ADVANCED SUPERSONIC TRANSPORT FIXED-BASE SIMULATOR EVALUATIONS AT LANDING APPROACH

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SUMMARY

Equations of motion simulating the landing approach case for the supersonic cruise vehicle have been programmed and exercised using a fixed-base simulation facility. The objectives of the study are to provide unaugmented and augmented system comparisons using this facility, and to make refinements as necessary for system performance improvement.

The unaugmented longitudinal responses to elevator commands are slow and sluggish, requiring augmentation to increase the speed of the response. In the lateral-directional case, the Dutch roll is highly underdamped and requires an augmentation system to increase this damping and provide satisfactory flying qualities. The status of this fixed-base study is that the longitudinal equations, updated with recent wind tunnel data, have been evaluated on the simulator and the system found to be satisfactory. The lateral-axis equations are linearized and have not yet been updated to large excursion capability; consequently, only limited, preliminary findings on this system are available.

The basic results so far indicate augmentation systems are required to provide a satisfactory longitudinal system, and that additional study and evaluation of the lateral-directional case are necessary before a more complete assessment can be made.

INTRODUCTION

Development of augmentation systems for flying qualities improvement was begun under previous NASA contracts (references 1 and 2) using linear system theory and modern control techniques. The longitudinal and lateral control systems were analyzed separately and the results assessed using reference 3 criteria to provide Level 1 flying qualities (pilot ratings of 3.5 or less). Results from these tasks were then used to develop a full six degree of freedom, non-linear simulation for real-time pilot in the loop evaluation. The subject of this paper is a review of this augmentation system development, a discussion of recent results, and a brief description of the on-going and planned simulator studies.

The unaugmented responses of the airplane in landing approach are acceptable in the pitch axis and unacceptable in the lateral directional axis. The longitudinal short period responses are sluggish, whereas the lateral Dutch roll is highly underdamped. Consequently, the augmentation systems for these two axes have rather diverse jobs to perform. The task, then, is to reshape the airplane responses so they are satisfactory, i.e., that they exhibit Level 1 flying qualities.

Analytical results stemming from past mechanization efforts to fulfill this stated task have been successful in providing Level 1 systems. These results are based on linear system techniques and criteria taken from MIL-F-8785B (ref 3) specifications for transport aircraft. The main objectives of the simulator studies to be discussed are the augmentation system evaluation using a pilot in the loop, and refinements to these systems as a result of these evaluations.

SYMBOLS

a_n	normal acceleration, m/sec^2 (ft/sec^2)
a_y	lateral acceleration, m/sec^2 (ft/sec^2)
$f_{\delta_{ij}}$	feedforward gain values
$f_{x_{ij}}$	feedback gain values
K_{an}	HSAS acceleration gain, deg per m/sec^2 (deg per ft/sec^2)
$K_{\dot{\phi}}$	roll rate gain to aileron, deg per deg/sec
$K_{\dot{\phi}_r}$	roll rate gain to rudder, deg per deg/sec
K_β	sideslip gain, deg per deg
$K_{\dot{\psi}}$	yaw rate gain, deg per deg/sec
t_2	time to double amplitude, sec
u	forward velocity, m/sec (ft/sec)
β	sideslip angle, deg
δ_{ac}	commanded aileron angle, deg
δ_{af}	feedback aileron signal, deg
δ_{col}	column deflection, deg
δ_e	elevator deflection, deg

$\delta_{e_{FB}}$	elevator feedback signal, deg
$\delta_{e_{FF}}$	elevator feedforward signal, deg
δ_p	rudder pedal deflection, cm (in.)
δ_r	rudder deflection, deg
δ_{rc}	commanded rudder angle, deg
δ_{rf}	rudder feedback signal, deg
δ_T	throttle servo position, deg
δ_{TH}	throttle setting, deg
$\delta_{T_{FB}}$	throttle feedback signal, deg
$\delta_{T_{FF}}$	throttle feedforward signal, deg
δ_w	wheel position, deg
δ_1	output of yaw rate washout, deg
ζ_{DR}	Dutch roll damping ratio
ζ_{PH}	phugoid damping ratio
ζ_{SP}	short period damping ratio
θ	pitch attitude angle, deg
τ_R	roll time constant, deg
ϕ	roll attitude angle, deg
ψ	yaw attitude angle, deg
ω_{DR}	Dutch roll natural frequency, rad/sec
ω_{PH}	phugoid natural frequency, rad/sec
ω_{SP}	short period natural frequency, rad/sec

