. $control_1 \cdots control_n$ $throttle_1 \cdots$ $throttle_n \cdots$ air pressure,....

(2) Perform safety comparison.

(3) Transmit signals to actuators.

(4) Verify configuration from data received.

This sequence of steps does not involve elements of the microprocessor control systems.

4.6 FAILURE MODE ANALYSIS

4.6.1 Manual Control System

The manual control systems for control of fan RPM and blade pitch angle were studied and the principal modes of failure determined. Since the automatic speed/q control system acts through the manual system, this also represents the majority of failure modes for the automatic system. (Distinct automatic system failure modes will be discussed below.)

The basis of this failure mode study is the system block diagram shown in Fig. 4.6-1. Likely failures affecting the operation of the major units were listed based on available information regarding their functional characteristics. For each failure were noted:

(1) the immediate effect;

(2) the overall impact;

(3) how the failure would presently be detected;

(4) procedure to clear; and

(5) effect on test status.

The failure list for the basic mechanical system comprises some 60 failure possibilities, as shown in Table 4.6-1. Analysis of these failures indicates the following:

(1) 24 possible failures of fan RPM control;

(2) 15 possible failures of blade pitch control;

(3) 17 events either causing or requiring immediate tunnel drive system shutdown; and

(4) 8 blade pitch control failures requiring special sensors.

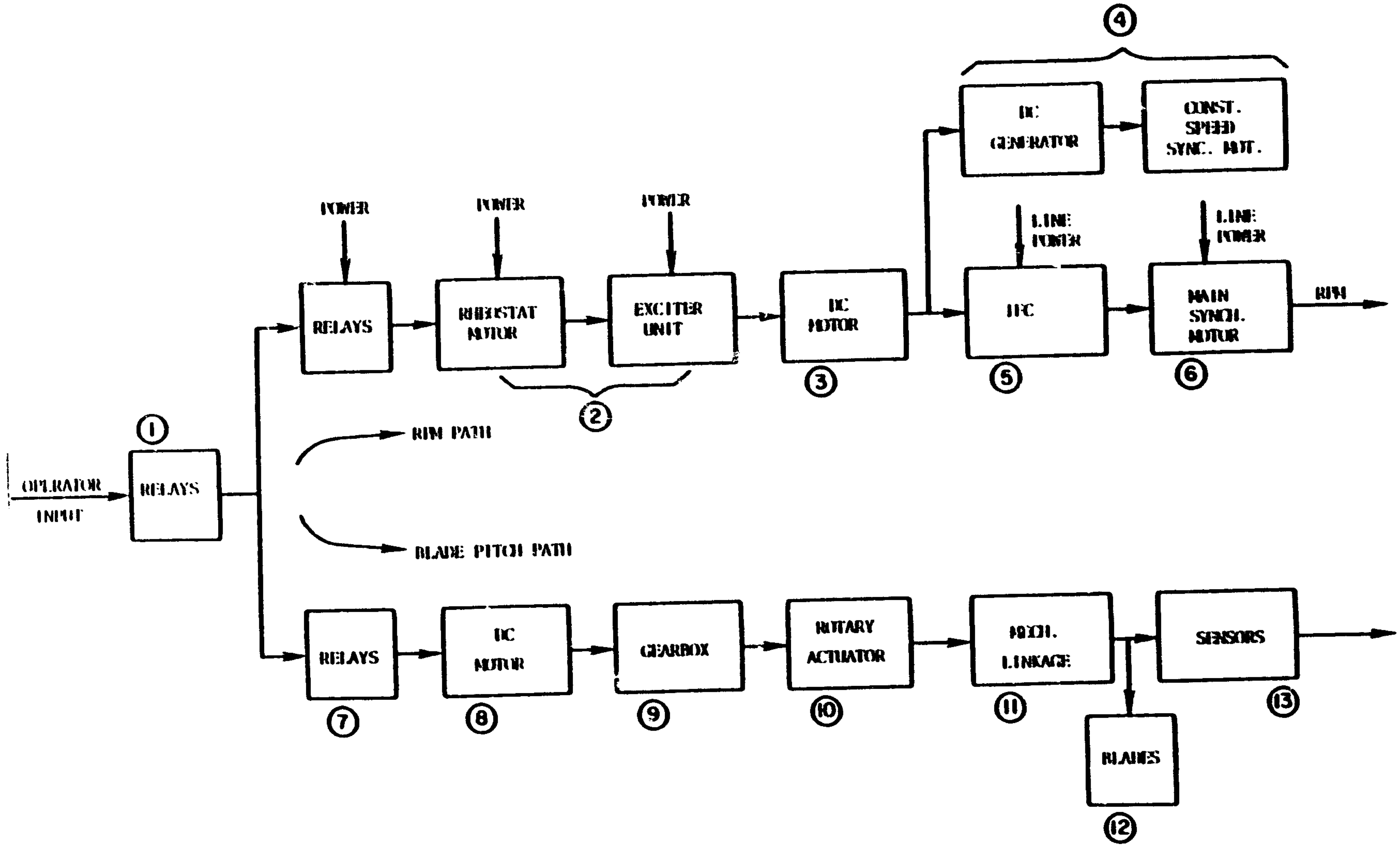


Figure 4.6-1 System Block Diagram for Failure Mode Analysis

Table 4.6-1

Manual Control System Failure Mode Analysis

UNIT	FAILURE	FAILURE EFFECT	FAILURE RESULT	[illegible] EFFECTED	PROCEDURE TO CLEAR	TEST EFFECT
1. Operator station	1.1 Loss of power to benchboard RPM control	Operator cannot change RPM	Cannot manually change q	Ω fails to respond; possible elect. alarms	Must emerg. stop if auto control not available	*Could destroy model during shutdown
	1.2 Loss of power to benchboard ε control	Operator cannot change ε	Cannot manually change ε	ε fails to respond; possible alarms	Slowly lower Ω or emerg. stop	Ends test
	1.3 Loss of power to instruments	Operator does not receive sensor or computer info.	---	Displays go dark	Rely on mechanical scale info.	May continue
	1.4 Loss of power to q transducers	Speed-q control system disengages	Operator must assume manual q control	Alarms	Manual control removed	Operator must set v/q conditions
	1.5 Electrical short in switch	cmd to max.	q increases	q inst.	Emergency stop	*Test halted
2. Exciter	2.1 Loss of drive power	Excitation lost due to DC1, DC2, (SM1)	*Loss of Ω control, loss of SM power; q falls	Ω falls	Emerg. stop or fix if possible while running	*Test halted
	2.2 Loss of rheostat power (motor)	Constant or random excitation to DC1, DC2, (SM1)	Constant or random control; q varies	Ω does not follow cmd	Emerg. stop or fix if possible while running	*Test halted
	2.3 Rheostat mechanical failure - jam	Constant excitation	q locked; Ω locked	Ω constant	Emerg. stop or fix if possible while running	*Test halted
	2.4 Rheostat elec. failure - short or open	Erratic or random excitation to DC1, DC, (SM1)	Erratic Ω response; q varies	Ω deviates from cmd	Emerg. stop or fix if possible while running	*Test halted
	2.5 Rheostat runaway (+) or (-)	Max or min. excitation, possible rheo. jam	Max. or min. condition; q varies	Ω incr. or decr.	Emerg. stop or fix if possible while running	*Test halted
	2.6 Exciter electrical fault	Excitation lost or randomly impaired	*Random Ω condition; q varies	Ω deviates from cmd	Emerg. stop or fix if possible while running	*Test halted
3. DC Motor (DC2)	3.1 Loss of excitation	Torque → 0; excess DC amps.; Ω_2 rises fast	IFC overspeed, Ω → 0	Ω falls; alarms	Repair fault	*May damage mod 1, MC machines
	3.2 Lube system failure	Threatens shaft integrity	Loss of machines	Instrumentation	Repair fault	May dam. MC machines
	3.3 Loss of armature current	Torque → 0; Ω_2 rises fast	IFC overspeed, Ω → 0	Ω falls; alarms	Repair fault	*May damage mode., MC machines
	3.4 Bearing overheat	Threatens shaft integrity	Loss of machines	Instrumentation	Repair fault	May dam. MC machines
	3.5 Excess IFC torque	---	Ω falls	Ω instr.	Repair fault	
	3.6 Loss of IFC torque	---	Ω_2 falls, Ω rises	Ω_2 instr., Ω instr.	Repair fault	
4. DC Generator (DC1)	4.1 Loss of excitation	Torque → 0	Arm. current increases rapidly; Ω increases; Ω_2↑, Ω_1 swings; can damage IFC	Alarms, Ω increases	Repair fault	*Testing halted
	4.2 Lube system failure	Threatens shaft	Loss of machine	Instrumentation	Repair fault	Testing halted
	4.3 Loss of armature current	Torque → 0	Ω_2↑, Ω↑, Ω_1 swings; loss of Ω control	Ω decreases quickly	Repair fault	*Testing halted
	4.4 Bearing overheat	Threatens shaft	Loss of machine	Instrumentation	Repair fault	Testing halted
	4.5 Loss of synchronous motor excitation	Q_{e_1} → 0		Ω decreases	Repair fault	*Testing halted
5. IFC	5.1 Loss of input (PGE) power	Q_{IFC} → 0	Ω_2 stops or reverses; Ω → 0.	Ω falls	Restart, or repair	*Testing halted
	5.2 Loss of drive torque (Q_{DC2})	Ω_2 accelerates	Ω_2↑, Ω↑	Ω falls	Repair	*Testing halted
	5.3 Loss of drive motor arm. current (power)	Q_{IFC} → 0	Ω_2 stops or reverses; Ω → 0.	Ω falls	Restart, or repair	*Testing halted
	5.4 Bearing overheat or loss of lubrication	Threatens shaft	Loss of machine	Instrumentation	Repair	Testing halted
	5.5 Excess drive torque (Q_{DC2})	Ω_2 falls below prescribed values	Possible IFC overload; Ω↑	Ω rises	Repair	* --- ---
6. Synchronous Drive Motor(s)	6.1 Excess aero. torque	Excess armature current drawn	Possible IFC damage; Ω_2↑, Ω↑	Ω falls	Reduce fan torque	May be halted
	6.2 Loss of input power (armature)	Torque → 0	Possible circulating currents in motor	Ω falls	Restart	*May be halted
	6.3 Ω_2 change	Ω change	Ω varies	Ω varies	Check cause	---
	6.4 Loss of excitation	Torque → 0	Ω → 0.	Ω falls	Restart	Halted
	6.5 Oscillation in excitation	P.F. varies	Ω varies; may reach high currents	Ω varies	Check cause	May be halted
	6.6 Excess excitation	P.F. varies	High IFC current drawn	---	Check cause	May be halted
	6.7 IFC switch failure	Locked in line mode	Ω fixed at 100	Ω nonrespon. to cmd.	Reduce Ω, drop breaker	*Halted

*= Recommended Emergency Stop

Table 4.6-1
(Continued)

UNIT	FAILURE	FAILURE EFFECT	FAILURE RESULT	HOW DETECTED	PROCEDURE TO CLEAR	TEST EFFECT
7. Blade Pitch Cond./ Relays (SCR)	7.1 Loss of control power to SCR	Motor power cannot be switched	Motor stays off or stays on; € lock or runaway	€ sensors, motor RPM sensors	Cut power if runaway	Testing sh[illegible] halt
	7.2 Loss of actuator (motor) power	Motor cannot run	€ fixed at last value	€ sensors, motor RPM sensors	Repair SCR	Halted
	7.3 Oscillatory failure	Motor power alternates	Motor damage	--?--	Repair SCR	Should halt
	7.4 Mechanical failure	Switches or relays fail; panel damaged	Erratic motor command, possible motor damage	--?--		
	7.5 Closed actuator circuit failure	Motor runs without command	€ changes without command	€ sensors, motor RPM sensors	Cut motor power	Should halt
8. DC Drive Motor	8.1 Oscillatory input power	Motor power & torque alternates	Motor damage from overheating	?	Repair SCR or DC source	Halted
	8.2 Lube system failure	Bearing failure	Possible shaft damage or jam	Bearing temp., oil temp., oil pressure	Repair oil pump or relubricate	Halted
	8.3 Bearing failure	Shaft failure or jam or vibration	Possible motor damage or locked shaft; locked.	Vibration, fails to respond to cond.	Repair motor	Halted
	8.4 Low voltage	Low torque or RPM	Low € rate; may fail to drive through gearbox torque	rate abnormality	Repair motor power supply	Should halt
	8.5 Excess DC voltage	High torque or current or RPM	High € rate; possible motor damage	€ rate abnormality	Repair motor power supply	Should halt
	8.6 Loss of excitation (if not self-excit.)	Motor fails to operate	€ locked	€ fails to respond	Repair motor	Should halt
	8.7 Contamination of commutator	Erratic motor power	Erratic € rate	€ rate abnormality	Repair motor	Should halt
9. Gearbox	9.1 Lube system failure	Bearing & gear overheat	Possible gear or bearing damage	Instrumentation (oil temp. or pressure)	Repair lube system	Should halt
	9.2 Broken gear(s)	Torque output unpredictable	€ may backdrive due to aero loads	€ drifts	Repair gearbox	Must halt
	9.3 Failed bearings	Possible jam	€ locked at last position; possible motor damage	€ stopped	Repair gearbox	Must halt
	9.4 Foreign objects	Possible jam	€ locked at last position; gear damage	€ stopped	Repair gearbox	Must halt
10. Screwjack/ Ball/Sliding Ring	10.1 Bearing jam	Shaft cannot rotate	€ locked	€ will not move	Repair	Should halt
	10.2 Sliding ring jam	Ring cannot move	€ locked	€ will not move	Repair	Should halt
	10.3 Mech. failure of ball [illegible]	Ring free to move	€ floats	Unwanted movement	Repair	Must halt
11. Collective/ Linkage (Ring to Blades)	11.1 Link failure; pin lost	Blade free to move	Blade moves to undesired setting; may flutter; vibration	?		
	11.2 Link jam	Pinned joint becomes rigid	Broken pin; binding of sliding ring; 1 or more blades affected; motor forced to operate off-condition	€ does not respond as "normal"	Repair	Should halt
	11.3 Loose link attachment to ring (bolt fail)	Blade free to move within limits	Blade mis-set, may flutter; vibration	?	Repair	Should halt
12. Blades	12.1 Bearing jam	Blade locked	Failed bearing or jammed ring (no blades move)	No € response	Repair	Should halt
	12.2 Structural failure	Blade lost	Severe vibration; damaged support structure	vibration	Repair	Must halt
13. Blade position Sensors	13.1 Loss of power	Blade position unknown	---	?		
	13.2 Elect. output short or open	Faulty blade position indication	May give faulty signal to control sys. or operator	?		

Many of these failures are extremely unlikely; others depend on the inherent reliability of the elements of the motor-generator and blade pitch actuators, for which statistical data are required. In particular, it should be noted that many of the failures noted are also possible in the present M-G system. This analysis shows no failure modes that are more severe than those currently possible in the 40 x 80 tunnel, and the use of many components of the existing M-G system in the new system implies good component reliability.

The motor-generator system will be protected against fault damage by conventional electro-mechanical means. With regard to the blade pitch actuation system, the output of the motor driver (SCR) and motor RPM should be monitored and compared to nominal values to detect certain mechanical jams and oscillatory electrical signals.

With regard to blade positioning, while it is true that the position of each blade can only be ascertained by attaching a sensor to each blade, the probability of a blade falling out of setting relative to the other blades (on a given hub) must be claimed as extremely low due to the anticipated overdesign of the actuation arms and linkage. This implies that this failure is no more likely than a failure of the fan support structure. If such overdesign is employed, then serious concern need not be given to a single blade setting failure, rather only to accurate determination of true blade angle settings.

In summary, this qualitative study shows that additional monitoring equipment is required on the electric blade pitch actuation system. The principal failure indication in the RPM control system is failure of RPM to respond to control or its deviation from the commanded setting. In most of these cases, the system fault clearing will have shut the system down (most of the failures occur in IFC mode) and the principal use of sensors is as diagnostics. In cases where RPM is locked, the operator has the choice of decelerating the tunnel by slowly flattening blade pitch (increasing ξ) and then initiating an emergency stop, or initiating an emergency stop immediately. While the choice depends on model vulnerability, decelerating the tunnel makes possible an emergency stop from a lower power level, causing a smaller utility grid disturbance.

