REAL-TIME SIMULATION OF THE TF30-P-3 TURBOFAN ENGINE USING A HYBRID COMPUTER

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**Title and Subtitle**

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**Abstract**

A real-time, hybrid-computer simulation of the TF30-P-3 turbofan engine has been developed. The simulation is primarily analog in nature but uses the digital portion of the hybrid computer to perform bivariate function generation associated with the performance of the engine's rotating components. FORTRAN listings and analog patching diagrams are provided in the report. The hybrid simulation was controlled by a digital computer programmed to simulate the engine's standard hydromechanical control. Both steady-state and dynamic data obtained from the digitally controlled engine simulation are presented. Hybrid simulation data are compared with data obtained from a digital simulation provided by the engine manufacturer. The comparisons indicate that the real-time hybrid simulation adequately matches the baseline digital simulation.
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REAL-TIME SIMULATION OF THE TF30-P-3 TURBOFAN ENGINE
USING A HYBRID COMPUTER
by John R. Szuch and William M. Bruton
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SUMMARY

This report describes the development of a real-time hybrid-computer simulation of the Pratt & Whitney TF30-P-3 augmented turbofan engine. The simulation is intended to support research programs involving this engine.

The simulation is primarily analog in nature but does use the digital portion of the hybrid computer to perform bivariate function generation associated with modeling the performance of the engine's rotating components. The digital portion of the engine simulation requires about 10,000 words of core storage. The digital sampling interval is about 4.6 milliseconds and does allow real-time simulation of engine dynamics. Approximately 185 amplifiers and 85 multipliers are required to perform the analog calculations. FORTRAN listings and analog patching diagrams are provided in appendixes to this report.

The hybrid simulation was controlled by a general-purpose digital computer programmed to simulate the standard TF30-P-3 hydromechanical fuel and variable geometry controls. Both steady-state and dynamic data obtained from the digitally controlled engine simulation are presented. Hybrid simulation data are compared with data obtained from a digital simulation provided by the engine manufacturer. These comparisons indicate that the real-time hybrid simulation does adequately match the baseline digital simulation. The real-time simulation should, therefore, provide a valuable analytical tool for research studies involving the TF30-P-3 turbofan engine.

INTRODUCTION

Aircraft propulsion systems have become steadily more complex. With engines and inlets operating at higher levels of performance, propulsion system controls have also necessarily increased in complexity. In order to obtain maximum performance for all
flight conditions, digital control systems (ref. 1) are being considered for inlets and engines. The use of a digital computer, with its logic and memory capabilities, would provide maximum flexibility and versatility to propulsion control systems.

The development of controls for aircraft propulsion systems is facilitated by an ability to predict engine performance accurately over a wide range of operation. Computer programs for analyzing steady-state and dynamic performance of turbojet and turbofan engines have previously been developed (refs. 2 to 8). Some of these engine simulations have been expanded to include the simulation of engine controls.

In the development of digital controls for turbojet and turbofan engines, both computer simulations and experimental testing will be required to evaluate new control laws. The experimental tests can be more efficiently planned and executed if the digital control software can be tested and "debugged" by using the engine simulation. This imposes another requirement on the engine simulation. That is, the simulation must operate in "real time." The real-time requirement exists because timing and sequencing are extremely important in the development of digital control software. Also, the effects of digital sampling intervals on engine performance (ref. 9) can be predicted by using a real-time simulation.

Turbojet and turbofan engines can be simulated by using either analog (ref. 6), digital (refs. 2 to 5), or hybrid (refs. 7 and 8) computers. The real-time simulation requirement, however, limits the possible choices to the analog and hybrid computers. A purely analog simulation of a turbofan engine requires a large amount of computing equipment. Much of this equipment is needed to perform the bivariate function generation associated with modeling the engine's fan, compressor (or compressors), and turbine (or turbines). Unfortunately, analog function generation is often plagued by a lack of precision and repeatability. The precision and memory capabilities of the hybrid's own digital computer can be used to perform the required function generation, thus reducing the required amount of analog computing equipment.

This report describes the development of a real-time hybrid-computer simulation of the Pratt & Whitney TF30-P-3 augmented turbofan engine. The simulation is intended to support research programs involving this engine. The hybrid simulation was patterned after the engine manufacturer's digital simulation of the TF30-P-3 engine and was implemented on the Lewis Research Center's Electronic Associates, Inc., (EAI) Model 690 Hybrid Computing System and two EAI Model 231-R Analog Computers.

The TF30-P-3 hybrid-computer simulation was controlled by a general-purpose digital control computer (ref. 10) programmed to simulate the standard TF30-P-3 hydromechanical fuel and variable geometry controls. This digital control system was developed for on-line control of airbreathing engines during experimental testing.

Both steady-state and dynamic data obtained from the digitally controlled simulation are presented for a full range of power settings. Data were obtained at both sea level and simulated altitude conditions. Hybrid simulation data are compared with data ob-
ENGINE DESCRIPTION

The Pratt & Whitney TF30-P-3 engine (fig. 1) is an axial, mixed-flow, augmented, twin-spool, low-bypass-ratio turbofan. A single inlet is used for both the fan airflow and the engine core airflow. Airflow leaving the fan is separated into two flow streams: one stream passing through the engine core, and the other stream passing through the annular fan duct. A nine-stage low-pressure compressor includes the core portion of the three-stage fan and is connected by a through-shaft to the three-stage low-pressure turbine. A seven-stage high-pressure compressor is connected by a hollow shaft to the single-stage high-pressure turbine. A seventh-stage compressor bleed system discharges air into the fan duct at flight Mach numbers above 1.75. A 12th-stage bleed automatically discharges air into the fan duct for compressor surge control. Cooling of high-pressure and low-pressure turbine blades is accomplished by using 16th-stage compressor bleed air.

The TF30-P-3 combustor is located between the discharge of the high-pressure compressor and the inlet of the high-pressure turbine. The combustor section consists of an annular diffuser and eight combustion chambers. Each combustion chamber contains four dual-orifice fuel spray nozzles. The main fuel control meters fuel to the combustor as a function of the power lever angle PLA, the high-pressure-compressor speed \( N_H \), the fan inlet total pressure \( P_2 \) and temperature \( T_2 \), and the high-pressure-compressor discharge static pressure \( P_{s,3} \). (All symbols are defined in appendix A.) In the combustor, airflow from the compressors reacts with the injected fuel, producing high-energy gas to run the turbines.

The engine core and fan duct flow streams combine in an augmentor and are discharged through a variable-area convergent nozzle. The augmentor consists of a diffuser section and a combustion chamber. The fuel is introduced into the combustion chamber through spray rings which are arranged into five separate zones. The augmentor fuel control meters fuel to the five zones as a function of PLA, \( N_H \), \( T_2 \), \( P_{s,3} \), the nozzle area \( A_N \), and the turbine discharge total pressure \( P_6 \). The hydraulically actuated nozzle is adjusted to maintain a scheduled ratio of \( P_{s,3}/P_6 \) during augmentor operation.
ENGINE MODEL

The first step in developing an engine simulation is the formulation of an analytical model. This model, in equation form, represents the functional relations that exist between engine variables such as pressures, temperatures, and flows. In the case of the TF30-P-3 hybrid-computer simulation, the engine model should be capable of accurately predicting both steady-state and dynamic performance of the engine. Wide-range performance maps for the engine's rotating components should be included in the simulation for steady-state accuracy. Factors such as fluid momentum, mass and energy storage, and rotor inertias should be included to provide the desired transient capability.

Wherever possible, the TF30-P-3 model was patterned after the engine manufacturer's baseline digital simulation of the TF30-P-3 engine. The following sections describe the various elements which comprise the TF30-P-3 hybrid-computer simulation. Figure 2 illustrates the flow of calculations in the hybrid simulation and should help the reader in understanding the relations of the individual elements in the engine model.

Inlet

The real-time, hybrid-computer simulation of the TF30-P-3 engine does not include a dynamic simulation of an inlet. However, a steady-state representation of a typical inlet recovery is included in the simulation. The following equations are used in the hybrid simulation to calculate the total pressure \( P_2 \) and total temperature \( T_2 \) at the fan inlet from the values of \( P_0 \), \( T_0 \), and \( M_0 \) for a specified flight condition:

\[
\frac{T}{T}_I = 1 + 0.2 M_0^2 \tag{1}
\]

\[
\frac{P}{P}_I = \left(\frac{T}{T}\right)_I^{3.5} \tag{2}
\]

\[
\eta_I = \begin{cases} 
1.0 & \text{if } M_0 \leq 1.0 \\
1.0 - 0.075(M_0 - 1)^{1.35} & \text{if } M_0 > 1.0
\end{cases} \tag{3}
\]

\[
T_2 = \left(\frac{T}{T}\right)_IT_0 \tag{4}
\]

\[
P_2 = \left(\frac{P}{P}\right)_IP_0\eta_I \tag{5}
\]
There are basically two methods that can be used to model multistage fans and compressors. One method is to represent multistage fans and compressors with individual stage models (i.e., to compute pressure and temperature rises across each stage). This technique is referred to as stage stacking (ref. 6), but it requires a large computing facility when used in a total engine simulation. The method used in the real-time, hybrid-computer simulation involves the use of overall component performance maps. Interstage gas dynamics were not considered.

The TF30-P-3 three-stage fan was modeled with separate performance maps for the fan hub (core) and tip (duct) sections. Separate maps were required because of the radial pressure gradient which exists at the fan discharge at high rotor speeds.

Overall fan performance for the hub and tip sections is described by a pair of bivariate functions. In the baseline digital simulation, the fan tip pressure ratio and fan corrected speed were selected as independent variables and used to compute the total fan corrected airflow and the fan tip adiabatic efficiency. The same pair of independent variables were used to compute the fan hub pressure ratio and fan hub adiabatic efficiency.

To obtain the fan discharge temperature from efficiency requires additional calculations (including exponentiation). Because of the real-time requirement and equipment limitations, it was necessary to minimize the function generation and algebraic computations associated with modeling the fan (and compressors). Data obtained from the baseline simulation indicated that the fan hub and tip efficiency maps could be eliminated and the corresponding temperature ratios calculated as linear functions of the pressure ratios. In the TF30-P-3 hybrid-computer simulation, the fan model is described by the following equations:

\[
(\dot{w}_c)_{\text{FAN}} = f_1 \left[ \left( \frac{P_{1.3}}{P_2} \right), \left( \frac{N_L}{\sqrt{\theta_2}} \right) \right]
\]  

\[
\dot{w}_2 = \frac{(\dot{w}_c)_{\text{FAN}} \delta_2}{\sqrt{\theta_2}}
\]  

\[
(P/P)_{\text{FID}} = f_2 \left[ \left( \frac{P_{1.3}}{P_2} \right), \left( \frac{N_L}{\sqrt{\theta_2}} \right) \right]
\]

\[
P_{2.1} = P_2 (P/P)_{\text{FID}}
\]
Figure 3 contains plots of the bivariate functions representing the performance of the fan (eqs. (6) and (8)). The pressure ratios, corrected speed, and corrected airflow have been normalized by their design values. Equation (11) indicates that the 7th- and 12th-stage bleeds are assumed to enter the fan duct immediately behind the fan. The primed station designation (e.g., 1.3') refers to the entrance to the mixing volume.

Low-Pressure Compressor

Overall performance data are used to describe the TF30-P-3 low-pressure compressor (4th to 9th stages). The compressor corrected airflow and corrected speed were selected as the independent variables and were used to compute the compressor pressure ratio. As in the case of the fan, compressor temperature ratio was calculated from a linear function of pressure ratio, thus eliminating the need for generating the bivariate efficiency function. In order to better match the temperature ratio - pressure ratio relation over the range of operation, two linear functions were used for different ranges of pressure ratio.

The modeling of the low-pressure compressor was complicated by the effect of the 7th-stage bleed on the overall compressor performance. Based on information obtained from the digital simulation, the effect of the bleed on performance was represented by a shift in the compressor corrected speed used in the pressure ratio determination. The effect of bleed on efficiency (and hence, temperature ratio) was neglected in both the baseline digital and real-time hybrid simulations.

In order to compute the low-pressure-compressor corrected airflow with the 7th-stage bleed open, the following procedure was used: First, the corrected speed shift for a fully open bleed was determined from a function of the actual corrected speed. Linear interpolation was then used to determine the speed shift for a partially open
bleed. Finally, the pressure ratio was calculated from a bivariate function of the corrected airflow and shifted corrected speed.

The 7th-stage bleed flow was assumed to be proportional to the low-pressure-compressor inlet airflow and was assumed to leave the core stream at the compressor exit (station 2.2).

The TF30-P-3 low-pressure-compressor model is described by the following equations in the hybrid-computer simulation:

\[
\frac{(P/P)_{LC}}{f_3 \left( \frac{\dot{w}_{2.1}}{\delta_{2.1}} \right), \left( \frac{N_c}{M} \right)_{LC}} = \frac{P_{2.2}'}{P_{2.1}} (P/P)_{LC} 
\]

\[
T_{2.2'} = T_{2.1} \left( \frac{T}{T} \right)_{LC} 
\]

Figure 4(a) contains a plot of the bivariate function representing the low-pressure-compressor performance (eq. (14)) with the 7th-stage bleed closed. Figure 4(b) contains a plot of the corrected speed shift for the 7th-stage bleed fully open. The low-pressure-compressor map variables have been normalized by their design-point values.