ABBREVIATIONS AND SPECIAL SYMBOLS

A/D	Analog-to-Digital Converter
D/A	Digital-to-Analog Converter

DETAC	Digital Equipment Technology Analysis Center
MAC	Mean Aerodynamic Chord
HSAS	Hard Stability Augmentation System
ILS	Instrument Landing System
$\dot{(\ )}$	Time Derivative
(k)	sampled signal at k^{th} iteration
$\hat{(\ )}$	estimate or reconstructed signal

UNAUGMENTED AIRCRAFT DESCRIPTION

A three view of the MDC Supersonic Cruise Vehicle is shown in Figure 1. This 273 passenger aircraft is designed for ranges in excess of 8300 km (4500 n. mi.) at a takeoff gross weight of 340,194 kg (750,000 lb). It features a 929 m^2 (10,000 ft^2) arrow-type wing designed for a cruise Mach number of 2.2 with the planform based on the NASA SCAT-15F concept, a conventional horizontal tail, a single fuselage-mounted vertical tail, and four engines mounted in axisymmetric nacelles. The inboard leading edge of the wing has a sweep of 71 degrees, with the sweep reduced to 57 degrees outboard of the leading edge break. The average thickness ratio of the wing is slightly less than three percent. The thickness ratio is equal to 2.25 percent of the chord at the wing root and is constant at three percent of the chord from the trailing edge break to the wing tip.

Perturbation equations of motion for the landing approach flight condition have been developed for this configuration. These equations are documented for the longitudinal axis in Reference 1 and for the lateral axis in Reference 2. Instead of listing the detailed sets of equations for this aircraft here, only the important characteristics that have led to the decision that augmentation systems are required for flying qualities improvement will be given. Longitudinally, the pitch response to an elevator input is slow and does not exhibit Level 1 flying qualities. Decreased damping in pitch, therefore, is required of the longitudinal augmentation system. In the lateral directional case, the Dutch roll damping of the airplane is very low and an augmentation system to increase this damping is required. These two conditions are the reasons augmentation systems are necessary in both axes. In fact, in the lateral case, there is a tendency toward instability with a pilot in the loop for any inputs except those of very small magnitudes. This fact has led to development of a hard stability augmentation system (HSAS) in the lateral axis that provides Level 2 flying qualities. This HSAS contains fewer feedbacks and sensors than the full-up system and would operate in a back-up mode in case of primary augmentation system failure.

SIMULATION FACILITIES

The Digital Equipment Technology Analysis Center (DETAC) is a technology investigation facility at Douglas used for conducting studies and providing hands-on experience with digital equipment. This facility generally fulfills a requirement to upgrade the existing electronic system study capabilities, particularly in the area of aircraft digital systems, inclusive of flight control computers and advanced display systems. The DETAC has been used specifically to study the landing approach tasks of the supersonic cruise vehicle in real time with a pilot in the loop.

Figure 2 shows the general view of the facility, and Figure 3 is an interior view of the "soft cockpit." The controls available to the pilot here are side and center stick controllers, throttle, and flap setting controls. No rudder pedals are provided, but the software does have rudder pedal effectiveness coefficients included in it (which can be used by the augmentation systems as required). A CRT provides an Electronic Attitude Director Indicator (EADI) display that can be used in a heads-down configuration or projected on a TV screen. Figure 4 is a typical EADI format with the various display quantities as noted. The pilots' landing task using this type of EADI is to keep the aircraft symbol centered in the ILS box (marked with a + symbol).

Wind shear, gust inputs, and initial condition changes are options that can be input through the interactive CRT display. Several simulation outputs will be discussed later that have exercised these options.

AUGMENTATION SYSTEM DEVELOPMENT

Full Augmentation System

Both the longitudinal and lateral augmentation systems were developed using perturbation equations of motion and linear system theory. The main objective was to provide a control system configuration that could be incorporated into a six degree-of-freedom, non-linear simulation to verify the performance under real-time operating conditions.

Modern control theory was used in the longitudinal case to define the feedback and feedforward gains via implicit model following. The model used was selected to represent an airplane whose flying qualities were all Level 1. The resulting augmentation system approximates the model to the degree the two controls (elevator and throttle) permit. In the lateral case, it was found that classical root locus techniques could be used to determine the gains that produced a Level 1 augmented system. Yaw and roll rate gyro feedbacks were employed, plus a gain on sideslip angle β (reconstructed from measurable signals). The block diagrams in Figures 5 and 6 show the details of both augmentation systems. Digital implementation of the required calculations for augmentation purposes will be made for both of these systems.