4.6.2 Automatic Control System

The principal failure modes of the computerized automatic control system are those relating to the computer and sensor hardware and software, and fall into the following general categories:

1) System-critical hardware failure;
2) Loss of system power;
3) Software failure;
4) Operator error; and
5) System overload.

In the following, the control subsystems recommended in this study will be reviewed in the context of these failure categories:

(1) System-critical hardware failure. It is always possible for a computer system to be disabled by failures in the computer itself or in the sensor(s) which provide it data. By introducing redundancy through replicated computer channels, it is usually possible to reduce the probability that the overall system or subsystem will be lost and to reduce the probability that a system will output faulty data as a result of some failure. The reliability level that results from a redundant system is largely determined by the number of channels and the extent to which the computers are programmed to check themselves, each other, and the sensor inputs. While outside the scope of this effort, the types of systems identified in Section 4.4.5 may be identified as a starting point for the design and analysis of redundant-channel systems.

The level of reliability of various hardware components is illustrated by the mean time between failure (MTBF) data presented in Tables 4.6-2 and -3. Table 4.6-2 relates to a minicomputer and commonly-associated peripheral equipment; the key item is the minicomputer itself, which is shown to have an MTBF of 5000-8000 hours.

Table 4.6-3 shows MTBF data for a particular proven microprocessor unit – chip, board, wiring, passive components, etc. The most carefully tested unit (high component quality and burn-in time) gave an MTBF over one million hours in cold (0°C) operation, and nearly

Table 4.6-2

Typical Values of MTBF for Minicomputers and Peripherals

Unit	MTBF (hr)
Minicomputer (CPU, 8K words of memory, real-time clock, automatic power restart, automatic load feature)	5000-8000
Line printer (impact, 300 lpm)	400-800
Paper tape reader	2000
Paper tape punch	1000
Card reader	1000
Card punch	200
CRT terminal	3000-5000
Keyboard printer terminal (nonimpact)	3000-5000
Keyboard printer terminal (impact)	300-1600
Fixed head disk	3000-10,000
Moving head disk	1000-5000
Magnetic tape unit (industry-compatible seven or nine track)	1500-3000
Modem	10,000-20,000
Typical peripheral interface	20,000

From Reference 12.

Table 4.6-3

MTBF Values for Motorola 6109 Microprocessor CPU Board

Grade Level	MTBF Values, Hours			
	Ambient Temperature			
	0°C	25°C	35°C	75°C
(1) MIL-STD 883	1,077,742.	697,775	146,226.	58,236.
(2) MIL-STD 833	-	-	19,148.	-
(3) Commercial	-	-	2,071.	-

Notes: (1) Levels 1 & 2 tested for precap visual, stabilization bake, temperature cycle, centrifuge, fine and gross leak;

(2) Level 1 burned in for 168 hours at 125°C;

(3) Benign ground environment;

(4) Failure rates computed per MIL HDBK 217B;

(5) Date of tests: May 1977.

Reference: Motorola data.

700,000 hours at near-room temperature (25°C). Notable is the rapid decrease of MTBF when less care is taken in component selection and preparation.

The difference between microprocessor and minicomputer failure rates, nearly two orders of magnitude in some cases, indicates a real reliability advantage in putting control functions on a microprocessor when, by their nature, this is appropriate.

(2) Loss of system power. Power loss to the CPU should never cause essential memory to be lost. In practice, batteries are often inserted between the computer and line power. They serve the dual function of protecting the power supply and filtering line power transients. Battery requirements for minicomputers are generally much larger than for microprocessors. For wind tunnel applications, in which instrument power may be lost for a variety of reasons, it is recommended that any computer system be able to sustain memory up to 72 hours on backup power. If microprocessor power requirements are low enough, consideration should be given to providing sufficient backup power to maintain system operation.

(3) Software failure. Latent software errors cannot be tolerated in a control system computer code. The control algorithms recommended in this study are uncomplicated by aerospace standards, but the task of implementing them on the selected microprocessors and minicomputers is intricate and expensive, so a few words are directed here to ways of maximizing software development effectiveness.

Most successful software development programs possess three key elements: (a) a proven organization plan; (b) an understanding of the software development process; and (c) engineering support and checkout of finished software.

(a) An effective organizational plan may be built on a series of milestone documents to be produced at key times in the software development program; the milestones are indicated in Table 4.6-4.

(b) The key phases of the software development process are shown in Table 4.6-5. In practice, these phases usually overlap one another.

(c) Engineering support is a corollary to (b), highlighting the importance of having the software code checked functionally, and simulated if necessary, by the engineers who designed the control laws.

Table 4.6-4

Software Development Project Milestones

Milestone	Document
1	Software Performance and Design Requirements
2	Functional Design and Test Plan
3	Software System Interface Description
4A	Software Module Design
4B	Software Module Test Procedure
5	System Interface Specification and Module Design (as-built)
6	Software Integration Test Procedure
7	Operating Instructions
8	System Configuration Index

Table 4.6-5

Software System Development Phases

Phase	Activity
1	System Requirements and Analysis
2	Software System Definition
3	Software Performance Requirements
4	Computer Program Design
5	Programming
6	Test and Demonstration
7	Acceptance and Delivery

This provides final confirmation that the software actually performs the tasks as required.

Following firm developmental procedures in the surest way to avoid software errors in the final system.

(4) Operator error. Operator error must be minimized by careful integration of operator inputs with computer function. This includes prevention of untimely inputs, detection of erroneous inputs by crosschecks, and a well-planned sequence of computer data displays and requests and operator responses. It also requires that adequate system status information be made available to the operator.

(5) System overload. It is specified in this study that the system shall have excess capacity when satisfying present operational requirements, which sets CPU performance. It is also necessary, however, to provide adequate data I/O capability and to realize that more advanced operations will likely process more data. Overload consideration should thus be given to the CPU and all its peripheral devices.

V. CONTROL SYSTEM SPECIFICATION

Introduction

This section presents standard specifications appropriate to the procurement of the computer systems discussed in Section IV of this report. Whereas the latter section considered the layout and function of the overall system and its component subsystems, the present section addresses the relevant requirements under which the system must be provided. This section is divided into three parts:

5.1 General Provisions

5.2 Equipment Specifications

5.3 Software Specifications

Sections IV and V together constitute a preliminary system description and specification which may be modified and enlarged by wind tunnel project personnel as required to procure the system(s) best suited to their requirements, at the appropriate time.

5.1 GENERAL PROVISIONS

5.1.1 Applicable Publications

The following publications of the issues listed below, but referred to thereafter by basic designation only, form a part of this specification to the extent indicated by the references thereto.

5.1.1.1 Non-Government Publications

Instrument Society of America, RP55.1-1971 Test Procedures

Instrument Society of America, 1967, Factory Hardware Witness Test Guidelines for Digital Systems

5.1.1.2 Government Publications

5.1.1.2.1 Standards

MIL-STD-415	Test Provisions for Electronic Systems and Associated Equipment, Design Criteria for
MIL-STD-483	Configuration Management Practices for Systems, Equipment, Munitions and Computer Programs
MIL-STD-499	Engineering Management
MIL-STD-831	Test Reports, Preparation of
MIL-STD-1364	Preferred General Purpose Electronic Test Equipment.

5.1.2 Quality Control

The Quality Control provisions of the General Requirements apply to this section. Approvals, except those required for field installations, field applications, and field tests shall be obtained before delivery of materials or equipment to the project site.

5.1.2.1 Quality Verification

The integration of the system into the facility shall be accomplished in small phases, and every effort shall be made to test the system without disrupting the facility operation. Each unit shall be completely tested for its functional characteristics before it is integrated into the total system. The following checkout phases shall be used in the checkout of the facility system:

PHASE	ACTIVITY
A	Remote Enclosure Function Tests
B	Microprocessor Controller Center (MCC) Test
C	Central Console/MCC Communication Test
D	Central Control Console Function Test
E	Software Integration

5.1.2.2 Test Reports and Console Messages

All test reports and console messages shall be retained for proof of performance to the Contracting Officer. They shall also be utilized to their maximum extent to isolate any hardware/software problems. The reports shall be prepared in accordance with MIL-STD-831.

5.1.2.3 Final Acceptance

The criteria for the final acceptance test shall be defined by the contractor and approved by the Contracting Officer at a specified time, early in the contract. This mutually acceptable and agreed-upon test procedure shall be designed according to MIL-STD-415, and shall be used to demonstrate the system performance for final acceptance.

5.1.2.4 Configuration Control

Configuration control shall be maintained through strict discipline of the system design baseline. Changes shall be made via an Engineering Change Notice (ECN) or a similar control vehicle. Strict control shall be exercised for any updates to the baseline. Guidance shall be supplied by MIL-STD-483.

5.1.3 General Description, Control and Monitoring System for the 40 x 80/80 x 120-foot Subsonic Wind Tunnel

The control and monitoring system (CMS) shall be used to control and monitor the operation of the NASA/Ames 40 x 80/80 x 120-foot subsonic wind tunnel and the associated test models. Specifically, the CMS shall provide:

(a) Ability to monitor, record, and output data defining all parameters designated.

(b) Ability to provide all control functions as defined.

(c) Required automation of CMS functions.

(d) Fully interactive dynamic control of all CMS functions while online by user personnel.

(e) Modular expandability to allow for the addition of further sensing points, actuation points, and equipment.

5.1.3.1 System Definition

The overall CMS shall consist of a central control console with appropriate peripherals, an CMS software set, a set of microprocessor controller centers, a cabling and communication network, and sensors and controllers needed to implement system capability. The basic configuration of the CMS is shown in Figure 5.1-1. Detailed requirements for each element of the CMS are specified in later paragraphs. The central control console with associated peripherals, the MCC's, and the cabling and communication network have been described in Section IV. The software is also described in Section IV.

5.1.3.1.1 All analog signaling devices shall provide standard ISA instrument signal sources such as 3 to 15 psig, 4 to 20 ma d.c. or 1 to 5 volts d.c.

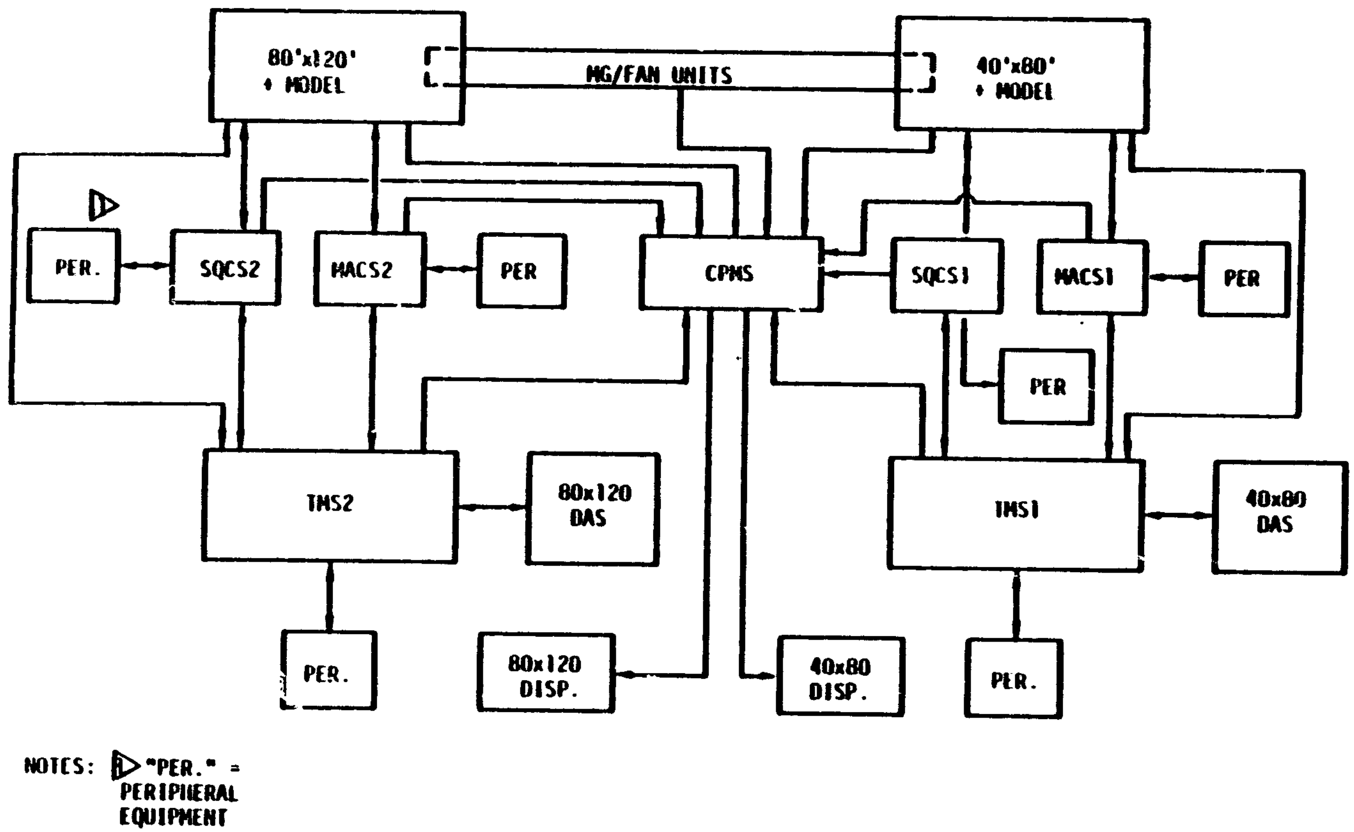


Figure 5.1-1 Wind Tunnel Control and Monitoring System Configuration

5.1.3.1.2 All analog and discrete digital data from the central system to the MCC's and/or sensor and MCC's and/or sensor to the central system shall be transmitted utilizing a digital data format (ANSI 3.4-1968 (ASCII), BCD, etc.). Systems which do not convert analog to digital or digital to analog signals as required at the remote panel or sensor shall not be acceptable.

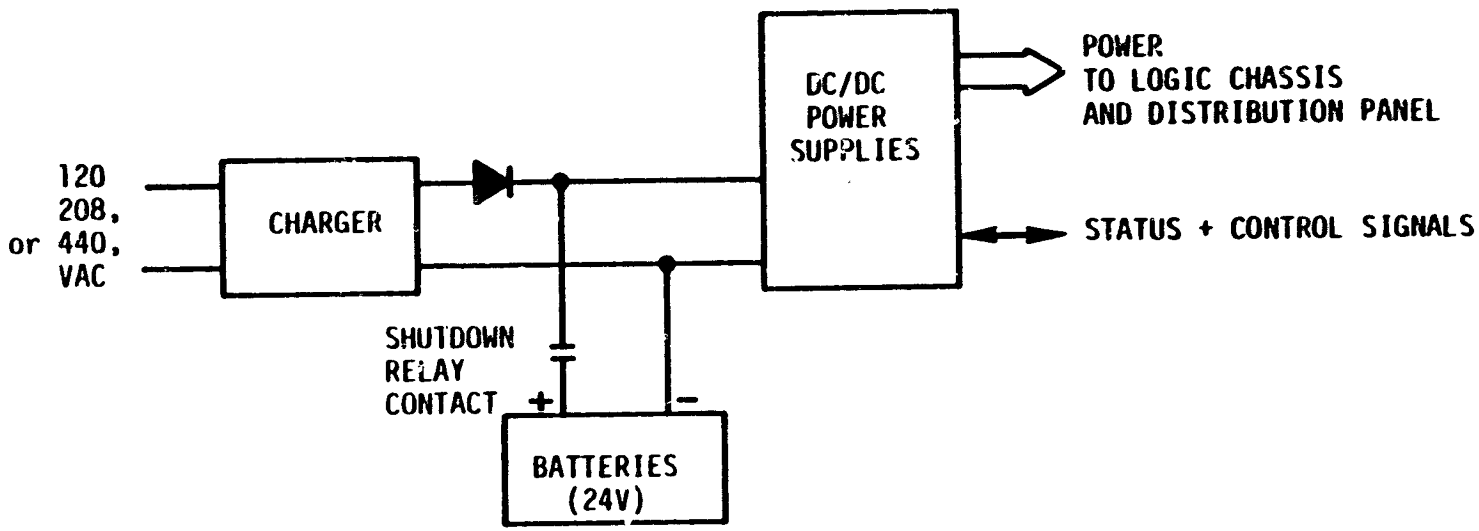
5.1.3.1.3 Analog and Digital Alarms: The CMS shall recognize any analog or digital alarm and provide an immediate "CAUTION" or "WARNING" display on an interrupt basis. The alarm display shall identify the alarm area and the nature of the alarm condition. Two or more alarms arriving in the same time period shall not be permitted to cause any confusion, nor shall any alarm be lost nor unnecessarily delayed in printout. The CMS shall provide a graphic display of the system diagrams which cover the alarmed equipment.