High-Pressure Compressor

The mathematical treatment of the high-pressure compressor (10th to 16th stages) was quite similar to that of the low-pressure compressor. The basic difference was in the treatment of the 12th-stage bleed and its effect on the overall compressor performance. Based on information obtained from the digital simulation, the effect of the bleed
was represented by a shift in the compressor corrected flow used in the pressure ratio
determination. The 12th-stage bleed flow was assumed to leave the core stream at the
compressor exit (station 3). The cooling bleeds for the high- and low-pressure turbines
are also extracted at the high-pressure-compressor exit. These bleed flows were as-
sumed to be proportional to the high-pressure-compressor inlet airflow.

The high-pressure-compressor temperature ratio was calculated from a linear func-
tion of pressure ratio. Data from the digital simulation indicated that the slope and in-
tercept of the function were sensitive to the bleed. Therefore, the slope and intercept
were assumed to be linear functions of the percent of fully open bleed. The TF30-P-3
high-pressure-compressor model is described by the following equations in the hybrid
simulation:

\[(P/P)_{HC} = f_4 \left[ \left( \hat{\omega}_c \right)_{HC}, M', \frac{N_H}{\sqrt{\delta_{2.2}}} \right] \quad (20)\]

\[P_{3'} = P_{2.2}(P/P)_{HC} \quad (21)\]

\[\left( \hat{\omega}_c \right)_{HC, M} = \frac{\hat{\omega}_{2.2} \sqrt{\delta_{2.2}}}{\delta_{2.2}} - XBL12 f_{10} \left[ \frac{N_H}{\sqrt{\delta_{2.2}}} \right] \quad (22)\]

\[(T/T)_{HC} = (1.0322 - 0.185 XBL12) + (0.12588 + 0.08032 XBL12) (P/P)_{HC} \quad (23)\]

\[T_{3'} = T_{2.2}(T/T)_{HC} \quad (24)\]

\[\hat{\omega}_{BL12} = 0.055 XBL12 \hat{\omega}_{2.2} \quad (25)\]

\[\hat{\omega}_{BLHT} = 0.04744 \hat{\omega}_{2.2} \quad (26)\]

\[\hat{\omega}_{BLLT} = 0.01985 \hat{\omega}_{2.2} \quad (27)\]

Figure 5(a) contains a plot of the normalized bivariate function representing the high-
pressure-compressor performance (eq. (20)). This plot represents the closed-bleed
performance of the high-pressure compressor (XBL12 = 0). Figure 5(b) contains a plot
of the normalized corrected flow shift for the 12th-stage bleed fully open.
High- and Low-Pressure Turbines

In the baseline digital simulation, overall turbine performance is represented by a set of bivariate functions. For each turbine, pressure ratio and a speed parameter \( \frac{N}{\sqrt{T}} \) were used as independent variables to determine the turbine flow parameter \( \dot{w} \sqrt{T/P} \) and enthalpy drop parameter \( \Delta h/T \). Based on previous simulation experience, the digital program map outputs were normalized by the speed parameter for use in the hybrid simulation models. The TF30-P-3 turbine models are described by the following equations in the hybrid simulation:

\[
\begin{align*}
(f_p)_{HT} &= f_5 \left[ \left( \frac{P_{4.1}}{P_4} \right), \left( \frac{N_H}{\sqrt{T_4}} \right) \right] \\
\dot{w}_4 &= \frac{(f_p)_{HT} P_4 N_H}{T_4} \\
(h_p)_{HT} &= f_7 \left[ \left( \frac{P_{4.1}}{P_4} \right), \left( \frac{N_H}{\sqrt{T_4}} \right) \right] \\
(\Delta h)_{HT} &= (h_p)_{HT} \sqrt{T_4} N_4 \\
(\dot{w}T)_{4.1} &= \dot{w}_4 \left[ \frac{c_p, 4}{c_p, 4.1} T_4 - (\Delta h)_{HT} \right] + \dot{w}_{BLHT} \left[ \frac{c_p, 3}{c_p, 4.1} T_3 - \frac{K_{BWHT} (\Delta h)_{HT}}{c_p, 4.1} \right] \\
(f_p)_{LT} &= f_6 \left[ \left( \frac{P_5}{P_{4.1}} \right), \left( \frac{N_L}{\sqrt{T_{4.1}}} \right) \right] \\
\dot{w}_{4.1} &= \frac{(f_p)_{LT} P_{4.1} N_L}{T_{4.1}} \\
(h_p)_{LT} &= f_8 \left[ \left( \frac{P_5}{P_{4.1}} \right), \left( \frac{N_L}{\sqrt{T_{4.1}}} \right) \right]
\end{align*}
\]
\begin{equation}
(\Delta h)_{LT} = (hp)_{LT} \sqrt{T_{4,1} N_L}
\end{equation}

\begin{equation}
(\dot{\omega}T)_5 = \dot{\omega}T_4 \left[ \frac{c_p,4,1}{c_p,5} T_{4,1} - \frac{(\Delta h)_{LT}}{c_p,5} \right] + \dot{\omega}_{BLT} \left[ \frac{c_p,3}{c_p,5} T_3 - \frac{K_{BWLT}(\Delta h)_{LT}}{c_p,5} \right]
\end{equation}

Figures 6 and 7 contain plots of the normalized bivariate functions representing the high-pressure- and low-pressure-turbine performance (eqs. (28), (30), (34), and (35)). The constants $K_{BWHT}$ and $K_{BWLT}$ appearing in equations (32) and (37) denote the fractions of the cooling bleed flows that are assumed to do turbine work.

**Combustor, Augmentor, and Duct**

The performance of the combustor can be represented by a total pressure loss due to friction and a temperature rise resulting from the heat release from the burned fuel. The ratio of the total pressure loss to the combustor inlet pressure $P_3$ was assumed to be proportional to the square of the compressible flow parameter $\dot{\omega} \sqrt{T/P}$ at the combustor inlet. The following equation is used in the hybrid simulation to calculate the resulting combustor exit pressure:

\begin{equation}
P_{4'} = P_3 - \frac{K_B \dot{\omega}^2 T_3}{P_3} = P_3 - \frac{K_B \dot{\omega}^2 V_3}{R A W_3}
\end{equation}

The use of the stored mass $W_3$ in equation (38) results in a savings in computing equipment.

The digital program makes use of a number of bivariate functions to describe the combustor efficiency and temperature rise. Data from that simulation indicated that a simple energy balance assuming constant combustion efficiency could adequately describe the steady-state temperature rise in the combustor. The following equation is used in the hybrid simulation to describe that process:

\begin{equation}
(\dot{\omega}T)_4' = \frac{c_p,3}{c_p,4} \dot{\omega}_3 T_3 + \eta_B \frac{HVF}{c_p,4} \dot{\omega}_{F4}
\end{equation}

The specific heats $c_p,3$ and $c_p,4$, together with the efficiency $\eta_B$ and fuel heating value $HVF$, were assumed to be constant.
The TF30-P-3 augmentor was represented by two sections having separate flow streams. In the baseline digital program, a static pressure balance between the streams was assumed at the entrance to the augmentor. However, only total pressures are used in the hybrid simulation. Data from the digital simulation indicated that the total pressure ratio $P_6/P_{1.6}$ was approximately constant along selected engine operating lines. Therefore, in the hybrid simulation, the total pressure $P_5$ and $P_6$ are calculated from

$$P_5 = P_6 = K_{PR6} P_{1.6}$$

Each section of the augmentor was treated in the same way as the combustor. The fuel flow to the core augmentor section was supplied from two zones, and the duct augmentor section was fed from the remaining three zones. The following equations described the TF30-P-3 augmentor model:

$$P_7 = P_6 - K_{CAB}(\dot{w}_{4.1} + \dot{w}_{BLLT})^2 \frac{T_6}{P_6}$$

$$\left(\dot{w}T\right)_6 = \left(\dot{w}T\right)_5$$

$$\left(\dot{w}T\right)_7 = \frac{c_p, 6 (\dot{w}T)_6 + \eta_{CAB} H_{VF} \dot{w}_{F7}}{c_p, 7}$$

$$T_7 = \frac{(\dot{w}T)_7}{\dot{w}_{4.1} + \dot{w}_{BLLT} + \dot{w}_{F7}}$$

$$P_{1.7'} = P_{1.6} - \frac{K_{DAB} \dot{w}_{1.6}^2 V_{1.6}}{R_{A} W_{1.6}}$$

$$\left(\dot{w}T\right)_{1.7'} = \frac{c_p, 1.6 \dot{w}_{1.6} T_{1.6} + \eta_{DAB} H_{VF} \dot{w}_{F1.7}}{c_p, 1.7}$$

As in the combustor, the specific heats and combustion efficiencies in the augmentor were assumed to be constant.

The total pressure drop in the bypass duct was modeled in the same manner as for the combustor sections. However, no temperature rise (or drop) was assumed in the
duct. The following equations describe the hybrid simulation duct model:

\[
P_{1.6'} = P_{1.3} - \frac{K_{D}w_{1.3}^{2}V_{1.3}}{R_{A}W_{1.3}}
\] (47)

\[
T_{1.6'} = T_{1.3}
\] (48)

Exhaust Nozzle

In order to match the analytical model used in the digital simulation, the TF30-P-3 exhaust nozzle was modeled as two separate nozzles fed by the separate core and duct augmentor sections. The sum of the physical areas of the two nozzles must equal the nozzle area set by the engine control.

The standard isentropic compressible flow equations were assumed to describe the flows through the two exhaust nozzles. Because of the assumption of an instantaneous pressure balance at the entrance to the augmentor (eq. (40)), it was possible to compute the low-pressure-turbine flow (eqs. (33) and (34)) without having to depend on volume dynamics downstream of the low-pressure turbine or resort to iterative procedures. The core augmentor equations (eqs. (41) and (44)) define the conditions at the entrance to the core exhaust nozzle and allow a direct calculation of the core nozzle area.

In the nonaugmented mode, the physical exhaust nozzle area is constant. In order to provide a degree of freedom in matching digital nonaugmented data, variable flow coefficients \( C_{d,8} \) and \( C_{d,1.8} \) were assumed for the core and duct nozzles, respectively. Each flow coefficient was calculated from a linear function of its corresponding nozzle pressure ratio. The slope and intercept of each flow coefficient were adjusted to best match the digital data.

During the augmented mode, the physical nozzle area was controlled so as to maintain engine variables near their military power values. Therefore, the separate nozzle pressure ratios (and hence, flow coefficients) were nearly constant over the range of augmentation. In order to provide a degree of freedom in matching digital data during augmentation, a total nozzle flow coefficient \( C_{d,N} \) was calculated from a linear function of the physical nozzle area. The slope and intercept were adjusted to best match the digital data. The following equations describe the TF30-P-3 exhaust nozzle model:

\[
\frac{P_{0}}{(P/P)CN} = \frac{P_{0}}{P_{7}}
\] (49)
\[ A_8 = \frac{K_{CN}(\dot{w}_4.1 + \dot{w}_{BLTT} + \dot{w}_{F7})\sqrt{T_7}}{P_7 FN7 C_{d, 8}} \] (50)

\[ FN7 = \begin{cases} 
0.2588 & \text{if } (P/P)_{CN} \leq 0.53 \\
\left[\frac{P}{P}\right]_{CN}^{0.7143} \sqrt{1 - \left[\frac{P}{P}\right]_{CN}^{0.2857}} & \text{if } (P/P)_{CN} > 0.53 
\end{cases} \] (51)

\[ C_{d, 8} = 1.3625 - 0.7158(P/P)_{CN} \quad \text{where } 0.825 \leq C_{d, 8} \leq 1.0 \] (52)

\[ A_{1.8} = C_{d, N}^A_N - A_8 \quad \text{where } C_{d, N}^A_N = A_N, \text{MIN} \] (53)

\[ C_{d, N} = 1.049 - 1.622 \times 10^{-4} A_N \] (54)

\[ \dot{w}_{1.7} = \frac{C_{d, 1.8}A_{1.8}P_{1.7} FN17}{K_{DN}\sqrt{T_{1.7}}} \] (55)

\[ \frac{(P/P)_D}{P_{1.7}} = \frac{P_0}{P_{1.7}} \] (56)

\[ FN17 = \begin{cases} 
0.2588 & \text{if } (P/P)_D \leq 0.53 \\
\left[\frac{P}{P}\right]_{DN}^{0.7143} \sqrt{1 - \left[\frac{P}{P}\right]_{DN}^{0.2857}} & \text{if } (P/P)_D > 0.53 
\end{cases} \] (57)

\[ C_{d, 1.8} = 1.575 - 1.00(P/P)_D \quad \text{where } 0.825 \leq C_{d, 1.8} \leq 1.0 \] (58)

**Engine Dynamics**

The equations previously discussed describe the steady-state operation of the various engine components. However, a transient engine simulation must also consider the effects of fluid compressibility, fluid momentum, energy storage, and rotor inertias.
In the TF30-P-3 hybrid simulation, intercomponent volumes were assumed at engine locations where either (1) gas dynamics were considered to be important or (2) gas dynamics were required to eliminate the need for iterative solutions (fig. 3). Modified forms of the continuity, energy, and state equations (ref. 11) were written for each volume and solved for the stored mass, temperature, and pressure in the volume. When mixing of gases was not involved, a simple first-order lag form of the energy equation was used. The time constant for each lag was estimated to be equal to the ratio of the stored mass in the volume to the flow through the volume.