5.1.3.1.4 Mode Control: The CMS shall be capable of supporting three modes of operation. Mode 1 shall be a mode of subsystem operation from the MCC level only. Mode 2 shall be the system manual mode to be used as a fallback system. Mode 3 shall be the system automated mode.

5.1.3.1.4.1 Mode 1: The MCC's shall be considered individual self governing subsystems. This mode of operation shall be used when the MCC is not able to communicate with the higher level computers of the system. See Figure 5.1-2 for the MCC fallback power supply system.

5.1.3.1.5 Control Point Adjustment: The system shall provide the capability to vary control setpoints of remote analog controllers for supervisory control and to improve system performance through keyboard entry at the console.

5.1.3.1.6 Start/Stop Capabilities: The CMS shall have the resident capacity for at least 36 time programs. Each program



BATTERIES IN THE MCC* POWER SYSTEM ARE USED TO POWER A DC/DC MULTIPLE OUTPUT POWER SUPPLY.

* MICROPROCESSOR CONTROL CENTER

Figure 5.1-2 MDC Fallback Power Supply

shall be capable of starting and stopping an arbitrary number of pieces of equipment, at an arbitrary number of predetermined times.

5.1.3.1.7 Reports: The CMS shall be capable of providing at least, but not be limited to, the following reports.

5.1.3.1.7.1 Automatic Logs: The CMS shall maintain continuous logs on all system parameters. The CMS shall print out or display any predefined report on occurrence of a designated triggering event. Trigger designation may be on the basis of elapsed time, system event, or operator command. The CMS shall also be able to extrapolate trends based on the data logged and include this trend information in the printout.

5.1.3.1.7.2 Alarm Summary Log: The system shall provide as an operator initiated command, or on an elapsed time basis, a summary of all alarms within a given period of time.

5.1.3.1.7.3 Status Summary Log: The CMS shall provide as an operator initiated command, or on an elapsed time basis, a status of all of the points under the system's responsibility.

5.1.3.1.7.4 Singular Group Logs: The CMS shall provide as an operator initiated command, a listing of an individual group of points which reports location, individual point identification, normal condition, and status.

5.1.3.1.7.5 All Points Log: The system shall provide as an operator initiated command, a listing of all points governed by the system by group, location, individual point identification, normal condition, and status.

5.1.3.1.7.6 Trend Logs: As an operator initiated command, or on an elapsed time basis the system shall provide trend reports over recent reporting periods which summarize utilization, consumption, and demand of the monitored facility resources.

5.1.3.2 Control and Monitoring Functions

The CMS shall be a multiple task, multiple user system capable of providing continuous monitoring and control functions in the foreground while simultaneous program development, fault isolation efforts proceed in the background. The specific monitoring and control functions to be provided are described in the following paragraphs.

5.1.3.2.1 Control Functions: The CMS shall sense and output all points necessary to implement the functions defined by the control algorithms and other requirements in Section IV. Duty cycle shall not exceed those times specified in Section IV.

5.1.3.2.2 Monitor Functions: The CMS shall sense all points necessary as designated, convert these points to appropriate formats, and transmit these points to the central computer for storage, processing, and display. All points shall be sampled at specified intervals not to exceed 50 seconds. The parameters to be sensed shall include but not be limited to those presented in the discussions in Section IV.

5.1.3.2.3 Support Functions: The CMS shall be organized in totally modular fashion which will facilitate addition and deletion of system elements to meet changing requirements. The CMS shall also be provided with a built in self-diagnostic capability. This capability shall, at least, isolate any problem to a major functional area (e.g., computer, MCC number x, a specific peripheral). Isolation to a replaceable card is preferred. In addition, capability to support software development and to provide recordkeeping for maintenance support shall be included in the CMS.

5.1.3.3 Operational and Organizational Concepts

5.1.3.3.1 Operator Attendance: The operator's role in the performance of the CMS shall be:

(a) Mode 1 shall not require an operator's attention for any service other than data entry or as an assistant in the fault finding of system malfunctions. If the failure is other than a CMS malfunction there shall be no other need for an operator to be in attendance until the system is capable of being restored to the Mode 2 or Mode 3 condition. At this time the operator shall be responsible for system initialization.

(b) Under the Mode 2 operation, the operator shall be manually controlling the equipment under the responsibility of the CMS through utilization of the manual console. The operating criteria shall remain the same, only the CMS shall be disabled.

(c) With the CMS in the Mode 3 operation, that is, automatically controlling and monitoring all equipment under the system's responsibility, the operator shall respond to alarm or fault conditions by notifying the responsible engineer of the alarmed conditions. The operator shall also be capable of altering operating criteria and initializing new assignments to the system's automated tables.

5.1.3.3.2 Support Capabilities in the Central Control Area: The central control room shall be specified and equipped as a fault isolation and correction center. For this purpose the contractor shall provide the following:

(a) Master tape or disk files containing all programs.

(b) Backup card decks plus up-to-date program listings.

(c) Equipment and system technical manuals.

(d) Special purpose test tools (including diagnostic programs) adequate to fault isolate to a single replaceable card.

(e) Intercommunication capabilities needed to coordinate failure diagnosis and correction during system installation and checkout.

5.1.3.3.3 Flexibility Requirements: The CMS user interface shall be set up such that a trained operator, without special programming knowledge, will readily be able to:

(a) Add, or delete, sensor points to any MCC with full system capabilities available to this point when designated from the operator console.

(b) Change system schedules, system control and operating points, alarm conditions, or triggering events.

5.1.3.4

5.1.3.4.1 Point Sensing: The CMS shall monitor all scheduled digital and analog points. Conversion accuracy of the analog points shall be at least (as required) bits plus sign.

5.1.3.4.2 Data Transmission: The data transmission system shall include security codes, parity code checks and other types of transmission characteristics specified. The transmission system shall be suitable for transmitting all digital information for remote sensors over communication lines as indicated in Section IV in accordance with the performance characteristics specified in Section 5.2. The data transmis-system shall be of the continuously active type providing positive supervision of data transmission. All interruptions or cessation of transmission shall be detected, alarmed, and displayed at the control center. In addition, the console shall also identify the location of trouble by digital display of the address. Scanning systems which are dependent on alarm initiation will not be acceptable. Transmission security measures shall be included which will preclude simultaneous alarm occurrences from causing garbled or erroneous information transfer. The first detected alarm shall be capable of a complete message transfer before the second can transmit its alarm message. Under no circumstances shall any alarm messages be lost. Failure of an element of the MCC shall be annunciated as an alarm condition. Alarm lockout shall be provided upon equipment startup and system shutdown except for startup and shutdown alarm conditions.

5.1.3.4.3 Limit Checking and Alarm Signalling: The system shall print or display alarms for out-of-tolerance parameters or on change of state. The system shall indicate running status and alarm critical parameters. Alarms may include special messages or instructions to be performed. Alarm logging shall be performed in a clearly identifiable manner sharply differentiated from normal data pintouts. Upon specified alarm conditions, the system shall immediately sound the audible alarm, and shall show the point in alarm as well as the unit associated with the alarm. The system shall have the capability of setting or changing individual alarm limits for each input point at the keyboard by authorized operators at any time. It shall be possible to read back assigned high and low alarm limits at any time.

5.1.3.4.4 Alarm Response: An event programming feature shall be provided to automatically initiate certain specified commands upon an alarm condition. Initial capacity shall be for the event program channels. It shall be possible to assign limit values to analog inputs on a per point basis--both high and low values. In addition, it shall be possible to automatically lock out alarms on a per point basis when the associated primary equipment is shut down. Event triggered responses shall be completed up to the point of application of a corrective signal to the appropriate equipment within (as required) seconds of occurrence of the alarm condition.

5.1.4 <u>Submittals</u>

5.1.4.1 Test Plans

The contractor shall provide test plans for factory testing before shipping to the site, and plans for proving to the Contracting

Officer that the system is installed and operational. These plans shall be presented 60 days before start of the respective tests.

5.1.5 <u>CMS Maintenance</u>

5.1.5.1 The Contractor shall provide all services, materials and equipment necessary for and incidental to the maintenance and repair of the entire Control and Monitoring System (CMS) for a period of one year plus five additional years to be contracted annually at the option of the Government. The responsibility of this contract when interfaced to control systems maintained by others shall be limited to the interface panel of the existing system.

5.1.5.1.1 General: The contractor shall maintain sufficient qualified personnel, equipment, supplies and materials to accomplish promptly and satisfactorily all work under this Section. Prior to commencement, the Contractor shall advise the Contracting Officer in writing the name of the designated representative of the Contractor. Changes in representatives shall be furnished the Contracting Officer in writing prior to making such changes.

5.1.5.1.2 Supervision: The Contractor shall have competent supervision, approved by the Contracting Officer, at all times during progress of the work, with full authority to act for the Contractor. When working at the facility the supervisor shall effect daily liaison, during the normal working hours, with the Contracting Officer. Adequate and competent supervision shall be provided for all work done by the Contractor's employees to assure performance in strict accordance with the provisions contained in this specification.

5.1.5.2 Schedule of Work: The Contractor shall provide all maintenance and service as outlined below:

(a) Clean all CMS equipment as required by the manufacturer.

(b) Provide signal, voltage and system isolation checks of all equipment as required by the manufacturer but not less than twice a year.

(c) Provide preventive maintenance for all CMS equipment as recommended by the CMS supplier or equipment manufacturer.

(d) Check and/or calibrate each field input/output device on which maintenance/repair is performed.

(e) Run system software diagnostics as required.

5.1.5.3 Service Calls

The Government will initiate service calls when there is indication that the CMS is not functioning properly. Maintenance and repair service shall be available during the normal working day, and emergency repair service shall be available as required on a 24-hour basis. Service must be provided the same day if notification was given during the first hour of the maintenance contractor's normal work day. Otherwise, service must begin the following working day. The Contractor shall furnish the Contracting Officer with a telephone number where service personnel can be reached.

5.1.5.4 Repairs

Repairs shall include the repair of parts or complete controls and the removal of defective parts or complete controls and the testing of the installation of new or reconditioned equivalents in place of those removed. All repair and replacement parts or complete controls shall be equal to or exceed the original manufacturer's specifications.

5.1.5.5 Operation

The performance of the foregoing noted items and all other services required shall provide proper sequencing of the equipment and satisfactory operation of the existing computerized automation systems based on original design conditions and shall be as recommended by the manufacturer.

5.1.5.6 Records and Logs

Records and logs shall be kept of each repair and maintenance task; cumulative records for each major component and for the complete aggregate system shall be organized chronologically. Forms, in the format prescribed by the Contracting Officer, shall be completed and submitted monthly to the Contracting Officer by the tenth day of the succeeding month indicating that planned and systematic maintenance has been accomplished for the CMS.

5.2 CONTROL AND MONITORING SYSTEMS (CMS) SYSTEM EQUIPMENT

5.2.1 Applicable Publications

The following publications of the issues listed below, but referred to thereafter by basic designation only, form a part of this specification to the extent indicated by the references thereto.

5.2.1.1 Federal Information Processing Standards (FIPS) Publications

FIPS PUB 1 1 Nov 1968	Code for Information Interchange.
FIPS PUB 15 1 Oct 1971	Subsets of the Standard Code for Information Interchange.
FIPS PUB 16 1 Oct 1971	Bit Sequencing of the Code for Information Interchange in Serial-By-Bit.
FIPS PUB 17 1 Oct 1971	Character Structure and Character Parity Sense for Serial-By-Bit Data Communications in the Code for Information Interchange.

FIPS PUB 18 1 Oct 1971	Character Structure and Character Parity Sense for Parallel-By-Bit Data Communications in the Code for Information Interchange.
FIPS PUB 22 1 Nov 1972	Synchronous Signalling Rates between Data Terminal and Data Communication Equipment.
FIPS PUB 24 30 Jun 1973	Flowchart Symbols and Their Usage in Information Processing.

5.2.1.2 American National Standards Institute (ANSI) Publications

B31.1-1973	Power Piping (Including addenda B31.1b (1971); B31.1c (1972); and B31.1d (1972).
X3.4-1968	Code for Information Interchange (ASCII)
X3.9-1966	FORTRAN (ISO 1539)
Y10.19-1969	Letter Symbols for Units Used in Science and Technology.
C2-1973	National Electrical Safety Code (NESC).

5.2.1.3 EIA Standard RS-232-C, Interface between Data Terminal Equipment and Data Communication Equipment Employing Serial Binary Data Interchange.

5.2.1.4 Government Publications

5.2.1.4.1 Standards

MIL-STD-454	Standard General Requirements for Electronic Equipment
MIL-STD-461	Electromagnetic Interference Characteristics Requirements for Equipment
MIL-STD-462	Electromagnetic Interference Characteristics, Measurement of
MIL-STD-463	Definition and System of Units, Electromagnetic Interference Technology

MIL-STD-470	Maintainability Program Requirements for Systems and Equipment
MIL-STD-785	Reliability Program for Systems and Equipment Development and Production
MIL-STD-882	System Safety Program for Systems and Associated Subsystems and Equipment, Requirements for

5.2.1.4.2 Handbooks

MIL-HDBK-217	Military Standardization Handbook, Reliability Prediction of Electronic Equipment
MIL-HDBK-472	Military Standardization Handbook, Maintainability Prediction

5.2.2 General Requirements

Section 5.1, Monitoring and Control Systems (CMS), General Requirements, with the following additions and modifications, applies.

5.2.2.1 Equipment shall be provided as specified with all necessary auxiliary facilities required to form a complete operational system. The system block diagrams in Section IV depict one concept of major equipment configuration defined in this Section.

A. All stock numbered equipment shall be new, and of the manufacturer's latest design and technology and be in production at the time of technical proposal submittal.

B. The digital computing equiomem shall be supplied with wired-in expansion capabilities to meet a minimum of 150% of the specified system requirements.

5.2.2.2 Test and Inspection Certification

Provide a certification for each piece of equipment stating that the specific item of equipment shipped for this project had been tested and inspected for proper function in compliance with these specifications.

5.2.2.3 Operation and Maintenance Manuals

Furnish two copies each of operation and maintenance manuals for the following items of equipment if required to meet specified functions:

A. Central Processing Units.

B. Programmer Control Panel.

C. Real-Time Clocks.

D. Disk and Other Storage Systems.

E. Floating Point Processors.

F. External Clocks.

G. Cathode Ray Tube Terminals.

H. Keyboard Printers.

I. Graphic Display

J. Multiplex Panels.

K. Microprocessor Control Centers.

5.2.2.4 Equipment Documentation

For each item of equipment, the Contractor shall furnish full hardware/software support documentation, which shall include, without being limited to, the following:

A. General description and specifications.

B. Installation and initial checkout procedures.

C. Principles/theory of operation.

D. Detailed electrical and logical description.

E. Complete trouble-shooting procedures, diagrams, and guidelines.

F. Maintenance manual.

G. Detailed schematics and assembly drawings.

H. Complete spare parts list.

I. Interface manual.

J. Signal identification and timing diagrams.

K. Complete alignment and calibration proceedings for all components.

5.2.2.5 Level I Diagnostics

Unless specified otherwise, provide a fully commented binary and source diagnostic, showing true fault, for each item of equipment which can be entered into the Binary Operator Panels. The results of the diagnostic tests shall be indicated at any selected display. The diagnostic architecture shall be such that the operator may provide input and receive output from the Binary Operator Panel.

5.2.2.6 Interface

All equipment provided under this project shall be compatible at and through their points of interface. Equipment shall have EIA RS 232C data transmission compatibility.

5.2.2.7 Environmental Conditions

While Central Processing Units and their immediate peripheral devices will be located in an environmentally controlled location where conditions will not be subject to extreme variations, the equipment shall be able to operate properly under environmental conditions of 30 degrees F to 120 degrees F and a relative humidity of 20 to 90 percent. All other devices shall be able to operate under environmental conditions of 20 degrees F to 150 degrees F dry bulb and zero to 95 percent relative humidity.