Because of the real-time requirement and the computing equipment limitations, gas properties such as specific heats were assumed to be constant over the range of engine operating temperatures and fuel-air ratios. Gas properties were adjusted at the engine design point (sea-level, static, standard-day, military power setting) to achieve the desired steady-state cycle balance. The following equations describe the intercomponent volume dynamics in the TF30-P-3 hybrid simulation:

\[
W_{2.2} = \int_0^t (\dot{w}_{2.1} - \dot{W}_{BL7} - \dot{w}_{2.2}) \, dt + W_{2.2},_i \tag{59}
\]

\[
T_{2.2} = \frac{1}{\tau_{2.2}} \int_0^t (T_{2.2} - T_{2.2}) \, dt + T_{2.2},_i \tag{60}
\]

\[
P_{2.2} = \frac{R_A W_{2.2} T_{2.2}}{V_{2.2}} \tag{61}
\]

\[
W_3 = \int_0^t (\dot{w}_{2.2} - \dot{W}_{BL12} - \dot{W}_{BLHT} - \dot{W}_{BLLT} - \dot{w}_3) \, dt + W_3,_i \tag{62}
\]

\[
T_3 = \frac{1}{\tau_3} \int_0^t (T_3 - T_3) \, dt + T_3,_i \tag{63}
\]

\[
P_3 = \frac{R_A W_3 T_3}{V_3} \tag{64}
\]

\[
W_4 = \int_0^t (\dot{w}_3 + \dot{w}_{F4} - \dot{w}_4) \, dt + W_4,_i \tag{65}
\]
\[(WT)_4 = \gamma_4 \int_0^t [(\dot{\omega} T)_4, - \dot{\omega}_4 T_4] dt + (WT)_4, i \quad (66)\]

\[T_4 = \frac{(WT)_4}{W_4} \quad (67)\]

\[P_4 = \frac{R_A(WT)_4}{V_4} \quad (68)\]

\[W_{4.1} = \int_0^t (\dot{\omega}_4 + \dot{\omega}_{BLHT} - \dot{\omega}_{4.1}) dt + W_{4.1, i} \quad (69)\]

\[(WT)_{4.1} = \gamma_{4.1} \int_0^t [(\dot{\omega} T)_{4.1}, - \dot{\omega}_4 T_{4.1}] dt + (WT)_{4.1, i} \quad (70)\]

\[T_{4.1} = \frac{(WT)_{4.1}}{W_{4.1}} \quad (71)\]

\[P_{4.1} = \frac{R_A(WT)_{4.1}}{V_{4.1}} \quad (72)\]

\[W_{1.3} = \int_0^t (\dot{\omega}_2 - \dot{\omega}_{2.1} + \dot{\omega}_{BL7} + \dot{\omega}_{BL12} - \dot{\omega}_{1.3}) dt + W_{1.3, i} \quad (73)\]

\[(WT)_{1.3} = \gamma_{1.3} \int_0^t [(\dot{\omega} T)_{1.3}, - \dot{\omega}_1 T_{1.3}] dt + (WT)_{1.3, i} \quad (74)\]

\[T_{1.3} = \frac{(WT)_{1.3}}{W_{1.3}} \quad (75)\]

\[P_{1.3} = \frac{R_A(WT)_{1.3}}{V_{1.3}} \quad (76)\]
\[ W_{1.6} = \int_0^t (\dot{w}_{1.3} - \dot{w}_{1.6}) dt + W_{1.6, i} \]  
(77)

\[ T_{1.6} = \frac{1}{\tau_{1.6}} \int_0^t (T_{1.3} - T_{1.6}) dt + T_{1.6, i} \]  
(78)

\[ P_{1.6} = \frac{R_A W_{1.6} T_{1.6}}{V_{1.6}} \]  
(79)

\[ W_{1.7} = \int_0^t (\dot{w}_{1.6} + \dot{w}_{F1.7} - \dot{w}_{1.7}) dt + W_{1.7, i} \]  
(80)

\[ (WT)_{1.7} = \gamma_{1.7} \int_0^t [(\dot{w}T)_{1.7} - \dot{w}_{1.7}T_{1.7}] dt + (WT)_{1.7, i} \]  
(81)

\[ T_{1.7} = \frac{(WT)_{1.7}}{W_{1.7}} \]  
(82)

\[ P_{1.7} = \frac{R_A (WT)_{1.7}}{V_{1.7}} \]  
(83)

The effects of fluid momentum on the TF30-P-3 engine dynamics were also included in the hybrid simulation. While these effects are primarily high frequency in nature, their inclusion in the simulation also serves to eliminate algebraic or iterative loops. The momentum equation was solved for the flow through (1) the combined fan core and low-pressure compressor, (2) the high-pressure compressor, (3) the combustor, (4) the fan duct, and (5) the duct augmentor. The following equations describe the TF30-P-3 flow dynamics:

\[ \dot{w}_{2.1} = \left( \frac{Ag_c}{l} \right)_{FID+LC} \int_0^t (P_{2.2} - P_{2.2}^l) dt + \dot{w}_{2.1, i} \]  
(84)

\[ \dot{w}_{2.2} = \left( \frac{Ag_c}{l} \right)_{HC} \int_0^t (P_3, - P_3) dt + \dot{w}_{2.2, i} \]  
(85)
\[
\dot{w}_3 = \left( \frac{Ag_c}{l} \right)_B \int_0^t (P_{4'} - P_4) dt + \dot{w}_{3, i} \tag{86}
\]

\[
\dot{w}_{1.3} = \left( \frac{Ag_c}{l} \right)_D \int_0^t (P_{1.6'} - P_{1.6}) dt + \dot{w}_{1.3, i} \tag{87}
\]

\[
\dot{w}_{1.6} = \left( \frac{Ag_c}{l} \right)_{DAB} \int_0^t (P_{1.7'} - P_{1.7}) dt + \dot{w}_{1.6, i} \tag{88}
\]

Probably the most significant factors in governing the transient behavior of a turbofan engine are the rotor moments of inertia. The rotor speeds were computed by using the conservation of angular momentum. The following equations are used in the TF30-P-3 hybrid simulation to compute the rotor speeds:

\[
(NQ)_{HT} = \frac{30J}{\pi} (\Delta h)_{HT} (\dot{w}_4 + K_{BWHT} \dot{w}_{BLHT}) \tag{89}
\]

\[
(NQ)_{HC} = \frac{30J}{\pi} \dot{w}_{2.2} (c_p, 3T_3' - c_p, 2T_2') \tag{90}
\]

\[
N_H = \frac{30}{\pi I_H} \int_0^t \left[ \frac{(NQ)_{HT} - (NQ)_{HC}}{N_H} \right] dt + N_{H, i} \tag{91}
\]

\[
(NQ)_{LT} = \frac{30J}{\pi} (\Delta h)_{LT} (\dot{w}_4.1 + K_{BWLT} \dot{w}_{BLLT}) \tag{92}
\]

\[
(NQ)_{FID+LC} = \frac{30J}{\pi} \dot{w}_{2.1} (c_p, 2T_2' - c_p, 2T_2) \tag{93}
\]

\[
(NQ)_{FOD} = \frac{30J}{\pi} (\dot{w}_2 - \dot{w}_{2.1}) (c_p, 1.3T_1.3' - c_p, 2T_2) \tag{94}
\]

\[
N_L = \frac{30}{\pi I_L} \int_0^t \frac{(NQ)_{LT} - (NQ)_{FID+LC} - (NQ)_{FOD}}{N_L} dt + N_{L, i} \tag{95}
\]
HYBRID SIMULATION

The equations describing the TF30-P-3 mathematical model were implemented by using the Lewis Research Center's Analog and Hybrid Computing Facility. The Lewis EAI Model 690 Hybrid Computing System consists of an EAI 640 Digital Computer, an EAI 693 Hybrid Interface Unit, and an EAI 680 Analog Computer. Two EAI 231-R Analog Computers were also used in this simulation.

The bulk of the calculations were performed on an EAI 680 and two 231-R Analog Computers. The analog computers perform all the operations characteristic of analog machines (i.e., summing, integration with respect to time, multiplication, attenuation, univariate function generation, etc.). The use of peripheral equipment such as x-y plotters and strip-chart recorders allows continuous monitoring by the user of computed variables. All the required analog computers can be tied together by means of a Centralized Trunk System to allow the transmittal of information between analog consoles.

The 640 Digital Computer was used primarily to perform the bivariate function generation associated with fan, compressor, and turbine performance. The digital computer also provided teletypewriter output listings of selected engine variables. In order to minimize the core storage requirements and digital cycle time, scaled-fraction variables and arithmetic routines were used in the digital program. Scaled-fraction variables are limited to values between \( \pm 1 \). The use of scaled fractions necessitates the scaling of digital variables in the same manner as the analog variables are scaled.

Figure 8 illustrates the split of the computational load between the various computers used in the TF30-P-3 real-time simulation. The split of the computational load was based on the computing equipment complement of each console and a desire to minimize trunking. The control inputs to the TF30-P-3 simulation (i.e., \( \dot{w}_{F4}, \dot{w}_{F7}, \dot{w}_{F1.7}, XBL7, XBL12, \) and \( A_N \)) were provided by an independent digital computer representation of the TF30-P-3 hydromechanical control system. That control simulation was implemented on the Lewis SEL 810B computer and is described in a separate report (ref. 10).

Digital Program

**MAIN digital program.** - The MAIN digital program performs the following tasks in the TF30-P-3 hybrid simulation: (1) reads unscaled component performance data and map scale-factor data by means of paper tape, performs the required map scaling, and stores the scaled map data in the MAP2 COMMON block which is shared with the bivariate function interpolation routine; (2) computes fan inlet conditions \( P_2 \) and \( T_2 \) from equations (1) to (5) and sets potentiometers on the analog to values corresponding to \( P_2 \),
accepts map input data from the analog by means of the analog-to-digital converters (ADC's); (4) performs the required function generation by means of calls to the bivariate function interpolation routine MAP2 (discussed in a separate section); (5) outputs map values to the analog by means of the digital-to-analog converters (DAC's); (6) provides teletype listing (if desired) of selected engine variables in both engineering and SI units. Additional ADC's are used to input analog data when obtaining teletype listings.

Appendix B contains a FORTRAN listing of the MAIN digital program and a detailed discussion of its operation. Appendix C contains a description of the required format for digital input data (component performance data). Samples of the digital data format are also provided.

**MAP2 function routine.** - Because of the nature of the fan and compressor performance maps (figs. 3, 4(a), and 5(a)), rectilinear interpolation cannot be used to generate these functions. Therefore, a radial-interpolation, bivariate-function-generation routine, MAP2, was developed at the Lewis Research Center for generating this type of function. The MAP2 routine is based on the MAPFUN routine described in reference 12. The MAP2 routine uses scaled-fraction arithmetic routines to minimize core storage requirements and execution time. Because of its favorable qualities, MAP2 was also used to perform the bivariate function generation associated with the turbine performance, although rectilinear interpolation could have been used.

Appendix D contains a FORTRAN listing of the MAP2-MAP2L function generation routine and a detailed discussion of its operation. Also included in appendix D is an assembly language listing of MAP2-MAP2L. The assembly language version was used in the real-time simulation of the TF30-P-3 engine to further reduce the execution time and core storage requirements.

The digital program (with assembly language MAP2-MAP2L) required approximately 10,000 words of core storage. The resulting digital sampling interval (with steady analog inputs) was 4.65 milliseconds.

**Analog Program**

The analog portion of the TF30-P-3 hybrid simulation performs all the required computations except the bivariate function generation previously discussed. The analog computation load is split between the 680 Analog Computer and two 231-R Analog Computers. The 680 Analog Computer also serves as the interface between the engine simulation and the SEL 810B digital control simulation. Approximately 185 amplifiers and 85 multipliers were required to perform the analog calculations.

Appendix E contains the analog patching diagrams for the TF30-P-3 hybrid simulation. For the most part, conventional analog techniques were used to implement the
engine model. Scale factors are not shown on the analog diagrams. Appendix E also contains a list of the scale factors and a list of the potentiometer settings at the design point. The following sections describe two features of the analog portion of the simulation.