5.2.3 Equipment

5.2.3.1 Central Control Center Main Console

A. The main console shall be functional and convenient to operate. Important factors to include in the design of the console are:

(1) Minimize physical separation of devices.

(2) Maximize CRT usage.

(3) Minimize operator motion and decisions.

(4) English language labeled pushbottons.

(5) Pushbutton and indicators readily accessible.

(6) Steel and fiberglass construction.

(7) Efficient utilization of space.

B. The control console shall include but not be limited to the CRT system, failover control board, external uninterruptable clock, microphone and telephone communication panel, and work and writing area and undercounter storage compartments. Convenient service access to all components shall be provided from the front or rear of the console, as required. Movement of the console shall not be necessary.

C. CRT System

(1) Dynamic color graphic CRT system shall consist of the following:

a. CRT Display Unit: Display unit shall consist of heavy duty, solid-state, 17 inch (min. diagonal measurement), raster scan color television broadcast monitors, mounted in the console or at a location otherwise designated. All setup and convergence controls shall be front-panel mounted. Each unit shall be supplied with 2 sets of switch-selectable inputs with a front-panel accessible switch. Video frequency response shall be flat to 10 MHz. Geometric distortion shall be less than 2 percent based on picture height. Screen refresh rate shall be not less than 50 times per second.

b. CRT Controller: A CRT controller shall be provided to convert digital information from the computer into alphanumeric characters and graphic symbols for display on the respective CRT display units. The controller shall be capable of generating the full 96-character standard SSCII character set and a minimum of 64 graphic symbols.

The controller shall be provided with an EIA RS-232C computer interface capable of transmitting data from computer at a rate sufficient to write the entire CRT screen in 1 second or less. Response to operator request shall occur within 2 seconds after a request is made. The facility shall be provided and fully implemented to display "live" process data. This feature shall allow data displayed on the CRT screen to be continuously updated from the current process data base at intervals of not greater than 5 seconds. Controller shall be mounted in console.

c. Keyboard Functions: Keyboard functions shall be provided to control the display of data on the CRT's and to enter commands to regulate the processes.

The following operator functions shall be provided, as a minimum:

a. Alarm Acknowledge - Silences audible alarm horn and calls up display of all unacknolwedged alarms.

b. Index - Calls up the first page of the Master Index display on the CRT.

c. Alarm Summary - Calls up the first page of the Alarm Summary display on the CRT.

d. Print Alarm Summary - Prints all alarms in the Alarm Summary on the alarm printer, if present in the system.

e. Page Forward - Calls up next page of a multi-page display if one exists, otherwise command is ignored.

f. Page Backward - Calls up preceding page of a multipage display if one exists, otherwise command is ignored.

g. Log Request - Prints requested log report on log printer, or other display.

h. Copy Page - Causes current CRT display to be copied on log printer.

i. Freeze Page - Causes CRT display to be frozen in time by preventing computer from updating it, but has no effect on process control.

j. Freeze Cancel - Restores display to normal updating mode.

k. Select - Select target on CRT display at current cursor location.

l. Entry Accept - Causes action associated with target selected on CRT screen to be executed.

m. Entry Cancel - Cancels previous selection of target on CRT screen.

n. Cursor Control Keys - Up, down, left, right, home. Each key (except home) shall have automatic repeat feature.

o. Numerals 0-9, minus sign, and decimal point - arranged in adding machine layout for loop and point identification and data entry.

The following command functions shall be provided, as a minimum:

a. Manual - Places previously selected control loop in manual control mode.

b. Auto - Places previously selected control loop in automatic control mode.

c. On - Initiates control output command to energize equipment previously selected using the CRT.

d. Off - Initiates control output command to de-energize a selected piece of equipment.

e. Start - Initiates control output command to start a selected motor, compressor, etc.

f. Stop - Initiates a control output command to stop a selected motor, compressor, etc.

g. Raise Fast - Raises a selected setpoint or opens a directly controlled valve, etc., at the rate of 10 per cent of full scale per second.

h. Raise Slow - same as "g", but at the rate of 1 per cent of full scale per second.

i. Lower Fast - Lowers a selected setpoint or closes a directly controlled valve, etc., at the rate of 10 per cent of full scale per second.

j. Lower Slow - Same as "i", but at the rate of 1 per cent of full scale per second.

k. Clear Screen - Clear display from selected CRT.

l. Alternate Printer - Reverses the assignments of printer and line printer. Reversal of assignments shall remain in effect until button is again depressed.

m. 10 spare functions shlal be provided as a minimum.

n. 2 CRT select keys.

o. 10 function keys.

(2) Alphanumeric Keyboards: Alphanumeric keyboards shall be provided to be used in conjunction with each CRT.

The keyboard shall include, as a minimum, the following keys:

a. A standard 64 character ASCII character set, arranged in standard typewriter format.

b. Five button cursor control cluster including Up, Down, Left, Right, and Home.

c. Repeat key which causes automatic repetition of any other key that is depressed simultaneously.

d. Screen "Clear."

e. "Page Up."

f. "Page Down."

g. "Line Insert."

h. "Line Delete."

i. "Character Insert."

j. "Character Delete."

D. External Uninterruptable Clock

(1) Clock shall be oscillating quartz crystal type external clock with a continuously updated visual display of the form: MY:DM:HH:MM:SS, where:

a. MY: Month of the year

b. DM: Day of the month

c. HH: Hour of the day (Ø - 23)

d. MM: Minutes

e. SS: Seconds

(2) The clock shall be fully interfaced to the CPU.

(3) When recovering from a power failure, the system Automatic Restart Routine shall automatically read the clock and, without human intervention:

a. Reconstitute the time of day within the Real Time Operating System.

b. Adjust all time dependent parameters within the foreground (or background) Monitoring and Control Software.

5.2.3.2 Central Processing Unit

The central processing unit (CPU) shall be a field proven digital computer of modern design based upon a family of integrated circuits currently having a minimum of two sources of supply. The CPU shall provide minimum features as defined herein.

A. Power Failsafe

The CPU shall have a power failsafe feature that will detect an imminent failure of primary power and save critical operational data for restart purposes. Similarly, after a shutdown, this feature shall sense that power has returned to normal level and automatically cause the machine to resume computation at a desired point.

B. The CPU shall indicate an alarm condition in the event of an I/O device (printer, CRT, etc.) failure. Automatic transfer of output data from the failed device to a program assigned backup serviceable device shall be provided. See CMS software for specific failover program requirements.

C. Real-Time Clocks

A crystal controlled clock shall be provided with the CPU as required for elapsed time, pulse counts, time of day, and other system timing functions. Time shall be maintained to the nearest second. After restart, the time of day clock shall be updated from time data within the external uninterruptable clock.

D. Registers

The CPU shall have a minimum of eight addressable general purpose hardware registers, which can be manipulated under program control. Each register must be a minimum of 16 bits long.

E. Instruction Repertoire

The basic instruction repertoire of the CPU shall include, but not be limited to, the following: loading and storing of registers, arithmetic operations, logical operations, index register operations, input/output operations, and other miscellaneous operations such as status and control operations.

F. Shift Operations

The CPU shall be capable of shifting by means of a single instruction, one arithmetic register by itself or two arithmetic registers together. It shall be capable of shifting both to the left and to the right and be capable of shifting up to two full word lengths in logical and arithmetic modes.

G. Floating Point Operations

The CPU shall have a floating point hardware option which permits addition, subtraction, multiplication, and division, each accomplished by a single instruction. Floating point numbers shall be expressed with a minimum word length of 32 bits.

H. Priority Interrupt System

The CPU shall have a priority interrupt system which shall be able to provide a minimum of 16 vectored interrupts. Each interrupt shall have its unique assigned address in memory and unique priority. Transfer to that location shall be accomplished by hardware and shall require less than 5 microseconds for an enabled external interrupt. Hardware shall automatically handle and identify the priority such that no special programming is required. Each interrupt level shall be individually controllable to the extent that it can be: ignored, remembered but not recognized, recognized when it is the highest priority interrupt pending, or simulated under program control.

I. Main Memory

(1) Memory Type: The memory shall be designed using the complementary metal oxide semi-conductor as a basic storage

console shall be used to manually change data, acquire data, and manually adjust system parameters or change data loops.

B. The controller shall be designed around a field proven family of solid state integrated circuits utilizing metal oxide and complementary metal oxide semiconductor logic design. At least two sources of supply shall be currently available. Word size shall not be less than 8 bits in parallel.

C. The controller shall consist of input and output function cards all under the supervision of the microprocessor card. Timing, purpose, and operation of each card shal be defined by the control (software) stored on the microprocessor card. Data routing and processing shall be varied by changing microprocessor programs. The net effect shall be standard hardware with specialized software.

The system shall be a combination of printed circuit cards contained in card stages, installed in controller equipment bays. These bays shall be separate from the CPU bays, but of similar construction and external appearance. Printed circuit cards shall be standard pre-engineered type having provisions to ensure that improper card installation is not possible.

D. The following card types shall be provided as a minimum:

(1) Microprocessor card.

a. The microprocessor card shall control every card in the associated card cages and direct traffic over a motherboard data bus.

b. The microprocessor shall incorporate a CPU, real time clock, random access memory (RAM), read-only memory (PROM/ROM), 16 bit buffered I/O, priority interrupt control logic, power failure and automatic restart and system interface and support features required to provide a stand-alone backup controller.

c. The microprocessor on-card memory capacity shall be a minimum of 150 percent of that required to meet specified system needs. Memory expansion shall be accomplished by insertion of additional chip or memory cards into the card cages provided.

(2) Digital input card (DIC): The DIC shall provide protected interface parallel input lines to the microprocessor via the motherboard data bus. Optical isolation shall be employed to eliminate direct electrical connection to provide transient and surge protection.

(3) Digital output card (DOC): The DOC(s) shall reside on the motherboard data base and shall provide digital output to specific associated terminal strip lugs immediately after being so directed by the microprocessor. The output lines shall have the capability of direct relay and lamp drive or use as a digital interface to other systems.

(4) Teletype Interface Card (TIC): The TIC shall provide serial digital input and output compatible with keyboard printers and the like with 20 milliampere current loop or EIA RS-232C interface. Codes shall be standard ASCII 7, or 8 bit with even/odd parity. This card shall be used in each TTY interface application and communication between processors.

(5) Analog output card (AOC): The AOC(s) shall retrieve digital data from the output bus, load the converter, perform D.A. conversion and output standard 4-20 M.A. D.C. proportional signal to drive a connected device.

(6) Analog input card(s) (AIC): The AIC shall scan each connected analog input one at a time, perform A/D conversion, and hold the digital value in active memory for microprocessor interrogation. Optical isolation shall be provided on each electronic input connection.

(7) Provide a minimum of one spare card of each card type used.

E. Signal Conditioning

(1) The contractor shall be responsible for providing approved signal conditioning circuitry at the MCC to prevent poor signal data caused by EMI/RFI from affecting the system. Signal input and output voltage and current ranges shall be as recommended by the manufacturers. These ranges shall be sufficient to transmit signals to and from sensors and controllers. The system shall be designed to respond to standard industrially available analog signals. It shall be the responsibility of the contractor to take the signal from the transmitter/transducer, condition it, and convert it to a digital signal for transmission to the central control console. The MCC shall provide photo-insolation between the system logic and the equipment power circuit. Accuracy of converted analog signals shall be at least __ bits plus sign. The contractor shall indicate in his proposal the expected total system (from sensor to digital presentation) accuracy and repeatability. Overload protection shall be provided to prevent:

a. Higher than normal voltage.

b. High current draw.

c. Misapplied voltage.

element. Word length shall be at least 16 bits plus parity. Memory shall be addressable and alterable by word and double word quantities.

(2) Memory Speed: Memory shall have a cycle time no greater than 1.0 microseconds for one full word.

(3) Memory Size: Main memory supplied shall be sufficient to provide efficient use of all programs to be supplied. A memory map detailing the intended main memory utilization shall be provided. This map shall identify resident programs and the main area in which they reside. It shall identify overlay areas and the hierarchy of the overlay programs. It shall identify areas allocated for owner use. State in the Technical Proposal Data the size of memory to be provided.

(4) Memory Expansion: Memory shall be field expandable to at least 128K words in maximum increments of 8K words (where K = 1024).

(5) Memory Addressability: The main memory shall be directly addressable within a 256 word block. Addressing beyond this 256 word block shall be accomplished via base registers, indirect addressing, for added program security or indexing.

(6) Memory Protection: The CPU shall have programmed memory protection feature(s).

J. Input/Ouptut

(1) Channel or Program Input/Ouptut: Data transfer shall be over a bidirectional asynchronous communications data bus. It shall be possible to transfer blocks of data, indepenently of, and concurrently with, CPU operation after initialization, CPU operation after initialization by the computer program. A minimum of twenty (20) I/O devices shall have access to the data bus.

(2) Parity: Any Read operation from memory must be provided with a parity checking capability.

(3) Direct Read/Write: It shall be possible to transfer single words directly between external devices and one or more of the registers.

K. Operational Aids

A programmer control panel located in the CPU cabinet shall be provided for manual operation of the CPU. The control features shall include, but shall not be limited to, the following:

(1) Display contents of arithmetic, index, and program counter registers.

(2) Alter contents of all registers.

(3) Indicators for parity errors, overflow, and flag registers.

(4) A lock to disable the control panel.

(5) A manual interrupt switch which causes a priority interrupt in the computer.

(6) The means to step through operations internal to the computer one instruction at a time.

(7) Control to initiate "bootstrap" loading of the computer from auxiliary memory.

5.2.3.3 Auxiliary Memory

A. Disk Memory Units

(1) Multiple identical moving head disk memory units having a maximum average access time of 70 m sec. shall be provided as required. Each unit shall consist of a controller, disk drive, and removable disk cartridge. Provide sufficient word storage capacity to meet or exceed the requirements of these specifications, 5 megabytes minimum or as required to support software and add spare capability. Each controller shall have the capability to control a minimum of four disk drives. Four spare disk cartridges sall be provided.

(2) Disk service assignment shall be made automatically or manually as selected by the operator.

B. Magnetic Tape

Provide controller slot for future magnetic tape unit.

5.2.3.4 Microprocessor Controller Center (MCC)

A. The MCC and its associated peripherals shall provide the controle functions as defined in Section IV. These controllers shall be at least dual redundant systems which can function independently of the central processor.

Normal man-machine interface to the controller shal be through the CPU assigned peripherals; however, in the event of a CPU failure, the operator assigned command terminal and control

(2) Electromagnetic Interference (EMI): The mission of the CMS as a control and monitoring system demands that the associated interfaces be subjected to the effects of EMI. In accordance with the signal description, all data transmission signals are of a low level type. The contractor shall take all necessary precautions to ensure that the signals received or generated by the CMS are shielded against any EMI which could affect RS-232-C or sensor operations. Erroneous data caused by EMI shall be indicated on the alarm display. Digital trunk cables shall be isolated by optically coupled isolators. Measurements of EMI shall be made in accordance with MIL-STD-462.

5.2.3.5 Uninterruptible Power Supply

A. Provide an uninterruptible power supply (UPS) which has the following characteristics:

(1) Sufficient capacity to maintain normal operation of the external uninterruptible clock, allow orderly shutdown of entire MCC and retain all memory for 72 hours.

(2) Provide sufficient regulation to allow entire MCC to be operated from emergency standby generator.

(3) Lead-calcium wet cell batteries.

(4) Maintain a float charge between 2.20 and 2.25 volts DC per cell.

(5) Include enclosed, ventilated racks and necessary interconnecting cabling to equipment. Enclosures shall match those of MCC, CPU and other system components.

(6) Provide a battery low voltage lamp and printout which shall indicate discharge to a certain fixed voltage level slightly above the inverter shutdown voltage level.

(7) Shall generate no unnecessary alarm upon restoration of normal power.

(8) Provide DC voltmeter to monitor battery voltage. Provide on-off switch.

(9) Provide AC voltmeter to monitor both input line voltages and inverter output.

(10) Provide a bypass switch that automatically transfers load to AC line if a failure occurs within the UPS. The transfer shall cause no interruption in power to the load.

(11) Provide alarm lamps and printouts to indicate if the UPS has failed and load has been transferred to bypass due to automatic or manual transfer.