**Digital-to-analog multiplier interface.** - One of the factors in determining the size (number of consoles) of an analog simulation is the complement of multipliers on each machine. On the 680 Analog Computer, a total of 24 multiuse multipliers are available. These multipliers may be used to multiply, divide, square, or take the square root. As a supplement to the multipliers, the 680 also has six digital-to-analog multipliers (DAM's) which allow a digitally supplied variable to be multiplied by an analog variable with the product appearing on the analog console. Each additional product is obtained at the cost of two DAC channels which may not be used as conventional DAC's. Appendix E contains a list of the products obtained with the DAM feature in the TF30-P-3 real-time simulation.

**Analog function generation.** - In order to decrease the digital sampling interval, the univariate function generation associated with the low- and high-pressure-compressor bleeds (figs. 4(b) and 5(b)) was performed on the 680 Analog Computer. Two 10-segment, variable-diode function generators (VDFG's) were used. The map input variables \((N_c)_{LC, M}\) and \((\dot{w}_c)_{HC, M}\) were computed on the analog from equations (16) and (22), respectively, and transmitted to the digital by ADC's.

Two 10-segment, fixed-diode function generators (FDFG's) were used on the 231-R Analog Computers to calculate the core and duct nozzle compressible flow functions \(FN7\) and \(FN17.\) These functions (eqs. (51) and (57)) assume a constant specific-heat ratio \(\gamma\) of 1.4.

**RESULTS AND DISCUSSION**

**Steady State**

The TF30-P-3 hybrid simulation with digital control was evaluated over a range of steady-state operating conditions. The purpose of the steady-state evaluation was to test the various curve fits and assumptions in the hybrid model.

With the simulation operating at the sea-level, standard-day, static, military power point, excursions along the operating line were made by ramping the PLA signal to a desired power setting. After the transient settled out, a steady-state listing of selected variables was obtained at the teletype. Table I contains the teletype data for the sea-level, static operating line for power settings of 15° (idle), 70°, and 120° (full augmentation).
Figure 9 contains plots of a number of the hybrid-computer-simulated engine variables over the range of power settings. For comparison, the corresponding values obtained from the baseline digital program were also plotted. In order to better match the digital data at the very low power settings, the 12th-stage bleed opening (XBL12) was limited to 70 percent of its fully open value (table I(a)).

Figure 9 shows good agreement between hybrid and digital data at PLA's above 30°. Below 30°, discrepancies occurred in the sensitivities of rotor speeds and compressor discharge pressure to the power lever angle. For power lever angles below 30°, the hybrid-computer-simulated fuel flow exceeded the baseline digital value. This resulted in discrepancies in rotor speeds, temperatures, and so forth, for this range of power lever angles. However, because of the nature of the control design, errors in the engine variables can also cause errors in control outputs such as fuel flow. The observed differences in fuel flow, rotor speeds, and compressor discharge pressure were probably due to inaccuracies in the engine model at the low power settings.

Since almost all the previously discussed assumptions were based on sea-level, static, operating-line data, it was decided to evaluate the steady-state performance of the hybrid simulation at a different flight condition. The steady-state data acquisition was repeated for a 6.096-kilometer (20,000-ft), Mach 1.2 flight condition. For this flight condition, the 12th-stage bleed was closed for the entire operating line, and its effect on the compressor performance need not be considered. The fan inlet conditions for this flight condition were computed by the digital program and were \( P_2 = 11.205 \text{ N/cm}^2 (16.252 \text{ psia}) \) and \( T_2 = 320.25 \text{ K} (576.45^\circ \text{ R}) \). Table II and figure 10 contain the teletype listings and comparison plots for this flight condition.

For this flight condition, excellent agreement between hybrid and digital data was observed at the low power settings. Some discrepancies were observed in the range of power lever angles between 45° and 69°. Some unexplained irregularities were observed in the digital values of \( P_s, 3, T_4, \dot{w}_2, \) and \( N_L \) in this range of power settings. In general, however, the same basic trends were observed in both the hybrid and digital data.

Other discrepancies were observed in the augmentation range of PLA between 110° and 120°. In the digital model, the nozzle area reached its maximum value only at a PLA of 120°, while in the hybrid model the area was near its maximum at 110°. This contributes to the observed differences in augmentor fuel flow since these control outputs are correlated in the digital control.

The general agreement of hybrid and digital data shown in figures 9 and 10 substantiates the assumptions of (1) constant combustor efficiency, (2) linear pressure ratio-temperature ratio relations, and (3) pressure-sensitive flow coefficients for the core and duct nozzles. The agreement of hybrid and digital data also substantiates the fan and compressor models used in the real-time simulation.

The observed discrepancies at low power settings can be compensated for by manipulation of the compressor bleeds (if applicable). Perhaps a more satisfactory solution to
the problem of matching steady-state data at low power settings is to implement variable specific heats $c_p$ at the compressor discharge stations. Experience with similar simulations indicates that linear $c_p$-T relations, used only in the load torque calculations (eqs. (90) and (93)) have strong effects on the speed split at low power settings and can be "tuned" to match low-power-setting data. This problem is eliminated completely in the simulation described in reference 7, where all fluid properties are assumed to be variable. Unfortunately, the necessary computing equipment and computing time were not available to do this in this simulation.

The use of digitally implemented bivariate functions in the hybrid simulation did result in a better wide-range match of steady-state data than previously obtained by the authors in all-analog simulations.

Transients

The TF30-P-3 hybrid simulation with digital control was evaluated for power lever slams (rapid increases) and chops (rapid decreases) between idle and military power settings and also between military power and full-augmentation power settings. Transients were run only for sea-level, standard-day, static conditions. Data obtained with the hybrid simulation were compared with the corresponding baseline digital data. The power lever angle signal was ramped from its initial value to its final value at a rate corresponding to 125 degrees per second. Selected analog variables were recorded by using strip-chart recorders. Details of the TF30-P-3 control simulation are contained in reference 13.

The simulation was operated at the idle power setting ($PLA = 15^\circ$). Table I(a) lists steady-state values for selected engine variables at that operating point. The power lever angle was then ramped to a value ($67^\circ$) slightly below the military power setting ($69^\circ$). The $2^\circ$ margin in power lever angle was chosen so as not to inadvertently initiate augmentation.

Figure 11 shows the response of selected engine variables to this throttle slam. Also shown are the corresponding baseline digital simulation variables. The power lever angle reached its final value in approximately 0.4 second. Significant increases in the combustor fuel flow (commanded by the digital control) were not seen until about 0.7 second into the transient.

The digital simulation of the fuel control (ref. 13) includes a secondary fuel manifold fill-drain calculation. The filling of the manifold was initiated when the commanded fuel flow reached 0.1260 kilogram per second, which is approximately equal to the sea-level, static, idle fuel flow. The manifold was filled when the commanded fuel flow reached 0.1638 kilogram per second. When the manifold was filled, the commanded fuel flow reached the engine without the lag associated with the fill dynamics. Figure 11 in-
icates that the manifold filling took 0.7 second in the hybrid simulation and 1.0 second in the digital simulation. This time difference was a result of the fuel flow differences caused by the discrepancies in the engine models at the low power settings.

Comparison with digital data indicates that the hybrid simulation variables responded more rapidly to the PLA slam. The differences in the $T_4$, $P_{s,3}$, and $N_H$ responses were caused by the differences in fuel flow supplied by the control.

The 12th-stage bleed doors which are open at the idle condition are closed during the acceleration when the low-pressure-compressor discharge static pressure exceeds $1.481 P_2 + 6.254 \text{ N/cm}^2$. Figure 11 shows that the hybrid simulation bleed doors closed approximately 0.6 second before the digital simulation bleed doors. This was due to the faster response of $P_{s,2.2}$ in the hybrid simulation.

The nozzle area was at its maximum value at the static, idle condition. It was reduced to its minimum value (fig. 11(e)) by the digital control at a rate consistent with the baseline digital simulation.

The hybrid simulation was operated at the PLA = 67° condition. A throttle slam was then run with the PLA signal ramped to 120° at the same 125-degree-per-second rate. Table I(c) lists steady-state engine variables at the full-augmentation condition. Figure 12 shows the resulting response of selected engine variables to this throttle slam. Also shown are the corresponding baseline digital variables. The fuel flows to the five augmentor zones are metered as functions of PLA, $N_H$, $T_2$, and $P_{s,3}$. The nozzle area is increased by the digital control so as to maintain a scheduled ratio of $P_{s,3}/P_6$ during the augmentor operation. This maintains all engine variables upstream of the augmentor approximately constant at their military power values.

Figure 12 indicates that the timings of the zone fuel flow initiations in the hybrid and digital simulations are in general agreement. Differences of 0.1 to 0.2 second were observed, except for zone 4. Zone 4 fuel flow came on about 0.5 second early apparently because of an incorrect hold calculation in the simulated augmentor control. This hold was intended to represent the time required to fill the zone 4 manifold.

Figure 12(h) shows agreement between the nozzle area responses. The same 0.1- to 0.2-second delay for the digital response was observed. The agreement in the area responses indicates that the augmentor inlet and high-pressure-compressor discharge pressure dynamics are approximately the same in the hybrid and digital simulations.

Figures 13 and 14 contain the hybrid and baseline digital engine responses to throttle chops from PLA = 120° to PLA = 67° and from PLA = 67° to PLA = 15°, respectively. Figure 13 shows agreement between the hybrid and baseline digital results for full augmentation to military chop. The timings of zone fuel flow shutoffs and the magnitudes of the selected engine variables are in agreement. Figure 13(i) does show slightly less damping in the hybrid simulation's response of $P_6$.  

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Figure 14 shows excellent agreement between the hybrid and baseline digital results for the military-to-idle chop. The response of fuel flow (and hence, $P_{s,3}$ and $T_4$) agrees since the line fill problem that existed for the corresponding acceleration does not exist at the start of the deceleration. This results in excellent agreement in the opening of the 12th-stage bleed when $P_{s,2,2} = 1.543P_2 + 6.495 \text{ N/cm}^2$. The response of the temperature $T_4$ to the throttle chops and slams was obtained by decreasing the gain of the $(WT)_4$ integrator (eq. (66)) by a factor of 25. This was necessary to match the baseline digital response and was an attempt to represent heat-transfer effects in the combustor. These effects were considered in the baseline digital program but were not included in the hybrid model.

**Frequency Responses**

A comparison of the hybrid and baseline digital engine dynamics (independent of the control) can be accomplished by opening the loops between the engine and the engine control. This was done with the hybrid simulation at the sea-level, static, $\text{PLA} = 50^\circ$ operating point. A constant combustor fuel flow was supplied to the engine with the 12th-stage bleed closed and the nozzle area at its minimum value. A sinusoidal fuel flow signal was superimposed on the constant fuel flow signal, resulting in sinusoidal oscillations in engine variables such as rotor speeds and pressures. The amplitude of the driving signal was $\pm 10$ percent of the constant input fuel flow. Both the driving signal and a selected output signal were input to an analog transfer function analyzer which calculated the amplitude ratio and the phase angle between the two signals.

Figures 15 to 17 contain the frequency responses of the high-pressure-rotor speed, the high-pressure-compressor discharge static pressure, and the core augmentor inlet pressure, respectively, to fuel flow perturbations. Also plotted are the results from a similar procedure using the baseline digital simulation and a digital transfer function analyzer. The digital transfer function analyzer could not perform adequately above 1.3 hertz because of low signal levels. The analog transfer function analyzer had provisions for increasing the signal levels at the higher frequencies, allowing analysis to 10 hertz.

Figure 15 shows general agreement between the hybrid and digital responses of $N_H$. Since the low-frequency dynamics are caused primarily by rotor inertia, agreement in the dynamics indicates that the rotor dynamics have been adequately modeled in the hybrid simulation. The observed difference in the steady-state gain (normalizing factor) would seem to indicate a discrepancy in the steady-state engine models. However, the steady-state digital data presented in figures 9(a) and (b) show a sensitivity
of 0.992 rpm/(kg/hr), which is close to the value obtained from the hybrid simulation data. Therefore, errors in the digital analyzer results are suspected.

Figure 16 shows the frequency response of the high-pressure-compressor discharge static pressure. Significant differences were observed in both the steady-state gain and the dynamics. The hybrid data show a break frequency around 2 hertz with higher order dynamics above 1 hertz. The higher frequency dynamics may be attributable to the inclusion of combustor momentum effects in the combustor. The digital response is flat with increasing phase lag, characteristic of a dead time. A study of the transient response of $P_s,3$ to the PLLA chop from $67^0$ to $15^0$ (fig. 14) shows a lag rather than a dead time between $P_s,3$ and $\dot{w}_{F4}$. Again, errors in the digital analysis are suspected.

Figure 17 compares the hybrid and digital responses of $P_6$ to the $\dot{w}_{F4}$ oscillations. Agreement in the steady-state gain was observed. The dynamics were in general agreement in the low-frequency range. However, the hybrid data show a resonant condition at about 3 hertz. The digital data indicate a similar condition above 1 hertz, but the inability of the digital analyzer to function above 1.3 hertz prevented a real comparison in that frequency range. The observed resonant condition may be attributable to duct dynamics since the pressure $P_6$ is assumed to be proportional to the duct augmentor pressure $P_{1.6}$.