5.2.3.6 Printers shall have the following minimum features:

A. Impact type.

B. 130 columns.

C. A speed of 30 characters per second.

D. An adjustable baud rate to 300 or more.

E. EIA RS-232C interface.

F. Minimum 96 character ASCII keyboard.

G. A noise level of less than conventional office machine (approximately 75 dBa at 5 feet).

H. Free-standing.

I. Fitted with a standard paper dispenser and take-up hoppers.

J. Fan-fold type paper.

K. Form Feeder.

L. Sprocket platen.

5.2.3.7 Workmanship

5.2.3.7.1 Workmanship: The criteria covered in this paragraph shall apply to all of the components incorporated in the CMS.

5.2.3.7.2 Panels, Enclosures, Cabinets, and Boxes: All panels, enclosures, cabinets, and boxes shall be factory engineered, prewired, and tested. Enclosures shall be fabricated of steel, enclosing all sides with a hinged door and a key lock. All locks shall be master keyed with a lock specifically keyed for this project. Seams, joints, and/or splices at corners or back edges of the enclosure shall be closed and reinforced by flanges formed from the metal from which the back is made by separate flanges. They shall also be free of burrs or roughness. Continuous welding is an acceptable substitute in providing a construction substantially equivalent to integral flange construction. In all cases, these panels and enclosures shall be primed to prevent damage from moisture before the manufacturer's standard color is applied.

5.2.3.7.3 Electronic Circuitry: All panels, enclosures, cabinets, and boxes shall have prewired circuitry for the CMS signals. This circuitry shall be of solid-state modular circuit board construction. The power supplies for the solid-state circuitry shall be allowed sufficient ventilation in the cabinet enclosure to provide optimum cooling.

5.2.3.7.4 Electrical Service: In accordance with Underwriter's Laboratories specifications for electrical enclosures and boxes, provisions for electrical service to all units shall be knock outs, covers, or plugs of metal which shall be secured in place so that they can be readily removed, but will not drop out with ordinary handling. All enclosures, cabinets, and panels shall connect to at least a 15-ampere, 120 VAC power circuit breaker located in a local power panel. In addition to this, each panel shall have a voltage regulation unit sufficient in size to control line power variances of plus or minus ten percent. The enclosures and panels shall be fitted with 120 volt convenience outlets for connecting AC powered test equipment. All wiring within the CMS shall be of sufficient wire gauge to meet the National Electrical Code. All wiring shall be in conduit except where it is necessary to separate, bundle, and tie for termination after the wire has entered the enclosure and exited the conduit.

5.2.3.7.5 Terminations: In all panels, enclosures, cabinets, and boxes, field wiring shall be terminated on the outboard side of terminal strips. Where applicable, there shall be two sections of terminal strip, the low voltage (DC) and the line voltage (AC) sections. Integral equipment affecting, or being affected by, the field terminations shall be connected to the inboard side of the terminal strips. All terminal strips shall be sequentially numbered. All field and integral wiring shall be labeled to reflect the individual wire termination number. All terminations shall be inspected visually and electrically before any power is applied.

5.2.3.8 Safety

A basic safety program shall be applied to the CMS in accordance with MIL-STD-882. In particular, no sharp edges nor burrs shall be acceptable. All dangerous voltages shlal be covered and protected by suitable interlocks. All moving parts shall also be covered and protected by interlock.

5.2.3.9 Human Engineering

The CMS equipment, documentation, and software shall be designed in such a manner that operations, repairs, adjustments, and system reconfigurations can be performed with an efficient flow along the man/machine interface.

5.2.3.9.1 Visual and Audible Alarms: All panels, consoles, peripherals, and associated equipment which have incorporated status lighting or indicators shall have an illumination which is clearly visible in a room with normal reading light, as well as a room which requires subdued lighting. Lamps or indicators used in signaling alarms shall be made to blink until the alarm is answered. This blinking shall be accompanied by an audible alarm of a type to attract the operator's attention in the presence of peak operating noise from tunnel and model, but not become offensive in the event of multiple alarms. The console layout shall be designed to allow visual as well as physical contact with all console controls. Equipment, such as line printers, which are subject to a high level of noise generation as to be accessible to the operator for general work flow but not close enough to be a distraction to the operator.

5.2.3.9.2 Maintainability: Maintainability of the equipment shall not be deterred by the placement of the equipment. All doors, removable panels, etc., shall have swing room of at least the width of the door or panel but never less than 30 inches clearance from any obstruction. All removable subsystems of the CMS equipment shall be mounted in such a manner as to facilitate service or removal. All connections shall be accomplished with suitable connectors so that repair by modular replacement of printed circuit cards can be accomplished easily and without rewiring. Each connector shall be clearly designated by a label showing its service and location. These connectors shall be keyed to prevent connections to the wrong jack or in a reverse direction. The connecting cable harness shall be suitably attached to the interior of the console and shall not be free hanging. The cable harness wiring distances shall be held to a minimum by proper organization of the equipment electronics.

5.2.3.10 Reliability

5.2.3.10.1 Reliability Design Techniques

5.2.3.10.1.1 Data Transmission: The success of the CMS operations is wholly dependent on the transmission and reception of accurate, clean, and stable data. To ensure data transmission link immunity to noise, the contractor shall as a minimum incorporate the following techniques:

A. All commands and data shall be transmitted digitally. The digital word shall consist of address, data or command, and a parity check bit. A parity check shall detect the insertion or dropout of any odd number of bits. When this occurs, the system shall reject the data or command to ensure that no bad data are used.

B. Balanced line transmission plus differential amplifiers shall be utilized to reject extraneous signal interference. Susceptibility to DC and low frequency noise and the prevention of ground loops shall be accomplished by providing isolation between the terminals.

C. Output commands, generated by the central control console and sent to a remote terminal, shall be sent back to the processor to verify, at the console, the accuracy of the command transmission. Only if proper transmission has been achieved in this closed loop shall theprocessor generate a command to the remote terminal to update its outputs.

5.2.3.10.1.2 Line Conditioning: To ensure proper operation under conditions where power line noise transients and power loss conditions occur, the following provisions shall be incorporated:

A. A radio frequency interference (RFI) filter shall be installed on the input 115 VAC line at the remote terminal. In any cases of doubt regarding RFI or EMI protection, MIL-STDs-461, -462, and -463 shall apply.

B. Primary to secondary shields shall be utilized on all power supply transformers to reduce the coupling of noise.

C. The output circuits shall be placed in a fail/safe condition in the event of long duration power droputs. Measures shall be taken to ensure that short duration power dropouts do not cause a change of state, subject to the manufacturers' specifications.

5.2.3.10.1.3 Alarm Conditions: To protect against false indications due to short term noise transients on the input lines to a remote terminal, the central console processor shall utilize time diversity for all alarm situations. Before an alarm can be annunciated, the alarm condition shall exist for two consecutive sample periods at the remote terminal input. Thus two separate indications of a specific alarm condition shall exist before the alarm can be annunciated on the operator's console.

5.2.3.10.1.4 Alarm Detection: To ensure detection:

A. The central control console shall indicate, on the display and printer and with an audible tone, any repeated parity errors or malfunction on the data transmission link. Action on data and commands shall be inhibited during this malfunction. Questionable data shall not be used to update the system.

B. Remote terminal or sensor power failures shall be alarmed at the central control console.

5.2.3.10.1.5 Conductors and Cabling: Conductors and cabling shall be protected in the following manner:

A. All transmission conductors of the data transmission cable which serve as exterior transmission links shall be provided with lightning arrestors at the remote terminal panels for the MCC to suppress line voltage spikes from lightning or other induced sources. This feature will provide maximum protection against MCC failures.

B. Shorts, grounds, and opens on a ciruit of the transmission cable shall be annunciated at the central control console with an audible horn, display, and the appropriate printed message. Only that link affected will alarm at the console. Remote terminal or sensor failures, either due to power supplies or component failures, shall also annunciate individually at the control console.

5.2.3.10.2 Reliability Requirements: The system development effort shall include a reliability program established in accordance with the guidelines of MIL-STD-785. Normal preventive maintenance and shutdowns for preventive maintenance shall not be considered as failures or as part of fault correction time. The mean time between failures (MTBF) for all equipment whose failure would constitute a major failure shall be greater than 2000 hours. MTBF for CMS system failures shall be greater than 500 hours. MTBF for minor failures shall be greater than 100 hours. All MCC's (with PCB's installed) shall be subjected to a 48 hour burn-in period before delivery. These MTBF figures shall not be demonstrated but shall be calculated in accordance with the procedures of MIL-HDBK-217. For purposes of the reliability requirements:

A. Major failures shall be defined to mean any failure that precludes operation of a significant portion of the system or of a subsystem function.

B. A minor failure is defined as a failure of system equipment which does not cause a failure as defined in A.

5.2.3.11 Maintenance Requirements

The CMS shall have a maintainability program established in general accordance with MIL-STD-470. The maintainability requirement for the CMS shall be a mean time to repair (MTTR) of 1 hour. This MTTR shall not be demonstrated but shall be calculated in accordance with the procedures of MIL-HDBK-472.

5.2.4 Installations

5.2.4.1 General

The equipment layout shall be designed to minimize hand wiring, reduce total system cost, and to provide a flexible, expandable control and monitoring network. The field equipment plan shall provide efficient, cost-effective installation through good equipment design and careful planning. Installation of the CMS shall be performed in accordance with the written instructions from the manufactuers of the component(s). It shall be the responsibility of the contractor to maintain the aesthetics of the equipment being installed as well as to restore the affected state of the equipment environs.

5.2.4.2 Installation

Installation shall be in dry interior areas of buildings. Do not install panels adjacent to heat generating devices.

5.2.5 Field Tests and Inspections

Upon completion of installation of each piece of equipment, field inspect and mechanically and electrically test equipment for proper function. Run diagnostic programs. The Contracting Officer shall witness the diagnostic programs. Submit a certification of such diagnostic tests signed by the witnessing Contracting Officer.

5.3 CONTROL AND MONITORING SYSTEMS (CMS) SOFTWARE

5.3.1 Applicable Publications

The following publications of the issues listed below, but referred to thereafter by basic designation only, form a part of this specification to the extent indicated by the references thereto.

5.3.1.1 American National Standards Institute (ANSI) Publication

X3.9-1966	FORTRAN (ISO R1539-1972)

5.3.1.2 Government Publications

MIL-STD-483	Configuration Management Practices for Systems, Equipment, Munitions, and Computer Programs

5.3.2 General Requirements

Section 5.1, Control and Monitoring Systems (CMS), General Requirements, with the following additions and modifications, applies.

5.3.2.1 Submittals

These shall include manufacturer's data, shop drawings, certified test reports, and operation and maintenance manuals.

5.3.2.2 Software System Manuals

All documentation wherever specified in these specifications shall become the property of the Government. All documentation shall be delivered to the Government including, as a minimum, Operators Reference Manuals; Programmer's Reference Manuals fully annotated source listing, source code on Mylar tape; and Program Flow Diagrams. Documentation on programs shall be sufficient to allow qualified Government personnel to make any changes that may be required in the software programs. If the required documentation contains proprietary information, all pertinent pages shall be so marked and will not be circulated outside the Government.

5.3.3 <u>Support Software for CMS Central Control Center</u>

5.3.3.1 General

Provide software to support the functions and application programs specified herein. The software shall be Multi-Tasking, Foreground/Background, Multi-User, as defined herein.

A. Multi-Tasking Software: Multi-Tasking means that more than one program may be core resident and executed concurrently within the machine under the management of a Real Time Operating System/Executive. Tasks shall be interrupt driven and on a priority basis. Provide design which allows addition of unique application tasks to the supplied software. Furthermore, it shall be possible to write additional tasks in FORTRAN.

B. Foreground/Background Feature: Provide foreground/background feature to operate concurrent with the running foreground or background progams without requiring interruption of the running foreground or background software.

C. Multi-User Structure: The term "multi-user" shall mean that multiple operations, from multiple input/output devices (e.g., CRT, Keyboard Printers, etc.) shall be able to concurrently issue commands to the running programs. Also, Government personnel shall be able to develop independent programs without requiring interruption of the foreground (or background)monitoring and control programs.

D. Applications program shall be written in FORTRAN.

5.3.3.2 System Utility Software

Provide the following system software in the assembler language source code:

A. Bootstrap Program: Provide a machine language bootstrap program to support initial system loading.

B. Editor: Provide an editor to adequately support input, modification and storage of assembler language source code and FORTRAN source code. Editor documentation shall provide the following:

(1) Operator's Reference Manual.

(2) Programmer's Reference Manual.

(3) Fully annotated source listing.

(4) Object code on disk.

(5) Program flow diagram.

C. Assembler:

(1) General: Provide an assembler to support the generation of machine-readable object code from assembler language source programs. The assembler shall include the following:

a. Conditional assembly.

b. Macro identification.

c. Error detection/reporting.

d. Full listing, including numbering of pages.

e. Fully cross-referenced symbol table.

(2) Assembler Documentation: The assembler documentation shall include the following:

a. Operator's Reference Manual.

b. Programmer's Reference Manual.

c. Fully annotated source listing.

d. Object code on disc.

e. Program flow diagram.

D. Loader

(1) General: Provide a general purpose loader with the capacity to load all object code programs from any applicable input device. The loader must be capable of linking a set of object programs and executing them as a single program/task.

(2) Loader Documentation: The loader documentation shall include the following:

a. Operator's Reference Manual.

b. Programmer's Reference Manual.

c. Fully annotated source listing.

d. Object code on disc.

e. Program flow diagram.

E. Debugger

(1) General: Provide a debugger with the capability to support diagnostic software development with any assembler or FORTRAN applications program. The debugger shall provide the following:

a. Display or modify any location within the program being "debugged."

b. Set multiple "break points" at any location within the program.

c. Obtain a printout of the contents of all registers.

d. Identify any location within the program by its name.

e. Preserve an executable copy of the corrected program on any applicable output device.

(2) Debugger Documentation: The debugger documentation shall include the following:

a. Operator's Reference Manual.

b. Programmer's Reference Manual.

c. Fully annotated source listing.

d. Object code on disc.

F. Utility Software

(1) General: Provide utility software capable of transferring any information between any two applicable devices in the system.

(2) Utility Software Documentation: The Utility Software Documentation shall include the following:

a. Operator's Reference Manual.

b. Programmer's Reference Manual.

c. Fully annotated source listing.

d. Source code on disc.

e. Program flow diagram.

G. CPU Diagnostics

(1) General: CPU Diagnostic is defined as one provided on a "hard" input medium (e.g., disc). A set of diagnostic assembler language programs shall be provided. These diagnostics shall, for all hardware and modules, exercise all features of the hardware and report all detected failures in mnemonic fashion.

(2) Diagnostic Documentation: The diagnostic documentation shall include the following:

a. Operator's Reference Manual.

b. Annotated source listing.

c. Source code on magnetic cassette or Mylar tape.

d. Program flow diagrams.

e. Object code on disk.

H. FORTRAN Compiler

(1) General: Provide a FORTRAN compiler conforming to ANSI X3.9. In addition, it shall contain sufficient file management and real-time extensions.

(2) FORTRAN Compiler Documentation: FORTRAN compiler documentation shall include the following:

a. Operator's Reference Manual.

b. Programmer's Reference Manual.

c. FORTRAN Library Manual.

d. Program flow diagram.

e. Object code on disk.

5.3.3.3 Real-Time Operating System/Executive (RTOS/E)

A. General: Provide a Real-Time Operating System/Executive. The program shall provide the following routine capabilities:

(1) Operation and management of all input/output devices.

(2) Support of concurrent execution of at least eight tasks/users according to an externally specified priority profile.

(3) Assignment of at least eight different levels of task priority.

(4) Error detection/recovery from arithmetic/logical faults (underflow, overflow, division by zero, etc.); illegal attempts by one task/user to write into another user's memory space; and power failure.

(5) Be callable from assembler FORTRAN programs.

(6) Selective generation to include only those features required by a given hardware configuration.

(7) Be readily modified to incorporate additional drivers for special purpose devices.

B. Real-Time Operating System/Executive Documentation: The Real-Time Operating System/Executive Documentation shall include the following:

(1) Operator's Reference Manual.

(2) Programmer's Reference Manual.

(3) Annotated source listing.

(4) Object code on disk.

(5) System flow diagram.

5.3.3.4 Real-Time Disk Operating System Expansion

Provide a Real-Time Disk Operating System to exhibit, without being limited to, the following additional features:

A. File management.

B. Random file structure.

C. Total file management support.

D. Minimum support of 64 concurrent tasks.

E. Minimum of 64 different task priority levels.

F. Full overlay capability.

G. Support of all Utility Routines.

5.3.3.5 Interactive Command Line Mnemonic Interpreter

Provide a high level language Command Line Mnemonic Interpreter to support all direct human interactions within the Control and Monitoring System (CMS).