**CONCLUDING REMARKS**

A real-time hybrid simulation of the TF30-P-3 turbofan engine has been developed. The simulation is primarily analog in nature but does use the digital portion of the hybrid computer to perform bivariate function generation associated with modeling the performance of the engine's rotating components. The digital sampling interval is approximately 4.6 milliseconds and does allow real-time simulation without compensation for the phase lag caused by the digital sample-and-hold process.

The hybrid simulation was based on the engine model used in a baseline digital simulation provided by the engine manufacturer. Differences between the hybrid and digital models were dictated by the real-time requirement. The hybrid model assumes constant fluid properties and combustor efficiencies to minimize analog equipment requirements. The hybrid model also includes momentum effects in the compressors and combustors which allow the use of flow as an input to the compressor performance maps without the need for iteration.

Results from the hybrid and digital simulations were compared. These comparisons indicated that the real-time hybrid simulation does adequately match the baseline digital
simulation for both steady-state and dynamic conditions. Discrepancies at low power settings did result in faster hybrid responses for accelerations from idle to military power. These discrepancies could be minimized by considering the effects of variable specific heats on the engine balance at low power settings.

The real-time hybrid simulation provides a valuable analytical tool for research studies involving the TF30-P-3 turbofan engine. In particular, digital controls may be developed and tested on the simulation prior to actual engine testing. Transient data obtained with the hybrid simulation and a digital control are presented. These data indicate that the simulation does provide a realistic test vehicle for the control. In fact, the generation of the data presented did result in the discovery of a number of "bugs" in the control which might otherwise have gone undetected.

Lewis Research Center,
National Aeronautics and Space Administration,
Cleveland, Ohio, July 8, 1974,
## APPENDIX A

### SYMBOLS

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>cross-sectional area, cm$^2$ (in.$^2$)</td>
</tr>
<tr>
<td>$C_d$</td>
<td>nozzle flow coefficient</td>
</tr>
<tr>
<td>$c_p$</td>
<td>specific heat, J/kg-K (Btu/lbm-°R)</td>
</tr>
<tr>
<td>$d_t$</td>
<td>time increment, sec</td>
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<tr>
<td>FN7</td>
<td>core nozzle flow function</td>
</tr>
<tr>
<td>FN17</td>
<td>duct nozzle flow function</td>
</tr>
<tr>
<td>$f_i$</td>
<td>general function, $i = 1, 10$</td>
</tr>
<tr>
<td>$f_p$</td>
<td>flow parameter, kg-K-cm$^2$/N-rpm-sec (lbm-°R-in.$^2$/lbf-rpm-sec)</td>
</tr>
<tr>
<td>$g_c$</td>
<td>gravitational conversion factor, 100 cm-kg/N-sec$^2$ (386.3 lbm-in./lbf-sec$^2$)</td>
</tr>
<tr>
<td>HVF</td>
<td>heating value of fuel, J/kg (Btu/lbm)</td>
</tr>
<tr>
<td>$\Delta h$</td>
<td>enthalpy drop, J/kg (Btu/lbm)</td>
</tr>
<tr>
<td>$h_p$</td>
<td>enthalpy drop parameter, J/kg-K$^{1/2}$-rpm (Btu/lbm-°R$^{1/2}$-rpm)</td>
</tr>
<tr>
<td>$I$</td>
<td>polar moment of inertia, N-cm-sec$^2$ (in.-lbf-sec$^2$)</td>
</tr>
<tr>
<td>$J$</td>
<td>work conversion factor, 100 N-cm/J (9339.6 in.-lbf/Btu)</td>
</tr>
<tr>
<td>$K$</td>
<td>constant (appropriate units)</td>
</tr>
<tr>
<td>$l$</td>
<td>length, cm (in.)</td>
</tr>
<tr>
<td>$M$</td>
<td>Mach number</td>
</tr>
<tr>
<td>m</td>
<td>second function map index, $m = 7$ to 12</td>
</tr>
<tr>
<td>N</td>
<td>rotor speed, rpm</td>
</tr>
<tr>
<td>n</td>
<td>first function map index, $m = 1$ to 6</td>
</tr>
<tr>
<td>P</td>
<td>total pressure, N/cm$^2$ (psia)</td>
</tr>
<tr>
<td>$P/P$</td>
<td>pressure ratio</td>
</tr>
<tr>
<td>PLA</td>
<td>power lever angle, deg</td>
</tr>
<tr>
<td>$Q$</td>
<td>torque, N-cm (in.-lbf)</td>
</tr>
<tr>
<td>$R_A$</td>
<td>gas constant of air, N-cm/kg-K (in.-lbf/lbm-°R)</td>
</tr>
<tr>
<td>T</td>
<td>total temperature, K (°R)</td>
</tr>
<tr>
<td>$T/T$</td>
<td>temperature ratio</td>
</tr>
</tbody>
</table>
V \quad \text{volume, } \text{cm}^3 \text{ (in.}^3\text{)}

W \quad \text{stored mass, } \text{kg (lbm)}

\dot{W} \quad \text{mass flow rate, } \text{kg/sec (lbm/sec)}

\text{XBL7} \quad \text{fraction of 7th-stage bleed}

\text{XBL12} \quad \text{fraction of 12th-stage bleed}

\text{XI} \quad \text{ADC channel I input, } I = 0, 23

\text{XSC} \quad \text{scale factor on } x \text{ map input}

x \quad x \text{ input to bivariate map (normalized by design-point value)}

x_j \quad \text{array of } x \text{ inputs for } j^{\text{th}} \text{ value of } y \text{ input, } j = 1, 8

\text{YI} \quad \text{DAC channel I input, } I = 0, 23

\text{YSC} \quad \text{scale factor of } y \text{ map input}

y \quad y \text{ input to bivariate map (normalized by design-point value)}

\text{ZSC(1)} \quad \text{scale factor on first function of } x \text{ and } y

\text{ZSC(2)} \quad \text{scale factor on second function of } x \text{ and } y

z_1 \quad \text{first function of } x \text{ and } y \text{ (normalized by design-point value)}

z_2 \quad \text{second function of } x \text{ and } y \text{ (normalized by design-point value)}

z_{1j} \quad \text{array of first function outputs for } j^{\text{th}} \text{ value of } y, j = 1, 8

z_{2j} \quad \text{array of second function outputs for } j^{\text{th}} \text{ value of } y, j = 1, 8

\gamma \quad \text{specific-heat ratio}

\delta \quad \text{total pressure (normalized by sea-level value)}

\eta \quad \text{efficiency}

\theta \quad \text{total temperature (normalized by standard-day value)}

\tau \quad \text{time constant, sec}

\text{Subscripts:}

\text{B} \quad \text{combustor}

\text{BLHT} \quad \text{high-pressure-turbine bleed}

\text{BLLT} \quad \text{low-pressure-turbine bleed}

\text{BL7} \quad 7\text{th-stage bleed}

\text{BL12} \quad 12\text{th-stage bleed}

\text{BWHT} \quad \text{portion of high-pressure-turbine bleed doing work}

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BWLT  portion of low-pressure-turbine bleed doing work
CAB  core augmentor
CN  core nozzle
c  corrected to inlet conditions
D  duct
DN  duct nozzle
F  fuel
FAN  total fan
FID  fan hub section
FID+LC  fan hub and low-pressure compressor
FZ1  augmentor zone 1
FZ2  augmentor zone 2
FZ3  augmentor zone 3
FZ4  augmentor zone 4
FZ5  augmentor zone 5
FOD  fan tip section
H  high speed
HC  high-pressure compressor
HT  high-pressure turbine
I  inlet
i  initial condition
L  low speed
LC  low-pressure compressor
LT  low-pressure turbine
M  map
MIN  minimum value
N  total nozzle
PR6  core-duct pressure ratio
s  static
0  ambient
1.3 fan tip discharge
1.6 duct augmentor inlet
1.7 duct nozzle inlet
1.8 duct nozzle throat
2 fan inlet
2.1 fan hub discharge
2.2 low-pressure-compressor discharge
3 high-pressure-compressor discharge
4 high-pressure-turbine inlet
4.1 low-pressure-turbine inlet
5 low-pressure-turbine discharge
6 core augmentor inlet
7 core nozzle inlet
8 core nozzle throat

Superscript:
( )' inlet to mixing station

FORTRAN symbols - MAIN program:
AN total nozzle area, in.\(^2\)
ANSI total nozzle area, m\(^2\)
ETAI inlet efficiency
I integer
IERR error flag for linkage routines
IX array containing number of points per curve for each map pair
J integer
JX map scaling index
JY array containing number of curves for each map pair
JZ1 map scaling index
JZ2 map scaling index
KX array containing \(x\) out-of-range counts for each map pair
KY array containing \(y\) out-of-range counts for each map pair
30
M integer
MAP2 bivariate function (first function)
MAP2L bivariate function (second function)
MM function relay address
M0 Mach number
N map index
NCV number of curves for map being read in
NTBL number of data points for map being read in
NX number of points per curve for map being read in
NY number of curves for map being read in
PADR array of addresses of digitally set potentiometers
PLA power lever angle, deg
PS22 low-pressure-compressor discharge static pressure, psia
PS22SI low-pressure-compressor discharge static pressure, N/cm²
PS3 high-pressure-compressor discharge static pressure, psia
PS3SI high-pressure-compressor discharge static pressure, N/cm²
PVAL array of settings for digitally set potentiometers
P0 ambient pressure, psia
P0SI ambient pressure, N/cm²
P2 fan inlet pressure, psia
P2Q0 inlet pressure ratio
P2SI fan inlet pressure, N/cm²
P3Q22 high-pressure-compressor pressure ratio
QRBADS linkage routine for reading ADC's
QSHYIN linkage routine for console selection
QSRUN linkage routine for setting logic mode
QSSECF linkage routine for setting time scale
QSTDAl linkage routine for transferring DAC contents
QWBDAS linkage routine for loading DAC registers
QWFRL linkage routine for setting function relays
QWPR linkage routine for setting potentiometers
SENSW logical array for testing sense switches
T0 ambient temperature, \( ^{\circ}R \)
T0SI ambient temperature, K
T2 fan inlet temperature, \( ^{\circ}R \)
T2QO inlet temperature ratio
T2SI fan inlet temperature, K
T22 low-pressure-compressor discharge temperature, \( ^{\circ}R \)
T22SI low-pressure-compressor discharge temperature, K
T3 high-pressure-compressor discharge temperature, \( ^{\circ}R \)
T3SI high-pressure-compressor discharge temperature, K
T4 high-pressure-turbine inlet temperature, \( ^{\circ}R \)
T4SI high-pressure-turbine inlet temperature, K
T6 core augmentor inlet temperature, \( ^{\circ}R \)
T6SI core augmentor inlet temperature, K
VALS array containing unscaled, normalized map data
VI potentiometer settings, I = 1, 3
WA2 fan airflow, lbm/sec
WA2SI fan airflow, kg/sec
WAR2 fan corrected airflow, lbm/sec
WAR22M low-pressure-compressor map corrected airflow, lbm/sec
WF4 combustor fuel flow, lbm/sec
WF4SI combustor fuel flow, kg/sec
WF7 core augmentor fuel flow, lbm/sec
WF7SI core augmentor fuel flow, kg/sec
WF17 duct augmentor fuel flow, lbm/sec
WF17SI duct augmentor fuel flow, kg/sec
WR22SI low-pressure-compressor corrected airflow, kg/sec
XI ADC input variables, I = 0, 23
XNH high-pressure-rotor speed, rpm
XNL  low-pressure-rotor speed, rpm
XNLR2 fan corrected speed, rpm
XSC  scale factor for x breakpoints on map being read in
XVALS array containing scaled x breakpoints for each map pair
YI  array containing DAC initial conditions
YI_ DAC output variables, I = 0, 23
YSC  scale factor for y breakpoints on map being read in
YVALS array containing scaled y breakpoints for each map pair
ZSC(1) scale factor for first function in map pair being read in
ZSC(2) scale factor for second function in map pair being read in
ZVALS array containing scaled map outputs for each map pair

FORTRAN symbols - MAP2 (MAP2L) function routine:

I  index for x breakpoints
IX  array of last search indices for x breakpoints
J  index for y curves
JY  array of last search indices for y curves
KX  array of x out-of-range counts
KY  array of y out-of-range counts
MAP2  bivariate function (first function)
MAP2L bivariate function (second function)
N  map index
NX  array of number of points per curve
NXP number of points per curve for map being read
NY  array of number of curves per map
NYC number of curves for map being read
XFRAC fractional location of XIN between XLO and XHI
XHI  \((I + 1)^{th}\) breakpoint on inferred YIN curve
XIN  x input to map
XLO  \(1^{st}\) breakpoint on inferred YIN curve
XVALS array of scaled x breakpoints for each map pair
YIN  y  input to map
YINCR  fractional location of YIN between $J^{th}$ and $(J+1)^{th}$ curves
YVALS  array of scaled y breakpoints for each map pair
ZL  map output for XLO, YIN inputs
ZR  map output for XHI, YIN inputs
ZVALS  array of scaled map outputs for each map pair
APPENDIX B

MAIN DIGITAL PROGRAM - DESCRIPTION AND FORTRAN LISTING

Description

The primary function of the MAIN digital program is to read the bivariate function input variables on the ADC channels, to call the function generation routine MAP2, and to transfer updated function output variables to the analog computer through the DAC channels.