A. The Command Line Mnemonic Interpreter shall contain full English language words mnemonically selected to allow operators unfamiliar with data processing technology to become efficient users of the system without extensive training. The Command Line Mnemonic Interpreter shall be independent of syntactical consideration. All multi-level command-strings shall be arranged in a request/response sequence in which the machine prompts the operator for all required information. The response, required of the operator, shall never be more than a single full English word followed by a set of logical parameters.

B. The Command Line Mnemonic Interpreter shall adequately support both the stand-alone operation and the interactive operation of the system. The term "interactive" means that the system operator has "access" and control, while the program is running, to each system parameter affecting the dynamics of the control situation. The term "access" shall mean, as a minimum, the basic capabilities to create, display or modify all system strategies and related parameters. The Command Line Mnemonic Interpreter shall have in its inventory a "HELP" command which, when typed by the operator, shall produce a hard-copy printout of all Command Line Mnemonics provided in the system. Furthermore, the command "HELP" followed by a specific Command Line Mnemonic shall provide a short explanation of the purpose of the command, a brief example of its use, and a typical system reaction as a result of issuing the command.

C. Equipment and Point Parameters and Definition: Provide all software necessary to maintain static and dynamic information on equipment and points in the system inventory. By simply supplying to the system the information required for definition, the operator shall be able to interactively define pieces of equipment and/or points to be fully managed by the system.

(1) Equipment Definition: Each piece of equipment managed by the system shall be characterized by a set of fixed parameters. After interactively triggering the equipment definition process by means of a suitable Command Line Mnemonic the system Control Console shall prompt the operator for the following information:

a. A unique equipment identifier (EI).

b. Equipment control type straight ON/OFF, interlocked with other equipment, etc.

c. MCC identifier.

d. "ON" Control Address.

e. "OFF" Control Address.

f. Sense Feedback Address.

g. Delay before sensing feedback, with a dynamic range between 50 milliseconds and 30 minutes.

(2) Analog Point Definition: Each analog signal shall be introduced by means of a suitable Command Line Mnemonic, which shall cause the system to prompt the operator for the following information:

a. Point Address on the system.

b. MCC Identifier.

c. Analog-to-Digital Converter channel.

d. Factor for conversion to correct engineering units.

e. Weighting factor.

f. Lower tolerance of acceptable values.

g. Upper tolerance of acceptable values.

h. Alarm Notification: The following conditions shall be accounted for: no alarm; below lower tolerance; above upper tolerance; and out of range from above or below.

i. Action Identifier specifying the steps to be taken when an out-of-bounds condition occurs on the signal.

j. Correlated alarm class, if applicable. Provide the capability to associate a "master" alarm with an arbitrary set of "slave points." Upon detection of an alarm condition in the master point, an automatic printout may be generated of the status and/or values of all associated slave points. The number and designation of master and slave points shall be arbitrary and shall be interchangeable, e.g., any master point may be a slave point in another correlated sequence.

k. Signal Priority.

l. Graphic display identification.

(3) Digital Point Definition: Each digital input signal shall be introduced to a series of prompts for the following information:

a. Point Address on the system.

b. MCC Identifier.

c. Action Identifier specifying the steps to be taken when an alarm condition occurs on the signal.

d. Correlated alarm class, if applicable. Provide the capability to associate a "master" alarm with an arbitrary set of "slave points." Upon detection of an alarm condition in the master point, an automatic printout may be generated of the status and/or values of all associated slave points. The number and designation of master and slave points shall be arbitrary and shall be interchangeable, e.g., any mast point may be a slave point in another correlated sequence.

e. Condition which constitutes an alarm, "ON" condition, "OFF" condition.

5.3.3.6 Equipment and Point Dynamic Parameters

In addition to the static parameters noted above, provide software to maintain the following information:

A. Equipment Dynamics: The system shall retain the following dynamic parameters on each piece of equipment:

(1) Current status.

B. Point Dynamics: The system shall maintain the dynamic parameters for all types of input signals as follows:

(1) Present reading.

(2) Average value calculated according to signal type.

(3) Maximum value during the current time period.

(4) Date and time at which the maximum occurred.

(5) Minimum value during the current time period.

(6) Date and time at which the minimum occurred.

5.3.3.7 Equipment Point Modification

Provide the capability to perform any of the following equipment/point modifications without halting the Control and Monitoring System Program (CMS):

A. Equipment/Point deletion.

B. Equipment/Point Editing.

C. Equipment/Point Enable: Each equipment/point in the system inventory may be set to one of the following enable conditions:

(1) Equipment Enable:

a. Enabled for control (normally to be turned ON) during any combination of one or more time periods.

b. Totally disabled from computer control.

c. Enabled for reporting during any combination of one or more time periods.

d. Totally disabled from being monitored.

(2) Point Enabled

a. Enabled for monitoring during any combination of one or more time periods.

b. Totally disabled from being monitored.

c. Enabled for reporting during any combination of one or more time periods.

d. Totally disabled for reporting.

5.3.3.8 Control Sequencing Software

The following paragraphs describe software capabilities to create automated, algorithmic and operator independent control of correlated sets of equipment and sensors. It should be noted that the features specified are the minimum requirement and may not be sufficient to support all operational features discussed herein.

A. Control Sequence Definition: Provide a set of interactive commands to permit the definition of various classes of "Control Sequences." A "Control Sequence" shall consist of a list of equipment to be controlled, depending upon one or more of the following conditions: time of day, operator request, or correlated parameters (e.g., time-of-day, tempearture, load conditions, etc.). For each of the "Control Sequence" types specified below, it shall be necessary for an operator to enter the "Control Sequence" definition request by means of a Command Line Mnemonic. The system shall prompt the operator for the specific information required. None of the commands or the capabilities discussed herein shall require the stopping or interruption of the control and monitoring system software.

The minimum initial size of the Control Sequences shall be as described below. The capability to easily expand the size of sequences and the number of equipment units in each sequence shall be provided.

VI. CONCLUSIONS AND RECOMMENDATIONS

6.1 SUMMARY

The principal accomplishments of this study are a math model with which to simulate static and dynamic wind tunnel performance, a hierarchy of candidate computer systems to control airspeed or dynamic pressure and perform other control and monitoring functions, and a baseline specification set for the implementation of such systems. As a result, improved understanding has been gained of the tunnels' operating characteristics, of their control characteristics, and of the ability of computer-based systems to improve operating efficiency and safety. Of particular interest are the verification of the expected wind tunnel performance envelopes, the nature of tunnel q regulation using fan RPM and blade stagger angle as controls, and the requirements on various levels of automatic control as well as basic computer system cost estimates and implementation considerations. It is hoped that the results of this study, and the conclusions reached, will serve as starting points for further study of each of the areas mentioned above and be useful in the procurement of some or all of the control and monitoring functions considered.

6.2 CONCLUSIONS

6.2.1 Wind Tunnel Operation

Experience with the simulation math model developed in this study leads to the following conclusions relative to wind tunnel operational characteristics:

(1) Drive fan performance is such that drive motor power limits are reached before the fan surge pressure rise boundary is encountered. The 40'x80' requires higher

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fan pressures, and the surge boundary may be closely approached with high model drag and minimum stagger angle (ξ = 38° min.).

(2) Fan aerodynamics are such that low-speed power consumption is a direct function of RPM at a given tunnel speed.

(3) Flow acceleration simulations in line power mode show that the fan surge boundary is not encountered with acceleration rates an order of magnitude greater than those permitted due to power rate limits, due to pressure rise relief as the airflow accelerates.

(4) Power consumption rate limits the blade pitch change rate in high speed operation.

(5) Simulated emergency stops show that the fans experience higher negative loading in the 80 x 120 mode of operation. Flow deceleration time constants are similar to those of the existing tunnel.

(6) Fan RPM is a more effective airspeed controller in the IFC mode than is blade angle, due to low blade rate limit necessitated by high-power operation. Certain restrictions on the speed of RPM control may be imposed by the elements of the motor-generator system.

(7) Open-circuit tunnel airspeed disturbances caused by atmospheric turbulence are predicted to be small, and controllable with fan blade pitch angle, though attempts to minimize such disturbances may increase the maintenance requirements of the blade pitch actuation system.

6.2.2 Automatic Control and Monitoring Functions

The principal conclusions reached relating to the automation of wind tunnel speed/q control and other functions are as follows:

(1) Wind tunnel speed/q control may be accomplished by a relatively uncomplicated controller operating in parallel with the manual control system and utilizing the same control methodology as the manual system. The controller uses tunnel dynamic pressure as the measured and controlled parameter.

(2) Model attitude control may be accomplished by a controller utilizing sensed tail strut height and turntable yaw angle to generate on-off and desired rate

commands to the electric model attitude drive motors. This controller may be implemented in parallel with the manual control path. The automatic controller will provide direct readout of model attitude given tail strut and turntable settings; the dividing line between automatic and manual systems depends on further definition of the "manual" system.

(3) With a perfect pressure transducer, an automatic q-hold system such as studied in this effort appears capable of holding q to a tolerance of about ± 0.2 psf at high speeds and $\pm .05$ psf at low speeds. The main limitation on accuracy is imposed by nonlinearities in the RPM and blade pitch actuation systems which prevent full use of integral feedback control. The use of additional logic switches in the q- control law or the acceptance of larger errors may be required.

(4) Critical parameter monitoring applied to tunnel and model parameters is feasible and would provide an essential facility monitoring and diagnostic function. However, it will require a substantial system development effort to properly design and integrate the types of hardware required to sense parameters in a noisy environment with the hardware and software to process this information in a satisfactory (fast and reliable) manner. Numerous attractive hardware systems exist at the present time.

(5) Automatic test management is feasible using minicomputer technology and would relieve much of the workload of the test engineer. System development efforts must be directed toward redundancy/reliability matters since multiple minicomputers are considerably more costly (in terms of hardware) than multiple microprocessor units, and toward the development of fast algorithms to determine system faults from measured data.

(6) The cost of a system to perform the major speed/q control, model attitude control, critical parameter monitoring and test management functions for both wind tunnels is estimated at this time to be on the order of $400-$500K, with software and system development costs predominating and liable to escalation. Initial costs can be reduced by modular implementation of system functions.

(7) Microprocessor-based computer systems can be used for speed/q and model attitude control, as these functions are primarily logical in nature. Critical parameter monitoring can probably be done with microprocessors if care is

taken to optimize cycle times and minimize noise. Test management functions, to be effective, require minicomputer capability.

6.3 RECOMMENDATIONS

6.3.1 Recommendations on Automatic System Implementation

(1) Automatic computer-based systems should be implemented to regulate tunnel dynamic pressure and model attitudes; microprocessor hardware is recommended for these systems. The hardware should be selected with consideration toward compatibility with minicomputer systems that may be acquired to perform test management functions. Since sources of error outside the computer-based control laws are likely to be greater than those within (as caused, for example, by mechanical nonlinearities), dependable pressure transducers of the best available accuracy should be procured for the speed/q subsystem.

(2) To guard against computer malfunctions, the computers of the speed/q and model attitude control subsystems should be a minimum of dual redundant with appropriate software.

(3) Implementation of a critical parameter monitoring sub-system should be preceded by a study of the optimum configuration of such a system in light of hardware requirements and availability, system performance requirements, and software capability and cost. It is recommended that the monitoring be centered in a single fail-operational unit providing status information to both tunnel control rooms and a permanent monitoring station. It is further recommended that this sytem be microprocessor-hardware-based. Wherever possible, an automatic monitoring system should be used to collect and transmit status information from both electromechanical sensors and tests of computer operating status. The implementation of this system is strongly recommended if it can be shown that traditional electromechanical alarms cannot provide the scope and versatility of status and maintenance information required in this complex facility.

(4) Implementation of a test management sub-system should be minicomputer-based and utilize hardware and software selected for maximum compatibility with the microprocessor and other minicomputer systems with which it will interface and should be preceded by a study of the probable software requirements of test management system and data-based fault-detection system in order to establish memory and I/O requirements.

(5) Provisions for the expansion of system capacity should be made as suggested in the specifications discussed in Section V.

(6) The computer subsystems implemented to perform the four basic functions described here should be independent, stand-alone systems with specific means of intersystem communication, in order to obtain the greatest advantage from implementation flexibility, selective redundancy enhancement possibilities, and clear system failure paths to the manual level.

(7) To the greatest extent possible, digital computer hardware should be located in a temperature-controlled, vibration-free environment. Analog elements should be protected from electrical noise. Data transmission from sensors to computers should be performed digitally when any substantial distance is involved. Pressure transducers as well should be located in a controlled environment to achieve maximum accuracy.

(8) An estimate of the nonlinearity present in the blade pitch control system (mechanical hysteresis and deadzone) should be obtained to support further speed/q system studies.

6.3.2 Recommendation for Further Study

In support of the development of the control and monitoring systems described above, the following studies are recommended:

(1) Hardware and software trade studies for the fail-operational critical parameter monitoring system;

(2) Development of fault detection algorithms for the test management subsystem;

(3) Further modelling and system checkout planning for the motor-generator system;

(4) Selection of RPM-blade stagger angle trajectories yielding optimum IFC-mode performance.

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APPENDIX A

- TUNNEL GEOMETRIC DATA
- FAN AERODYNAMIC DATA

Table A.1. 40x80 TUNNEL CROSS-SECTIONAL AREAS AND SECTION LENGTHS

STATION (See Figure 2)	AREA, FT^2	LENGTH, FT (℄)
1	7539.82	--
2	22856.25	573.0
3	22856.25	232.78
4	2856.64	200.33
5	2886.52	80.0
6	7447.79	420.73
7	7447.79	238.90
8	7539.82	164.50

Table A.2. 80x120 FT TUNNEL CROSS-SECTION AREAS AND SECTION LENGTHS

STATION	AREA, FT^2	LENGTH, FT. (℄)
1	53439.0	--
2	9600.0	270.5*
3	9680.16	190.0
4	8446.25	204.3
5	7539.82	116.3
6	7539.82	107.75
7	21112.0	305.3
8	21112.0	269.8*