The MAIN digital program and the function generation routine MAP2 are capable of handling as many as six pairs of bivariate functions, with each function described by as many as eight curves and 10 points per curve. A COMMON block MAP2 is shared by the MAIN digital program and MAP2 (see FORTRAN listings). This COMMON block contains arrays for function data XVALS, YVALS, and ZVALS; search indices IX and JY; argument dimensions NX and NY; and out-of-range counters KX and KY.

The MAIN digital program reads the unscaled, but normalized, component performance data and associated scale factors and stores the data in the VALS array. Appendix C contains samples of the required format for reading the data. The data in the VALS array are divided by the appropriate scale factor; and the results are stored in the XVALS, YVALS, and ZVALS arrays. The search indices and out-of-range counters are initialized, and the argument dimensions are stored in the NX and NY arrays. The functions of the search indices and out-of-range counters are discussed in appendix D.

After scaling and storing the component performance data, the MAIN digital program reads scaled-fraction DAC initial-condition data. These data are stored in the YI array. By initializing the DAC's with specified values, the user can check the analog portion of the simulation prior to entering the digital computation loop. Appendix C contains a sample of the required format for the DAC initial condition data. Unused DAC's are initialized to zero.

Table III lists the scaled variables and associated DAC channels which are transmitted to the EAI 680 Analog Computer by the MAIN digital program. Since the desired initial condition corresponds to the engine design point, the initial values of the scaled map outputs should be equal to the inverse of the map output scale factors.

After initializing the DAC's, the MAIN digital program reads, from the teletype, unscaled values for the variables $P_0$, $T_0$, and $M_0$. The program calculates analog potentiometer settings corresponding to the variables $P_2$, $T_2$, and $P_0$ for the specified flight condition. The analog portion of the simulation is discussed in appendix E. The potentiometers to be set by the digital computer are specified as input data by means of paper tape. The format used for this data input is illustrated in appendix C.
The main computation loop in the MAIN digital program starts at statement 30. At this point, the required analog data are read from the appropriate ADC’s and stored in the locations specified by the arguments used in the call to the QRBADS linkage routine. These arguments indicate that a total of 10 ADC’s are to be read, starting with ADC0. The contents of these ADC’s are to be stored sequentially in the locations reserved for the variables listed in the SCALED FRACTION declaration, starting with the variable X0.

Table IV lists the ADC’s and the associated scaled input variables received from the EAI 680 Analog Computer. The scale factors associated with the map inputs are equal to the products of the design-point values and the XSC (or YSC) scale factors specified with the map data. For example, at the design point, ADC channel 5 receives a scaled signal equal to 1.0/1.9045, or 0.52507.

The MAIN digital program then calls the function generation routine MAP2 with the appropriate input variables. The calling statement is of the form:

\[ z_1 = \text{MAP2}(n, x, y) \]

The scaled map output values returned by MAP2 are transferred through the DAC channels to the analog computer. For certain of the functions, another called statement \( z_2 = \text{MAP2L}(m) \) is used. The reason for using a different calling statement is discussed in appendix D.

After the DAC variables in table III are transferred, a sense switch on the 640 control console is tested to determine if additional data are to be input from the analog. If the sense switch is depressed (analog should be in "HOLD" mode), the ADC channels listed in table V are read. Before teletype listing, the variables to be listed are unscaled to allow listing with both engineering and SI units. After teletype listing, the program returns to statement 30, where updated ADC’s are read.

FORTRAN Listing

```fortran
DIMENSION VALS(248),ZSC(2),PADR(3),PVAL(3)
C*****ADC VARIABLES
SCALED FRACTION X0,X1,X2,X3,X4,X5,X6,X7,X8,X9,X10,X11,X12,X13,
1 X14,X15,X16,X17,X18,X19,X20,X21,X22,X23
C*****DAC VARIABLES
SCALED FRACTION Y4,Y5,Y6,Y7,Y8,Y9,Y10,Y11
C*****OTHER VARIABLES
SCALED FRACTION XVALS(11,8,6),YVALS(8,6),ZVALS(11,8,12),YI(24),
1 MAP2,MAP2L,V1,V2,V3,SSQT
COMMON/MAPS/XVALS,YVALS,ZVALS,IX(6),JY(6),NX(6),NY(6),XX(6),KY(6)
LOGICAL SENSEW
REAL MO
```
C*****INPUT REAL COMPONENT MAP DATA AND SCALE FACTORS
  TYPE I
  1 FORMAT(/3X,5AHPLACE DATA TAPE FOR MAPS NO. 1-R IN HSPTR. THEN R-S-
   1R./)
  PAUSE
  DO 1 N=1,4
  READ(4,3) XSC,YSC,ZSC(1)
  3 FORMAT(4F11.4)
  IF(N-4) 4,5,5
  4 NCV=8
  GO TO 6
  5 NCV=7
  6 NTBL=17*NCV
  READ(4,7)(VALS(I),I=1,NCV)
  7 FORMAT(8FR,2)
  J=NCV+1
  READ(4,8)(VALS(I),I=J,NTBL)
  8 FORMAT(8FR,4)
C*****SCALE COMPONENT MAP DATA
  DO 9 J=1,NCV
  DO 9 I=1,6
   YVALS(J,N)=VALS(J)/YSC
   JX=NCV+2*((J-1)*R+I)-1
   XVALS(I,J,N)=VALS(JX)/XSC
  9 ZVALS(I,J,N)=VALS(JX+1)/ZSC(1)
  IX(N)=1
  JY(N)=1
  NX(N)=8
  NY(N)=NCV
  KX(N)=6
  KY(N)=6
  10 CONTINUE
  NCV=8
  NTBL=NCV*31
  DO 13 N=5,6
  READ(4,3) XSC,YSC,ZSC(1),ZSC(2)
  READ(4,11)(VALS(I),I=1,NCV)
  J=NCV+1
  READ(4,12)(VALS(I),I=J,NTBL)
  11 FORMAT(10FR,4)
  DO 12 J=1,NCV
  DO 12 I=1,10
   YVALS(J,N)=VALS(J)/YSC
   JX=NCV+3*((J-1)+I)
   XVALS(I,J,N)=VALS(JX)/XSC
   JZ1=JX+I
   ZVALS(I,J,N)=VALS(JZ1)/ZSC(1)
   JZ2=JX+2*I
   ZVALS(I,J,N+2)=VALS(JZ2)/ZSC(2)
  12 CONTINUE
  IX(N)=1
  JY(N)=1
  NX(N)=10
  NY(N)=NCV
  13 CONTINUE
C*****INITIALIZE DACS
  TYPE 14
  14 FORMAT(/3X,5AHPLACE DATA TAPE FOR DAC INITIAL CONDITIONS IN HSPTR.)
I THEN R-S-R./
PAUSE
READ(4,15)(YI(I),I=1,24)
15 FORMAT(5SR)
C*****INITIALIZE ANALOG CONSOLE
CALL QSHYIN(IERR,6R0)
CALL QRSRUN(IERR)
CALL QSERCF(IERR)
DO 200 M=1,24
MM=5*M-1
CALL QWFRL(MM,.FALSE.,IERR)
200 CONTINUE
C*****TRANSFER INITIAL DAC VALUES
CALL QWBDAS(YI,8,24,IERR)
CALL QSTDA
C*****SPECIFY OPERATING CONDITIONS FOR
TYPE I
16 FORMAT(/5X,33HTYPE DESIRED VALUES FOR P0,T0,M0,/
ACCEPT 17,P0,T0,M0
17 FORMAT(F7.3,F8.3,F5.2)
TQ0=(1.+2*M0*M0)
P2Q0=TQ0**3.5
ETA0=1.0
IF(M0.LE.1.) GO TO 18
ETA0=1.0-.875*(M0-1.0)**1.35
18 T2=TQ0*ETA0
P2=P2Q0*P0*ETA0
P0S=P0*.68948
T0S=T0*.55555
T2S=T2*.55555
TYPE 19,P2,T2
19 FORMAT(/3X,F7.3,F8.3)
V1=P2/40.
V2=T2/1000.
V3=P0/40.
****SET POTS WHICH ARE SENSITIVE TO OPERATING CONDITIONS
TYPE 20
20 FORMAT(/3X,55HPLACE DATA TAPE FOR POT ADDRESSES IN HSPTR. THEN R-S
I-R./)
PAUSE
READ(4,22)(PADR(I),I=1,3)
22 FORMAT(8A5)
PVAL(1)=V1
PVAL(2)=V2
PVAL(3)=V3
DO 25 I=1,3
DO 23 J=1,3
CALL QWPR(PADR(I),PVAL(I),IERR)
IF(IERR.EQ.1) GO TO 25
23 CONTINUE
TYPE 24,PADR(I),IERR
24 FORMAT(3X,A4,9H IERR = ,I1/)
PAUSE
25 CONTINUE
TYPE 26
26 FORMAT(3X,55HSLAVE CONSOLES 4 AND 5 TO CONSOLE 1. MANUALLY GO TO I
IC.)
TYPE 29
29 FORMAT(/3X,44HPROCEED TO DYNAMIC PART OF PROGRAM BY \(R-S-R./))
PAUSE

C*****READ ADC VALUES AND GENERATE MAP OUTPUTS
30 CALL QRBADS(X0,0,10,IERR)
   Y7=MAP2(1,X0,X1)
   Y4=MAP2(2,X0,X1)
   Y5=MAP2(3,X2,X3)
   Y6=MAP2(4,X4,X5)
32 Y8=MAP2(5,X6,X7)
   Y9=MAP2(7)
34 Y10=MAP2(6,X8,X9)
   Y11=MAP2(8)
C*****TRANSFER UPDATED DAC VALUES TO ANALOG
35 CALL QWDBA5(Y4,4,R,IERR)
CALL QSTDA
C*****OUTPUT UNSCALED DATA AT TELETYPETE IF DESIRED
   IF(.NOT.SENS W(I)) GO TO 30
   CALL QRBADS(X10,10,14,IERR)
   WA4=WA*3.
   WA4=WA**45359
   WA7=WA7**45359
   WA17=WA17**55555
   T22=T22**55555
   WAR2=WAR2**255
   WAR2=(WAR2*P2*1.5497)/SQRT(T2)
   WA2SI=WA2*.45359
   XNL2=X1
   XNL2=XNL2**255
   XNL=.04391*XNL2*SQRT(T2)
   WAR2M=X4
   WAR2M=WAR2M*40.
WR22SI = WR22M* . 45359
P3Q22 = Y6
P3Q22 = P3Q22* 5.
XNH = X2
XNH = XNH* 20000.
PLA = X23
PLA = PLA* 150.
TYPE 99
99 FORMAT (1RX, 36HTF3#-P3 SIMULATION STEADY-STATE DATA//)
TYPE 100, PPS1, P0
100 FORMAT (5X, 9HP0 = ,F7.3, 9X, 7HN/SQ CM, 7X, 2H( ,F7.3, 9X, RHP SIA )
1)
TYPE 101, T0SI, T0
101 FORMAT (5X, 9HT0 = , F7.2, 9X, 7HK , 7X, 2H( ,F7.2, 9X, 8HR )
1)
TYPE 102, M0
102 FORMAT (5X, 9HM0 = ,F7.4)
TYPE 103, P2SI, P2
103 FORMAT (5X, 9HP2 = ,F7.3, 9X, 7HN/SQ CM, 7X, 2H( ,F7.3, 9X, RHP SIA )
1)
TYPE 104, T2SI, T2
104 FORMAT (5X, 9HT2 = ,F7.2, 9X, 7HK , 7X, 2H( ,F7.2, 9X, 8HR )
1)
TYPE 105, PLA
105 FORMAT (5X, 9HP, PLA = ,F7.2, 9X, 3HDEG)
TYPE 106, WF4SI, WF4
106 FORMAT (5X, 9HWF4 = ,F7.4, 9X, 7HKG/SEC , 7X, 2H( ,F7.4, 9X, RHLBM/SEC)
1)
TYPE 107, WF7SI, WF7
107 FORMAT (5X, 9HWF7 = ,F7.4, 9X, 7HKG/SEC , 7X, 2H( ,D7.4, 9X, 8HLBM/SEC)
1)
TYPE 108, WF17SI, WF17
108 FORMAT (5X, 9HWF17 = ,F7.4, 9X, 7HKG/SEC , 7X, 2H( ,F7.4, 9X, 8HLBM/SEC)
1)
TYPE 109, X21
109 FORMAT (5X, 9HXBL7 = ,S7)
TYPE 110, X22
110 FORMAT (5X, 9HXBL12 = ,S7)
TYPE 111, ANSI, AN
111 FORMAT (5X, 9HAN = ,F7.5, 9X, 7HSQ M , 7X, 2H( ,F7.1, 9X, RHSQ IN )
1)
TYPE 112, XNH
112 FORMAT (5X, 9HXNH = ,F7.0, 9X, 3HRPM)
TYPE 113, XNL
113 FORMAT (5X, 9HXNL = ,F7.0, 9X, 3HRPM)
TYPE 114, PS22SI, PS22
114 FORMAT (5X, 9HPS22 = ,F7.3, 9X, 7HN/SQ CM, 7X, 2H( ,F7.3, 9X, RHP SIA )
1)
TYPE 115, PS3SI, PS3
115 FORMAT (5X, 9HPS3 = ,F7.2, 9X, 7HN/SQ CM, 7X, 2H( ,F7.2, 9X, RHP SIA )
1)
TYPE 116, WA2SI, WA2
116 FORMAT (5X, 9HWA2 = ,F7.2, 9X, 7HKG/SEC , 7X, 2H( ,F7.2, 9X, 8HLBM/SEC)
1)
TYPE 117, T22SI, T22
117 FORMAT (5X, 9HT22 = ,F7.2, 9X, 7HK , 7X, 2H( ,F7.2, 9X, 8HR )
1)
TYPE 118, T3SI, T3
118 FORMAT(5X,9HT3  = ,F7.1,9X,7HK  ,7X,2H( ,F7.1,9X,8HR  )
1)  TYPE 119,T4SI,T4
119 FORMAT(5X,9HT4  = ,F7.1,9X,7HK  ,7X,2H( ,F7.1,9X,8HR  )
1)  TYPE 120,T6SI,T6
120 FORMAT(5X,9HT6  = ,F7.1,9X,7HK  ,7X,2H( ,F7.1,9X,8HR  )
1)  TYPE 121,WR22SI,WAR22M
121 FORMAT(5X,9HWAR22M = ,F7.3,9X,7HKG/SEC  ,7X,2H( ,F7.3,9X,8NLBM/SEC)
1)  TYPE 122,P3Q22
122 FORMAT(5X,9HP3Q22  = ,F7.4)
GO TO 30
END
APPENDIX C

DIGITAL INPUT DATA

In the MAIN digital program, each map or set of component performance data is stored with an identifying map number in the XVALS, YVALS, and ZVALS arrays. The map numbers are required when calling the MAP2 routine to allow the location of the appropriate blocks of stored data. Table VI contains a list of the map numbers for the TF30-P-3 component performance data.

A basic requirement for the MAP2 data is that each curve of a given function must have the same number of breakpoints. However, different maps may have different numbers of curves or breakpoints per curve. In the TF30-P-3 simulation, the fan and compressor maps are represented by eight points per curve, while the turbine maps require 10 points per curve. All maps have eight curves except the high-pressure turbine, which has seven curves.

Tables VII to XII illustrate the format used to input the component performance data. Tables VII to X contain the data for maps 1 to 4, respectively. In the TF30-P-3 simulation, all component performance data are normalized by the sea-level, static, $PLA = 69^o$ value of the corresponding variable. Although normalized, the input data may exceed unity. In order to use the scaled-fraction function routine MAP2, these data must be scaled in the MAIN digital program. Therefore, the first line of data for each map contains scale factors XSC, YSC, and ZSC(1) which are used to scale the already normalized data. The second line of data contains the normalized y values. The remaining lines of data contain the x and z₁ pairs for each of the ascending values of y. For example, the third line of data contains the normalized values of the first four x and z₁ pairs for the lowest value of y. The fourth line of data contains the normalized map outputs corresponding to the last four x and z₁ for the lowest value of y. The x breakpoints can be different for each of the curves.

Tables XI and XII contain the data for map pairs (5, 7) and (6, 8), respectively. For convenience, data for pairs of maps describing the performance of a particular component are combined. In order to use the MAP2L feature described in appendix D, breakpoints for both maps in the pair must be common. For each map pair, the first line of data contains scale factors XSC, YSC, ZSC(1), and ZSC(2). The last scale factor is used to scale the second map output $z₂$. The second line of data contains the normalized y values. The remaining lines of data contain the x, $z₁$, and $z₂$ values for each of the ascending values of y. For the case of map pairs, the x, $z₁$, and $z₂$ data are separated with a whole line used for each.

The MAIN digital program accepts (by means of paper tape) the scaled-fraction initial conditions for all 24 (numbered 0 to 23) of the DAC's. The first five lines of data
shown in table XIII illustrate the format used to input these data. The last line of data in table XIII illustrates the format used to input the addresses of analog potentiometers to be set by the MAIN digital program for specified flight conditions.
MAP2 is a function generation routine developed for the EAI 640 Digital Computer for handling a special type of function of two variables. This special type of function contains curves (constant $y$ values) which are not defined over the same range of the $x$ variable. Examples of such functions are fan and compressor performance maps for turbofan engines. Normal rectilinear interpolation cannot be used for these functions so a special interpolation scheme is used in MAP2.

MAP2 can accommodate six pairs of independent input variables and twelve function output variables. That is, in addition to the six independent bivariate functions, six additional functions can be generated. However, these additional functions each must have arguments and argument breakpoints common to one of the six independent functions. This feature is useful in modeling fans, compressors, and turbines whose performance is usually described by pairs of bivariate functions.

In order to reduce storage requirements and execution time, MAP2 was designed to use scaled-fraction arithmetic and scaled-fraction data. The tables of function data, map input and output variables, and the routine MAP2 itself must be declared as scaled fractions in any program or subroutine which loads the function tables or calls MAP2.

The arrays IX and JY containing the search indices are initialized to 1 in the calling program. These search indices are updated during each execution of MAP2 and are used to speed up the table search for subsequent calls to MAP2. Details of the table search and interpolation scheme are discussed in reference 12.

The arrays KX and KY containing the out-of-range counters for each function are initialized to zero in the calling program. These counters keep track of the number of consecutive times an argument exceeds the range of the input data for its respective map. A limited number of out-of-range calls to MAP2 are allowed in order to permit short-duration increases in map inputs (caused by noise, etc.) without problem interruption. If the out-of-range count reaches 25 for either map input, the program is interrupted and subroutine MOOR (map out of range) is called. In the TF30-P-3 simulation, MOOR places the analog computer in "HOLD," prints an error message at the teletype, and pauses to await the user's corrective action. The maximum allowable out-of-range count and the action taken by MOOR are arbitrary and may be modified for a particular simulation.
As previously discussed, six additional functions can be accommodated by MAP2 if they have arguments and argument breakpoints common to one of the original six functions. This feature reduces the storage requirements for the input data arrays XVALS and YVALS. In addition, the execution time can be reduced by skipping the table search and going directly to the interpolation calculations.

Both FORTRAN and assembly language versions of MAP2 have been developed. These may be used interchangeably. However, for the digital sampling interval lengths required for real-time engine simulation, the assembly language version must be used. Both versions have been written in such a way that overflows are not possible if the scaled-fraction data have been loaded correctly.

In order to handle the additional functions for which the table search can be skipped, an additional entry point, MAP2L, was added to the assembly language version. The calling statement for these functions requires only the map number m. Since the FORTRAN compiler for the EAI 640 Digital Computer does not allow multiple-entry-point subprograms, a separate subprogram, MAP2L, was written.

FORTRAN Listings

```
SCALED FRACTION FUNCTION MAP2(N,XIN,YIN)
SCALED FRACTION XIN,YIN,YINCR,XHI,XLO,XFRAC,ZL,ZR,Y1,Y2,
   1 MAP2,XVALS(12,6),YVALS(6),ZVALS(10,8,12)
COMMON/MAPS/XVALS,YVALS,ZVALS,iX(6),jY(6),NX(6),NY(6),kX(6),kY(6)
C.....IF ENTRY IS FROM MAP2L LOCK UP OUTPUT ONLY.
   IF(N.GT.6) GO TO 400
   NYC=NY(N)
   NXP=NX(N)
   I=IX(N)
   J=JY(N)
 100 Y1=YIN-YVALS(J,N)
   IF(Y1.GT.0.999995) GO TO 110
   IF(Y1.LT.-0.999995) GO TO 120
   IF(J.LE.1) GO TO 140
   J=J-1
   GO TO 100
 110 Y2=YIN-YVALS(J+1,N)
   IF(Y2.LT.0.999995) GO TO 120
   IF(Y2.GT.0.999995) GO TO 130
   J=J+1
   IF(J.GE.NYC) GO TO 150
   Y1=Y2
   GO TO 110
 120 YINCR=.999995
   GO TO 150
 130 YINCR=-.999995
   GO TO 150
 140 YINCR=.999995
   GO TO 160
 150 YINCR=-.999995
```

J=J-1
160 IF KY(N).GE.25) GO TO 500
   KY(N)=KY(N)-1
   GO TO 210
180 YINCR=Y1/(Y1-Y2)
190 KY(N)=0
200 XLO=XVALS(I,J,N)+YINCR*(XVALS(I,J+1,N)-XVALS(I,J,N))
   IF(XIN.GT.XLO) GO TO 210
   IF(XIN.EQ.XLO) GO TO 220
   IF(I.LE.J) GO TO 240
   I=I-1
   GO TO 200
210 XHI=XVALS(I+1,J,N)+YINCR*(XVALS(I+1,J+1,N)-XVALS(I+1,J,N))
   IF(XIN.LT.XHI) GO TO 220
   IF(XIN.EQ.XHI) GO TO 230
   I=I+1
   IF(I.GE.NXP) GO TO 250
   XLO=XHI
   GO TO 210
220 XFACR=XIN/XLO
   GO TO 290
230 XFACR=.99999S
   GO TO 290
240 XFACR=.99999S
   GO TO 260
250 XFACR=.99999S
   I=I-1
260 IF(KY(N).GE.25) GO TO 500
   KX(N)=KX(N)+1
   GO TO 500
280 XFACR=(XIN-XLO)/(XHI-XLO)
290 KX(N)=0
300 I=1
   JY(N)=J
400 ZR=ZVALS(I+1,J,N)+YINCR*(ZVALS(I+1,J+1,N)-ZVALS(I+1,J,N))
   ZL=ZVALS(I,J,N)+YINCR*(ZVALS(I,J+1,N)-ZVALS(I,J,N))
   MAP2=ZL+XFACR*(ZR-ZL)
   RETU RN
500 CALL M00R(N,XIN,YIN)
   RETURN
END

SCALED FRACTION FUNCTION MAP2L(N)
SCALED FRACTION MAP2,MAP2L,XIN,YIN

C....XIN AND YIN ARE DUMMY ARGUMENTS AND DO NOT AFFECT RESULT.
MAP2L=MAP2(N,XIN,YIN)
RETURN
END
SUBROUTINE MOOR (M, XIN, YIN)
SCALD. FRACTI10N XIN, YIN
C..... TEST FOR OPERATE MODE
CALL CMAI(ILOC)
IF (ILOC .EQ. 4) CALL CMH(IFR)
TYPE APEP, M, XIN, YIN
C00 FORMAT (/*?M?P M0, .IL3, 29H INPUTS OUT OF RANGE/60XIN = ,S7,('
1 SH YIN = , S7/)'
PAUSE
IF (ILOC . EQ. 4) CALL CMHP(IFR)
RETURN
END

Assembly Language Listing

---

* COMPLETE FUNCTION GENERATION ENTRPY POINT

COMMON MAPS

NAME MAP2, MAP2L
EXTERN MOOR

MAP2: MAP2 ADR

MAP2: MAP2 ADR

* SET MAP CONSTANTS AND XVALS ADDRESS (X=N)
CALC0

SL

YLORH

X=I+1

EX

XMP

ACC=I+1

C

SL

J

X2BIG

X=I+1

EX

J

LOOPA

ACC=XHI

* XIN=XLO (X=I) OR XIN=XHI (Y=I+1)

YLORH

CLR

STA

XFRAC

J

RANDR

X2SM

EX

X=I

CLR

J

TXCNT

X2BIG

EX

Y=I+1

DCX

X=I

LA

MAXINC

='77777

TXCNT

STA

XFRAC

LA

XCNT

STA

XFRAC

DCX

X=I

STA

XCT

CLEAR COUNT

CALC0

S

XLO

STA

TEM1

=XHI-XLO

CLP

EQ

LA

XIN

CLP

D

TEM1

STA

XFRAC

DCX

I

X=I

STA

XCT

CLEAR COUNT

SET UP ENTRY CONDITIONS (X=I)

RANDR

STX

I

EX

ACCMH = I

LY

N

X=MAP NO.