*INCLUDES EXTENSION FOR EXTERNAL AIR MASS

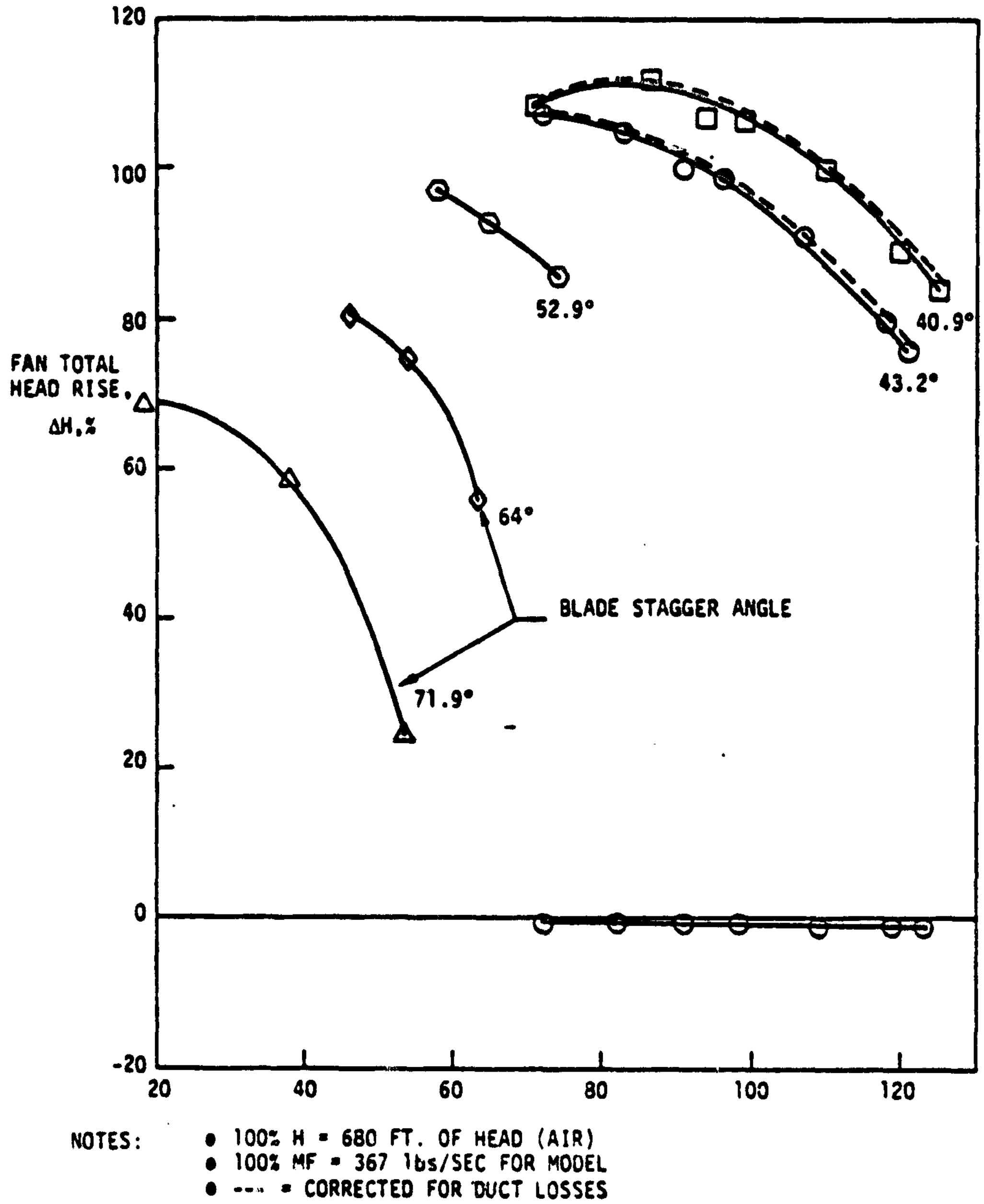

Figure A.1 NASA Fan Total-Head Rise from 1/6-Scale Model Fan

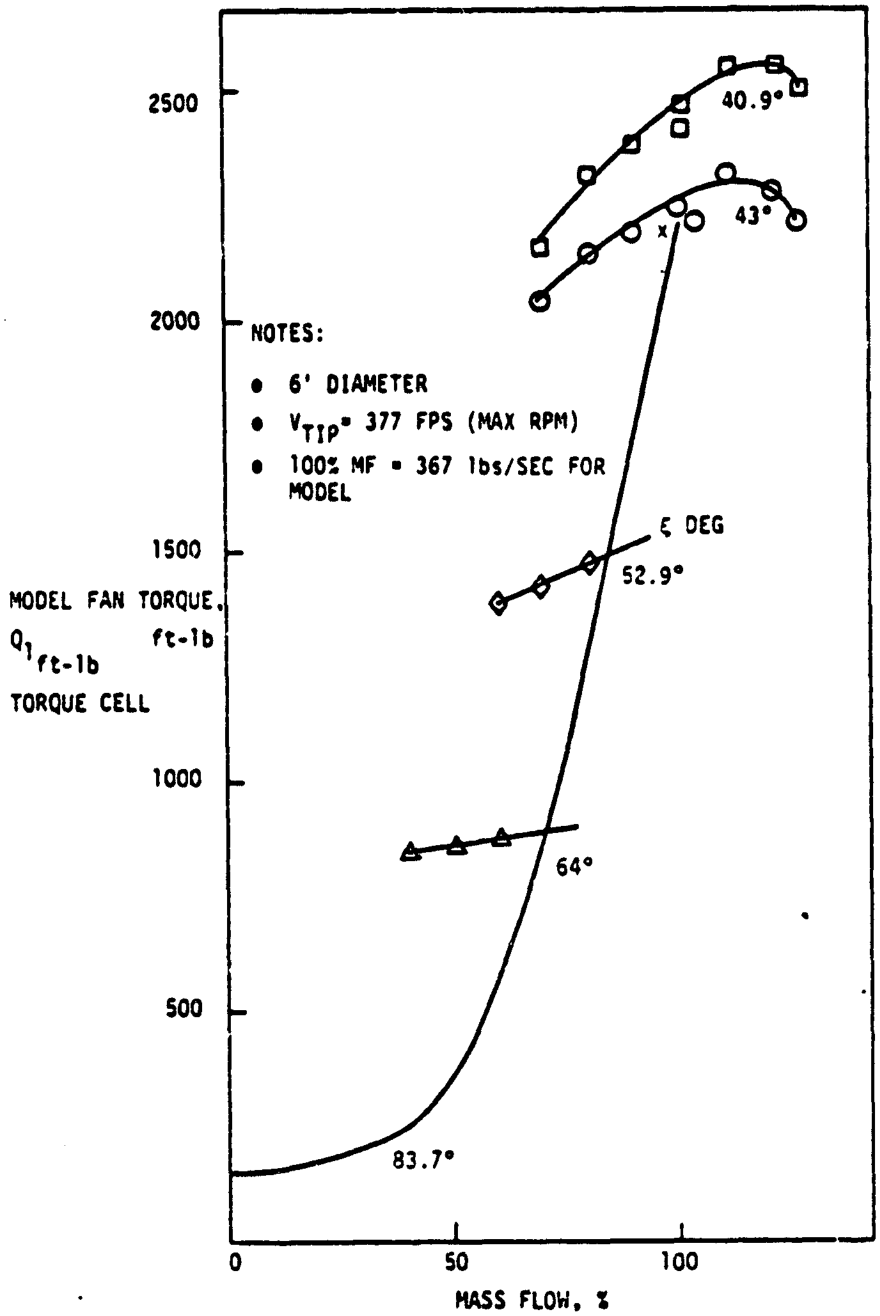

Figure A.2 NASA Fan Aerodynamic Torque Data from 1/6-Scale Model Fan

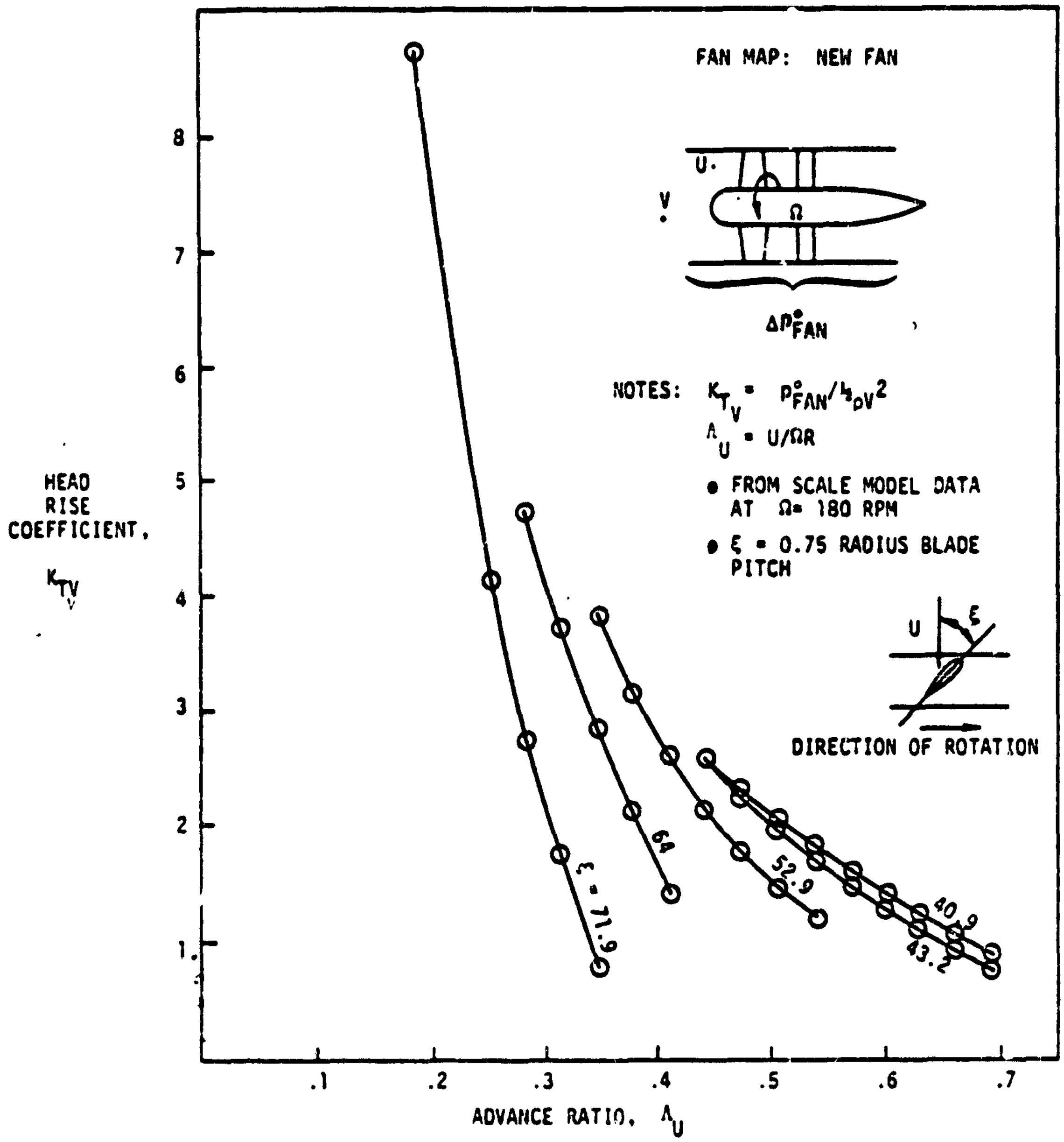

Figure A.3 Fan Head Rise Coefficient at Various Stagger Angles, from NASA Data

APPENDIX B
SIMULATION PROGRAM LISTING AND USERS' GUIDE

B.1 INTRODUCTION

Section 2.5 presents an overview of the computer program which implements the wind tunnel simulation math models. The user interface with this computer program is described here; and a full listing of the program is provided. The program is written in FORTRAN IV and resides on the NASA/Ames CDC 7600 computer system, it has also been run on a UNIVAC 1108 system.

B.2 COMPUTER PROGRAM DESCRIPTION

The simulation program can be executed in any of three modes:

(1) Trim;

(2) Simulate; and

(3) Generate linear models.

The Trim mode is used to compute equilibrium states at various tunnel operating points. It is also used (optionally) to perform automatic initialization for the Simulate mode, which computes the tunnel dynamic response at specified time intervals. The linear model generation mode calculates matrices which represent the linearized dynamics of the wind tunnel states; these matrices are useful in control design. The user may select the execution mode of the program as shown in Section B.3 below.

A full listing of the math model computer program is included at the end of this section. To aid in the inspection of the listing, the FORTRAN names of the subroutines which comprise the computer program are shown in Table B-1, along

Table B-1

Wind Tunnel Computer Program: Primary Subroutines

FORTRAN NAME	EXPANDED NAME	DESCRIPTION
BLADEP	Blade Pitch Actuator	Models the fan blade pitch actuator (lag, hysteresis, deadzone); also accommodates by-passing actuator dynamics.
BLKDTA	Block Data	Contains program data (fan maps, pressure drop tables, etc.).
CNTLW	Controller (Windspeed)	Contains RPM and blade pitch control laws.
DRAG	Drag Model	Calculates drag of the model in the test section.
ENERGY	Energy Parameters	Calculates work and heat flux in the tunnel segments.
EQUILB	Equilibration	Evaluates state variable rates of change so that they may be nulled by the trim initialization routine (SETUP).
EXEC	Executive	Maintains timing and sequencing control.
FANMOD	Fan Model	Calculates pressure and temperature changes across the fans.
FLOMOD	Flow Model	Computes the flow parameters (pressure, temperature, Mach no., etc.) at the eight selected tunnel stations; accommodates both open and closed tunnel circuits.
FLOPAR	Flow Parameters	Called by FLOMOD to perform Mach number and related fluid-dynamics calculations.
LINMOD	Linear Models	Computes matrices which represent the linearized dynamics of the wind tunnel states--used for control design.
MGMOD	Motor Generator Model	Models the functional characteristics of the tunnel motor generator system.

Table B-1 (Continued)

FORTRAN NAME	EXPANDED NAME	DESCRIPTION
PLOT	Plot Routine	Plots selected variables versus time using the line printer.
PRINT	Print Routine	Prints selected variables versus time.
SENSOR	Sensor Models	Models sensor noise and dynamics, if any.
SETUP	Set-up Routine	Performs trim initialization of the wind tunnel states.
STATE	State Integration Routine	Integrates wind tunnel state variables over time.
TABLE1 TABLE2 TABLE3	Table Look-up Routines	Performs one, two, and three-dimensional table look-up.
WTMAIN	Wind Tunnel Main Program	Main program--reads inputs, sets up the run, calls the run executive (EXEC).

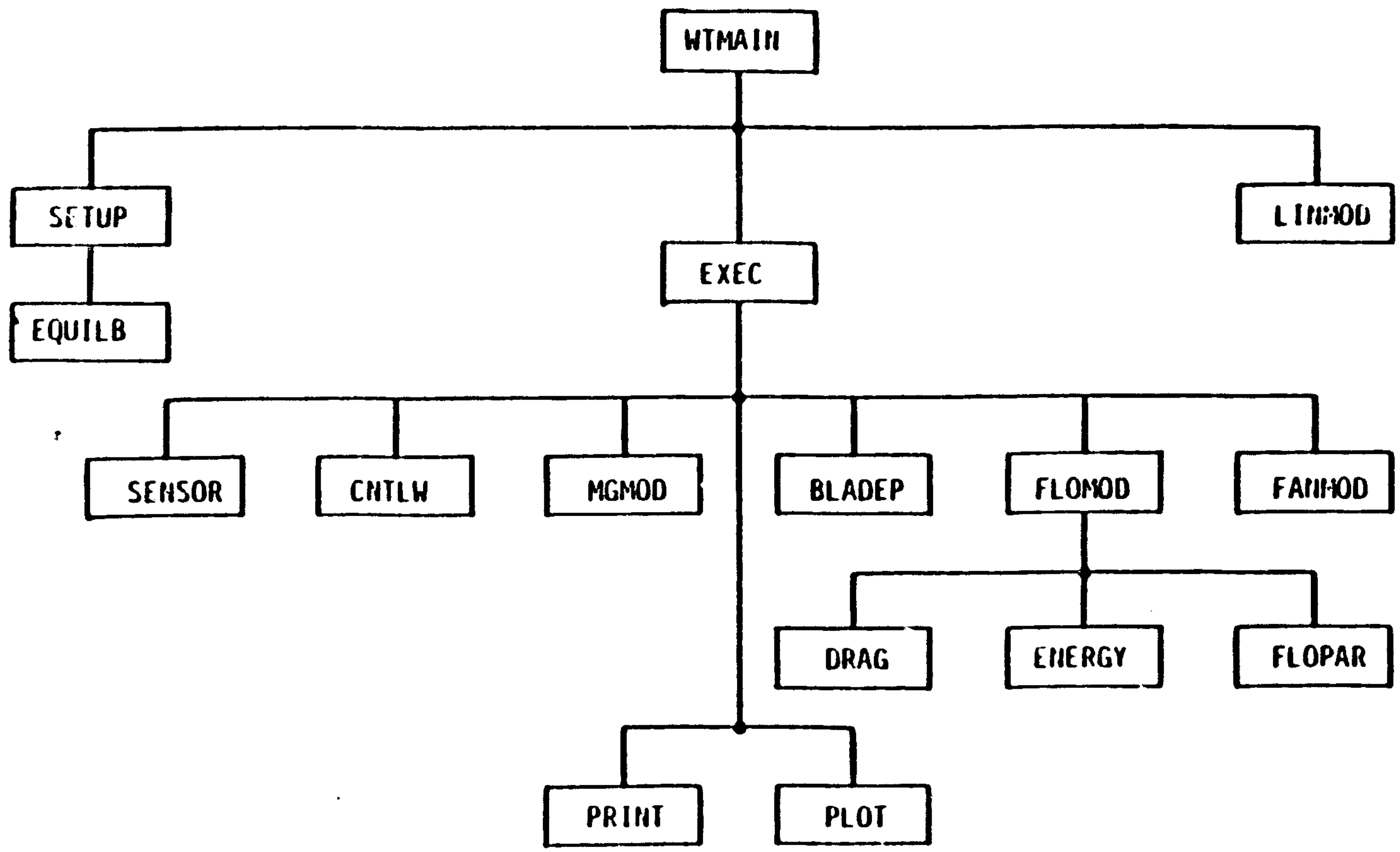

Figure B-1. Wind Tunnel Computer Program: Module Hierarchy with a brief description of the function of each subroutine. A hierarchy chart showing the inter-relationship of the subroutines (i.e., "who calls whom") is shown in Figure B-1.

B.3 PROGRAM INPUT

The math model computer program receives user inputs by way of the FORTRAN NAMELIST data entry mechanism; the title of the NAMELIST is "INPUT." Relevant NAMELIST variables are shown in Table B.2. These variables fall into the following categories, as shown:

(A) Execution and Mode Control

(B) I/O Control

(C) Run Initialization/Trim Criteria

(D) Model Gains/Parameters

(E) Operator Manual Inputs

Most of the inputs described in the table are straightforward. A notable exception is the vector of integers which selects options as to which variables constitute the trim criteria (NAMELIST variable IMENU). Pertinent values for the components of IMENU are shown in Table B.3. The trim routine will attempt to null all the selected quantities simultaneously. Default values for IMENU in the line power case (MODIFC=0) are:

IMENU = (1, 2, 7, 8, 14, 15)
NERF = 6
} LINE POWER

Thus, the trim attempts to null the rates of change of mass flow rate (MDOTD), for RPM (WFRD), synchronous motor power angle (DELTAD), and synchronous motor field voltage (EQPD) while simultaneously nulling the deviations of fan RPM and blade ptich angle from their set values. Default values for IMENU in the IFC power case (MODIFC ≠ 0) are:

IMENU = (1, 2, 3, 4, 7, 8, 14, 15, 17 or 18)
NERF = 8
} IFC POWER

Table B-2

User Input Variables (NAMELIST "INPUT")

NAMELIST VARIABLE	TYPE	DESCRIPTION	DEFAULT VALUE	UNITS
		(A) <u>Execution and Mode Control</u>		
TSTOP	Real	Total Simulation Time	10.	sec
DT	Real	Sample Interval	0.1	sec
LEVELC	Integer	Speed Control Level 0 = Direct Manual Control 1 = Level One (and above control)	0	-
ISETUP	Integer	Primary Mode Control 0 = Simulate Only 1 = Trim Only 2 = Trim and Simulate 3 = Generate Linear Models	0	-
MODIFC	Integer	IFC Control Mode 0 = Line Power 1 = IFC Power	1	-
MODEMB	Integer	Blade Pitch Control Mode 0 = Automatic Scheduling 1 = Manual Scheduling	0	-
MODEQC	Integer	$\bar{q}$/V Mode Select 0 = Velocity Command 1 = Direct $\bar{q}$ Command	1	-
IOPENC	Integer	Tunnel Circuit Designation 0 = Closed-Circuit Tunnel 1 = Open-Circuit Tunnel	0	-

Table B-2

User Input Variables
(NAMELIST "INPUT")

NAMELIST VARIABLE	TYPE	DESCRIPTION	DEFAULT VALUE	UNITS
		(B) I/O Control		
LEVELP	Integer	Print Level 0 = 1 = (See Table B.5) 2 =	0	-
NPRP	Integer	Cue to Print every NPRPth Point	10	-
IPLOT	Integer	Plot Flag 0 = No Plots 1 = Printer Plots	0	-
NPLP	Integer	Cue to Plot Every NPLPth Point	10	-

Table B-2

User Input Variables
(NAMELIST "INPUT")

NAMELIST VARIABLE	TYPE	DESCRIPTION	DEFAULT VALUE	UNITS
		(C) Run Initialization/ Trim Criteria		
		(1) Initial Conditions		
XIIC	Real	Fan Blade Pitch Initial Value	40.9	deg
RPMIC	Real	Fan RPM Initial Value	180.	RPM
MDOTIC	Real	Tunnel Mass Flow Rate Initial Value	2191.	Slug/Sec
RPM1IC	Real	Const.-speed DC Motor RPM	600.	RPM
RPM2IC	Real	IFC RPM	10.	RPM
DLTIC	Real	Const.-speed Synch Mat. δ Desired	-5.	deg
		(2) Desired "Set" or Trim Values		
XISET	Real	Fan Blade Pitch Set Value	40.9	deg
RPMSET	Real	Fan RPM Set Value	180.	RPM
MDOTST	Real	Tunnel Mass Flow Rate Set Value	2191.	Slug/Sec
QBARST	Real	Test Section $\bar{q}$ Set Value	129.5	lb/ft^2
UTSSET	Real	Test Section Velocity Set Value	345.1	ft/sec
PESET	Real	Synchronous Motor Electrical Power Set Value	1.	Per Unit
		(3) Trim Criteria Options		
IMENU	Integer Vector	Option Menu (See Table B.3)	See Text	-
NERF	Integer	Number of Options in Menu	See Text	-

Table B-2

User Input Variables
(NAMELIST "INPUT")

NAMELIST VARIABLE	TYPE	DESCRIPTION	DEFAULT VALUE	UNITS
		(D) Model Gains/ Parameters		
GXIDC	Real	Blade pitch rate limit	.08	deg/sec
TBNEG	Real	Blade actuator acceleration time constant	1.5	sec
TBPOS	Real	Blade actuator deceleration time constant	.25	sec
LA1	Real	DC Motor Armature Inductance	.05	Lenrys
LA2	Real	DC Generator Armature Inductance	.05	Lenrys
GPJ	Real	Q error proportional gain to	1.	--
GIJ	Real	Q error integral proportional gain to	.5	--
GDJ	Real	Q error proportional gain to RPM	1.	--
GPJI	Real	Q error integral gain to RPM	.5	--
GCJI	Real	Q error derivative gain to RPM	0.	--
ERRQLM	Real	Feedback signal limiter	20.	
XIDB	Real	Blade pitch actuator command deadband	.02	deg

Table B-2

User Input Variables
(NAMELIST "INPUT")

DZFBHY	Real	Blade pitch actuator net hysteresis	.1	deg
DZFBDZ	Real	Blade pitch actuator net deadzone	.025	deg
GVC	Real	V-command gain	1.	--
GQC	Real	Q-command gain	1.	--
GC	Real	Manual Q-command gain	1.	--

Table B-2
User Input Variables (NAMELIST "INPUT")

NAMELIST VARIABLE	TYPE	DESCRIPTION	DEFAULT VALUE	UNITS
		(E) Operator Manual Inputs		
		(1) Level 0 Controller (Direct Manual, LEVEL C = 0)		
XICDT	Real, Vector	Table of Fan Blade Pitch Rate Commands (ten max.) (allowable values = -1., 0., +1.)	10x0	-
TXIDC	Real, Vector	Table of Times at which Respective XIDCT Commands are Applied	0., 9x1000.	sec
RF2T	Real, Vector	Table of Fan Motor Field Current Commands (ten max.)	10x12	ohms
TRF2	Real, Vector	Table of Times at which respective RF2T Commands are Applied	0., 9x1000.	sec
XICT	Real, Vector	Table of Fan Blade Pitch Angles (ten max.) (between ξ=40.9 and 98 degrees)	0., 9x1000.	degrees
TXIC	Real, Vector	Table of Times at which Respective XICT Values Apply.	0., 9x1000.	sec.

Table B-2

User Input Variables
(NAMELIST "INPUT")

DRGT	Real, Vector	Table of Test Article Drag Values	10x0.0 lbs.	
TDRG	Real, Vector	Table of Times at which Respective Drag Values Apply.	0., 9x1000.	Sec.
		(2) Level 1 Controller (Augmented, LEVEL C = 1)		
XIMANT	Real, Vector	Table of Fan Blade Pitch Rate Commands (ten max.) (allowable values = -1., 0., +1.)	10x0.	-
TXIMAN	Real, Vector	Table of Times at which Respective XIMANT Commands are Applied	0., 9x1000.	sec
DHANDT	Real, Vector	Table of Speed Control Handle Commands (ten max.) (allowable range = -1., 0., +1.)	10x0	-
TDHAND	Real, Vector	Table of Times at which Respective DHANDT Commands are Applied	0., 9x1000.	sec

Table B-3

Trim Criteria Options: Allowable Values of the NAMELIST Input Parameter IMENU

IMENU ELEMENT VALUE	Corresponding Quantity to be Nulled	
	EXPRESSION	MEANING
1	MDOTD	Tunnel mass flow acceleration
2	WFRD	Fan shaft acceleration
3	WFR1D	Synchronous generator shaft acceleration
4	WFR2D	IFC shaft acceleration
5	Spare	----
6	Spare	----
7	RPM-RPMSET	Deviation of fan RPM from set value
8	XI-XISET	Devaition of fan blade pitch angle from set value
9	PE-PESET	Deviation of synchronous motor electrical power from set value (PESET=0 implies "minimize power")
10	$\dot{M}$DOT-MDOTST	Deviation of mass flow rate from set value
11	QBARTS-QBARST	Deviation of test section $\bar{q}$ from set value
12	UTS-UTSET	Deviation of test section velocity from set value
13	Spare	----
14	DELTAD	Synchronous motor power angle rate of change
15	EQPD	Synchronous motor field voltage rate of change

Table B.4
Sample Input Data

CARD	CONTENT	REMARKS
1	NPLP = 20.,	Plot every 20th point
2	NPRP = 20.,	Print every 20th point
3	LEVEL=1, LEVELP=3	Auto. control full printout denied
4	ISETUP=2, IPLOT=1	Trim and run, make plots
5	GPJI=2., GIJI=0.2,	Set controller gains
6	MDOTIC=1081.,RPMIC=100., XIIC=67.9, RPM2IC=229.,	
7	RPMSET=100., EISET=67.9, RF1REF=10.,	
8	DRGT=0.,0.,2000.,2000.,	Drag input
9	TDRG=0.,5.,5.1,100.,	Drag input times
10	TSTOP=60.,	

COMMENTS:

1. This deck is a set-up for a drag-step input with automatic q-hold.
2. Default values are assumed for all variables not otherwise specified. In particular, the closed-circuit tunnel is used, since IOPENC=0 (default), and IFC power is used, since MODIFC=1 (default).
3. RPM2IC and RF1REF are set according to rules given in the text.

In this case, the trim routine also attempts to null the synchronous generator and IFC shaft accelerations (WFR1D and WFR2D). The selection of state 17 or 18 depends on fan RPM for trim, as discussed below.

An example input deck is presented in Table B.4. The input deck represents program setup for the following trial: IFC mode, closed-circuit tunnel, $\Omega = 100$, $\xi = 67.9°$, full printout, modified controller gains, a 2000-lb. drag step input at t = 5 sec., and 60 seconds run time.

Two items of input, RPM2IC and RF1REF require careful consideration. First, the RPM of the IFC us uniquely related to the RPM of the fans in steady state, thus, if fan RPM is specified, Ω_2 is determined. The relation is:

$$\Omega_{2\,\text{I.C.}}(RPM) \equiv RPM2IC = \frac{60}{7}\left[60 - \frac{\Omega_{FAN}(RPM)}{3}\right]$$

where $\Omega_{FAN}(RPM) \equiv$ RPMIC.

The following table gives a range of values:

RPMIC	RPM2IC
40	400
60	343
80	285
100	229
120	171
140	114
160	57

The second item, RF1REF, results from the need to specify which field resistance is being adjusted to equilibrate fan RPM. If RPM $\leq$ 100, r_{f_2} whould be adjusted, and r_{f_1} is thus fixed at 10 and state 17 is called in IMENU. If RPM > 100, r_{f_1} is adjusted, and r_{f_2} is fixed at 17.0 and state 18 is called in IMENU. This procedure derives from the field resistance curves shown in Figure 2.4-9.

B.4 PROGRAM OUTPUT

The simulation program outputs tunnel flow and motor-generator system parameters on line printers in increasing levels of detail as selected by the user via the input parameter LEVELP. Table B.5 summarizes the types of printed output obtained. Detailed description of output variables is given in Table B.6.

Table B.5
Program Output Categories

LEVEL	DESCRIPTION	NOTES
0	Basic trim (tunnel flow and M-G system states and initial conditions); output summary	
1	As above, plus all tunnel and M-G system states and parameters at specified intervals of time	Current integration interval is t = 0.025 sec. Printer and plotter output may be printed every n computation points.
2	As above, plus all tunnel flow parameters at each tunnel station at each specified interval of time.	

Table B.6
Program Output Variables

FORTRAN NAME	SYMBOL	DEFINITION
AS(i)	$a(i)$	Speed of sound at flow station i,
DRG	D	[illegible] model drag, lbs.
DM		
DELT	δ	Synchronous fan motor power angle, deg.
D1LT	δ_1	Const. speed syn. motor power angle, deg.
EDIM	E	Synchronous motor voltage, volts
EE	E_e	Synchronous motor voltage, per unit
EF	E_f	Field voltage, per unit
EQP	E'_q	Excitation voltage per unit
EA1	e_{a1}	DC motor armature voltage, volts
EA2	e_{a2}	DC generator armature voltage, volts
IF1	i_{f1}	DC motor field current, amps
IF2	i_{f2}	DC generator field current, amps
IADC	$i_{a_{DC}}$	DC motor-generator armature current, amps
IA	i_a	Synchronous machine current, per unit
MACH(i)	$M(i)$	Mach no. at flow station i
MDOT	$\dot{m}$	Airflow rate, slugs/sec.
PDOT	$\dot{P}$	Power rate, MW/min
PE	P_e	Fan motor power, per unit
PE1	P_{e_1}	Const. speed syn. motor power, per unit
PHIE	ϕ_e	Fan motor power factor angle, deg.
PHI1	ϕ_1	Const. speed syn. motor PFA, deg.
PWAT	P	Motor power, watts
PSI	ψ	Turntable yaw angle (not presently used)
PTDF	Δp^o_{FAN}	Fan total pressure rise, psf
PT1U	p^o_1	Circuit initial stagnation pressure, psf
PT(i)	$p^o(i)$	Total pressure at flow station i, pst
PTDL(i)	$\Delta p^o(i)$	Total pressure loss between station i and i-1, psf
PTLG(i)	$\Delta t_{p^o}(i)$	Total pressure equilibration lag at station i (not presently used), sec.

Table B.6
(Continued)

FORTRAN NAME	SYMBOL	DEFINITION
PS(i)	$p(i)$	Static pressure at flow station i, pst
QBTS	$\bar{q}_{TS}$	Test section dynamic pressure, psf
QE	Q_e	Electrical fan torque, per unit
QE1P	$Q^{s}_{e_1}$	Cont. speed syn. motor torque, per unit
QAER	Q_{AERO}	Fan aerodynamic torque, ft-lb.
QDC1	Q_{DC1}	DC motor torque, ft-lb.
QDC2	Q_{DC2}	DC generator toruqe, ft-lb.
QIFC	Q_{IFC}	IFC torque, ft-lb.
RPM	Ω_{FAN}	Fan RPM
RPM1	Ω_1	Const. speed syn. motor RPM
RXTO	R_{X_T}	Flow resistance, lbs. (not presently used)
RF1	r_{f_1}	DC motor field resistance,
RF2	r_{f_2}	DC generator field resistance,
RHTS	ρ_{TS}	Test section air density, slugs/ft^3
RHOS(i)	$\rho(i)$	Air static density at station i, slugs/ft^3
RHOT(i)	$\rho^{\circ}(i)$	Air stagnation density at station i, slugs/ft^3
SLIP	σ	IFC machine slip, 1-W$_{HZ}$/60
TT1U	T°_1	Circuit initial stagnation temperature, °R
TT(i)	$T^{\circ}(i)$	Stagnation temperature at flow station i, °R
TS(i)	$T(i)$	Static temperature at flow station i, °R
TTDL(i)	$\Delta T^{\circ}(i)$	Stag. temperature change from station i-1 to station i, °R.
THET	Θ	Model pitch attitude, deg. (not presently used)
U(i)	$U(i)$	Airspeed at flow station i, fps.
VF1	v_{f_1}	DC motor field voltage, volts
VF2	v_{f_2}	DC generator field voltage, volts
WFR	w_{FAN}	Fan angular velocity, rad/sec
WFR1	w_1	DC motor ang. velocity, rad/sec
WFR2	w_2	DC generator/IFC ang. velocity, rad/sec
WE	w_e	Effective fan motor power frequency, hy.
XI	ξ	Blade stagger angle, deg.
XIC	ξ_c	Commanded blade stagger angle, deg.

COMPUTER PROGRAM LISTING