STA,X

IX-1

IX(M)=I

LA

J

STA,X

JY-1

JY(M)=J

LA

XCNT

STA,X

KY-1

KY(M)=XCNT

LA

YCNT

STA,X

KY-1

KY(M)=YCNT

LY

I

* CALCULATE FUNCTION OUTPUT (Y=1)

INRP

LA,IX

ZIJM

7(I,J+1,M)

LY

I

ZIJM

7(I,J,M)

M

YINCP

STA

TEM1

=ZL

ICY

Y=I+1

LA,IX

ZIJM

7(I+1,J+1,M)
<table>
<thead>
<tr>
<th>Line</th>
<th>Code</th>
<th>Description</th>
<th>Address</th>
</tr>
</thead>
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<td>00351</td>
<td>XCNT</td>
<td>112</td>
</tr>
<tr>
<td>00271</td>
<td>00354</td>
<td>YCNT</td>
<td>112</td>
</tr>
<tr>
<td>00272</td>
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<td>00273</td>
<td>00356</td>
<td>YCO</td>
<td>112</td>
</tr>
<tr>
<td>00274</td>
<td>00357</td>
<td>YFRAC</td>
<td>112</td>
</tr>
<tr>
<td>00275</td>
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<td>ZIJN</td>
<td>112</td>
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<td>00363</td>
<td>ZIJIN</td>
<td>112</td>
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<tr>
<td>00279</td>
<td>00364</td>
<td>RETURN</td>
<td>112</td>
</tr>
<tr>
<td>00280</td>
<td></td>
<td>END</td>
<td></td>
</tr>
</tbody>
</table>
APPENDIX E

ANALOG PROGRAM - PATCHING DIAGRAMS, POTENTIOMETER SETTINGS, AND SCALE FACTORS

The bulk of the calculations in the real-time TF30-P-3 simulation are performed on one EAI 680 Analog Computer and two EAI 231-R Analog Computers. Figures 18 to 20 contain the analog patching diagrams for those computers.

Table XIV contains a list of potentiometer definitions and settings for the analog portion of the simulation. Table XV contains a list of scale factors for the analog variables.

The EAI 680 Analog Computer has a complement of 24 quarter-square multipliers. This complement can effectively be increased by six by using the DAM feature. Digitally generated variables may be multiplied, on the 680, by analog variables with the product available at the analog. Table XVI lists the DAM variables in the TF30-P-3 hybrid simulation. Figure 18 illustrates the role of the DAM's in the TF30-P-3 simulation.
REFERENCES


### TABLE I. - TELETYPE OUTPUT LISTINGS FOR SEA-LEVEL, STANDARD-DAY, STATIC OPERATING LINE - CLOSED-LOOP CONTROL

#### (a) Power lever angle, 15°

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<tr>
<th>P#</th>
<th>T8</th>
<th>PLA</th>
<th>WFA</th>
<th>WFI</th>
<th>WF4</th>
<th>WF7</th>
<th>PL2</th>
<th>TL2</th>
<th>TP2</th>
<th>T2</th>
<th>T1</th>
<th>T0</th>
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<td>238.14</td>
<td>15.06</td>
<td>.1266</td>
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<td>10.132</td>
<td>238.14</td>
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<td>10.132</td>
<td>238.14</td>
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<td>10.132</td>
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</table>

#### (b) Power lever angle, 70°

<table>
<thead>
<tr>
<th>P#</th>
<th>T8</th>
<th>PLA</th>
<th>WFA</th>
<th>WFI</th>
<th>WF4</th>
<th>WF7</th>
<th>PL2</th>
<th>TL2</th>
<th>TP2</th>
<th>T2</th>
<th>T1</th>
<th>T0</th>
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<tbody>
<tr>
<td>10.132</td>
<td>238.14</td>
<td>15.06</td>
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<td>10.132</td>
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<tr>
<td>TABLE I. - Concluded. TELETYPYI OUTPUT LISTINGS FOR SEA-LEVEL.</td>
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<tr>
<td>STANDARD-DAY, STATIC OPERATING LINE -</td>
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<tr>
<td>CLOSED-LOOP CONTROL</td>
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<tr>
<td>(c) Power lever angle, 120°</td>
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</tr>
</tbody>
</table>

| P1 | 1,132 | N/SQ CM | 14.665 | PSIA |
| T1 | 2,284.14 | K | 518.66 | R |
| M1 | 1,088 | N/SQ CM | 14.665 | PSIA |
| P2 | 1,132 | N/SQ CM | 14.665 | PSIA |
| T2 | 2,284.14 | K | 518.66 | R |
| PLA | 110.04 | DEG | |
| WF4 | 924.83 | KG/SFC | 1,8526 | LBM/SFC |
| WF7 | 2,155 | KG/SFC | 4,7468 | LBM/SFC |
| WF17 | 2,571.4 | KG/SFC | 5,6699 | LBM/SFC |
| WB17 | .98897 | | |
| XBL12 | .90836 | | |
| AN | 1,653.80 | SQ M | 1,922.3 | SQ IN |
| XNH | 1,449.2 | | |
| XNL | 93.89 | | |
| P22 | 53.124 | N/SQ CM | 77.959 | PSIA |
| D3 | 161.19 | N/SQ CM | 233.79 | PSIA |
| WA2 | 194.47 | KG/SFC | 230.36 | LBM/SFC |
| TP2 | 555.16 | K | 850.56 | P |
| T5 | 711.7 | K | 729.15 | R |
| T4 | 1,276.9 | K | 2,966.9 | P |
| T6 | 91.6 | K | 1,466.6 | P |
| XAD2MM | 12.24 | KG/SFC | 28.211 | LBM/SFC |
| X22 | 2.2451 | | |

<table>
<thead>
<tr>
<th>TABLE II. - TELETYPYI OUTPUT LISTINGS FOR SIMULATED 6.096-KILOMETER (20 000-FT) ALTITUDE, MACH 1.2</th>
</tr>
</thead>
<tbody>
<tr>
<td>FLIGHT CONDITION - CLOSED-LOOP CONTROL</td>
</tr>
<tr>
<td>(a) Power lever angle, 15°</td>
</tr>
</tbody>
</table>

| P1 | 4.668 | N/SQ CM | 6.768 | PSIA |
| T1 | 2,486.4 | K | 447.56 | R |
| M1 | 1,1999 | | |
| P2 | 11.285 | N/SQ CM | 16.252 | PSIA |
| T2 | 328.29 | K | 576.45 | R |
| PLA | 15.81 | DEG | |
| WF4 | 2.478 | KG/SFC | .5445 | LBM/SFC |
| WF7 | .986 | KG/SFC | .986 | LBM/SFC |
| WF17 | .986 | KG/SFC | .986 | LBM/SFC |
| XBL17 | -1.83122 | | |
| XBL12 | .80146 | | |
| AN | 3,3851 | SQ M | 512.3 | SQ IN |
| XNH | 1,1687 | | |
| XNL | 782.9 | | |
| PS22 | 29.453 | N/SQ CM | 42.718 | PSIA |
| PS3 | 69.21 | N/SQ CM | 169.39 | PSIA |
| W22 | 76.72 | KG/SFC | 169.14 | LBM/SFC |
| T22 | 439.24 | K | 790.64 | R |
| T3 | 564.8 | K | 1,015.3 | R |
| T4 | 983.8 | K | 1,625.4 | R |
| T6 | 634.8 | K | 1,141.3 | R |
| WAD2MM | 11.945 | KG/SFC | 24.257 | LBM/SFC |
| P3Q22 | 2.2451 | | |

56
TABLE II. - Concluded. TELETYPEx OUTPUT LISTINGS FOR SIMULATED 6.096-KILOMETER (20 000-FT) ALTITUDE, MACH 1.2 FLIGHT CONDITION - CLOSED-LOOP CONTROL

<table>
<thead>
<tr>
<th>(b) Power lever angle, 70°</th>
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<tr>
<td>Pf</td>
</tr>
<tr>
<td>Tq</td>
</tr>
<tr>
<td>Mq</td>
</tr>
<tr>
<td>P2</td>
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<table>
<thead>
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<th>(c) Power lever angle, 120°</th>
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<td>Pf</td>
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TABLE V. - SUPPLEMENTAL ANALOG-TO-DIGITAL CHANNELS AND VARIABLES FOR TF30-P-3

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TABLE VI. - COMPONENT MAP DESIGNATIONS FOR TF30-P-3

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### TABLE IX. - TF30-P-3 LOW-PRESSURE-COMPRESSOR PRESSURE RATIO DATA

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### TABLE XIII. - TF30-P-3 DIGITAL-TO-ANALOG CONVERTER INITIAL CONDITION AND POTENSIOMETER ADDRESS DATA

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TABLE XIV. - POTENTIOMETER SETTINGS

(a) EAI 680 Digital Computer

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<th>Potentiometer</th>
<th>Definition</th>
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<td>$(0.84 - 0.515)/2$ (eq. (17))</td>
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<td>5(0.06)/3 (eq. (19))</td>
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<td>P33</td>
<td>3(0.2412)/2 (eq. (12))</td>
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<td>$A_{N,min}/1600$</td>
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<td>P35</td>
<td>$w_{F7,1}/6$</td>
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<td>P37</td>
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<td>$[(P/P)<em>{LC}/(P/P)</em>{LC,M}]^{10}$</td>
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<td>$[(P/P)<em>{FID}/(P/P)</em>{FID,M}]^{10}$</td>
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<td>$3(A_{c}/I)_{HC}/80$</td>
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<td>$(P/P)<em>{HC}/(P/P)</em>{HC,M}$</td>
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<td>Q24</td>
<td>$PLA_{r}/150$</td>
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TABLE XIV. - Continued. POTENTIOMETER SETTINGS

(b) EAI 231-4 Analog Computer

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<th>Setting</th>
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<td>1/3, 1/300</td>
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<td>3/8</td>
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<td>Q20</td>
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<td>.2000</td>
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<td>(WT) 1.3/6000</td>
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### TABLE XIV. - Concluded. POTENSIOMETER SETTINGS

(c) EAI 231-5 Analog Computer

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<th>Potentiometer</th>
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<td>$W_{4}$, $1/2$</td>
<td>0.7275</td>
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<tr>
<td>Q21</td>
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<td>Q25</td>
<td>$c_{p}$, $3c_{p}$, $4c_{p}$, $4$</td>
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65
### Table XV. - Scale Factors

<table>
<thead>
<tr>
<th>Variable</th>
<th>Scale Factor</th>
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</thead>
<tbody>
<tr>
<td>$T_1 \cdot \lambda$</td>
<td>$2 \cdot 10^4$ rpm</td>
</tr>
<tr>
<td>$T_2 \cdot \lambda$</td>
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<td>$2 \cdot 10^4$ rpm</td>
</tr>
<tr>
<td>$T_6 \cdot \lambda$</td>
<td>$2 \cdot 10^4$ rpm</td>
</tr>
<tr>
<td>$T_7 \cdot \lambda$</td>
<td>$2 \cdot 10^4$ rpm</td>
</tr>
<tr>
<td>$T_8 \cdot \lambda$</td>
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### Table XVI. - Digital-to-Analog Multiplier Utilization

**For TF30-P-3**

<table>
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<tr>
<th>DAC channel</th>
<th>DAM channel (analog output)</th>
<th>DAM variable</th>
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</table>

### Diagram

![Schematic of TF30-P-3 engine](image)

**Figure 1.** - Schematic of TF30-P-3 engine.
Figure 2. Real time simulation
flow diagram for TF30-P-3.
Figure 3. Bivariate functions representing performance of fan.
Figure 4. - Bivariate functions representing performance of low-pressure compressor.
Figure 5. - Bivariate functions representing high-pressure-compressor performance.
Figure 6 - Bivariate functions representing high-pressure-turbine performance.
Figure 7. Bivariate functions representing low pressure turbine performance.
Figure 8. - Split of TF30-P-3 simulation computation load.
Figure 9. - Comparison of hybrid and baseline digital results for sea-level, standard-day static conditions.
Figure 9. Concluded.
Figure 10. - Comparison of hybrid and baseline digital results for 6.096 kilometer (20,000-ft) simulated altitude, Mach 1.2 flight condition.
Figure 10. Continued.

(d) High-pressure-turbine inlet temperature as function of power lever angle.

(e) High-pressure-compressor discharge static pressure as function of power lever angle.

(f) Total fan airflow as function of power lever angle.
Figure 10. - Concluded.
Figure 11. - Comparison of hybrid and baseline digital simulation responses to throttle slam from power lever angle of 15° to 7° at 125 degrees per second.
Figure 12. Comparison of hybrid and baseline digital simulation responses to throttle slam from power lever angle of 67° to 120° at 125 degrees per second.
Figure 13 - Comparison of hybrid and baseline digital simulation responses to throttle chop from power lever angle of 120° to 60° at 125 degrees per second.
Figure 14. - Comparison of hybrid and baseline digital simulation responses to throttle chop from power lever angle of 67° to 15° at 125 degrees per second.
Figure 15. - Comparison of hybrid and baseline digital frequency responses of high-pressure-rotor speed to fuel flow oscillations. Sea-level, standard-day, static conditions; power lever angle, 50°.

Figure 16. - Comparison of hybrid and baseline digital frequency responses of high-pressure-compressor discharge static pressure to fuel flow oscillations. Sea-level, standard-day, static conditions; power lever angle, 50°.
Figure 17. Comparison of hybrid and baseline digital frequency responses of core augmentor inlet pressure to fuel flow oscillations. Sea-level, standard-day, static conditions; power lever angle, 50°.
Figure 18. - Patching diagrams for EAI 680 Analog Computer.
Q1 Low-pressure compressor.

Figure 18. - Continued.
Figure 18. - Continued.
(e) Control outputs.

Figure 18. - Concluded.
Figure 19. - Patching diagrams for EA1 231-4 Analog Computer.