Table 1 compares some of the basic parameters of the system with the criteria specified in MIL-F-8785B. Note that the unaugmented short period roots are both real in contrast to the usual complex conjugate pair. In the lateral axis, the Dutch roll roots have a damping ratio of only 0.074. This fact, coupled with the marginal roll time constant, produces a poorly responding system. The augmented system provides values for the indicated parameters that are within the Level 1 requirements, and it is this system that will be incorporated into the real-time simulation for evaluation.

Hard Stability Augmentation System

A much simplified augmentation system has been devised that would serve as a back-up system. This HSAS is depicted in Figures 7 and 8 for each axis. The longitudinal system is simply an accelerometer feeding back to the elevator actuator. The dynamic responses of this system are better than no augmentation but do not possess the Level 1 flying qualities of the fully augmented system. This accelerometer loop provides approximately a 0.7 damping ratio on the short period roots. The lateral system of Figure 8 is similar to the complete system except the sideslip feedback has been removed. This simplification allows only rate sensors to be used and eliminates the digital feedback filter for reconstructing β . The resulting system exhibits Level 2 flying qualities when assessed by reference 3 criteria.

Simulation Checkout

The simulation program containing linear aerodynamic data was checked against the perturbation results previously obtained for both axes. Nonlinear coefficients were then included in the longitudinal equations as obtained from recent wind tunnel data. (Time considerations prevented the lateral equations to reflect the tunnel data, and the results to be presented are based on simplified, linear lateral equations.)

STUDY RESULTS

The results to be presented are based on pilot-in-the-loop evaluations of the longitudinal and lateral systems. The evaluations to be discussed include pilot assessments obtained from the fixed-base simulator utilizing its capabilities and the various types of visual presentations available. Since these visual displays are limited in their data presentation and no motion is provided to the pilot, the results are used basically to compare the various augmentation systems.

Longitudinal Axis

Pilot evaluations have led to modifying the previously developed augmentation system gains for the longitudinal case. Two specific points were noted. First, the cross feed from throttle to elevator servo caused an unwanted pitch command when the throttle settings were changed. The gain $f_{\delta 12}$ of Figure 5 was reduced to zero and improved responses resulted. Second, the gain from accelerometer to elevator servo, f_{x12}, was increased by a factor of two in order to provide better handling as noted by pilot comments during the augmentation system evaluation.

A shift in center-of-gravity from the nominal 24% MAC was made and the pilot was given pitch tracking tasks under these conditions. Even though the augmentation system was developed for a 24% cg location, other aft cg locations (which would otherwise be unstable) were stabilized by the system. For a cg shift to 36% MAC, the pilot could still maintain control, but this was the limit for aft cg locations based on pilot comments. Figure 9 shows the response in pitch to a step elevator input with the augmentation on at a cg location of 36%. This response shows convergence of response for this condition.

Only preliminary simulator data on evaluating the HSAS system have been taken so far. It appears that the flying qualities can be made acceptable (Level 2) in the pitch axis. Additional evaluation of the HSAS system is planned on the simulator.

Lateral Axis

As noted previously, the Dutch roll damping is very low and leads to large oscillations in roll rate for aileron inputs. The linear system technique used to define the lateral augmentation system gains and compensation networks was successful in providing a Level 1 system. The linear system roots were shifted to the Level 1 region, and the response as assessed by the roll rate oscillation criterion was improved by the addition of the augmentation system. The system was determined to be satisfactory based on the criteria of reference 3; consequently, this augmentation system was included in the six degree-of-freedom equations programmed on the fixed base simulator. Pilot-in-the-loop evaluations of the unaugmented airplane confirmed its uncontrollability in the lateral case. The current simulation effort is a continuing evaluation of the augmented airplane with a pilot in the loop. The results are of a preliminary nature and are not complete, but the indication is that adjustment of the previously developed gains and/or addition of compensation networks will be necessary to provide a satisfactory system when the pilot is included in the loop.

Responses of the airplane degrees of freedom to gust inputs for the lateral axis with augmentation are lower than without augmentation because the natural frequency of the Dutch roll roots has been decreased. Figure 10 compares the system roll response, ϕ , with and without augmentation for a gust input level of 1 kt RMS. The pilot controls were fixed during this run. This result is consistent with the improvement in flying qualities as in Table 1, and follows from the increase in Dutch roll damping.

Step response results also show improvement in the lateral case with the augmentation system engaged. Figure 11 is a comparison of roll rate transients to a step wheel command with and without augmentation. The decreased damping is evident in this comparison, and the system is augmented to Level 1 when assessed by the criterion of MIL-F-8785B.

CONCLUDING REMARKS

The simulator evaluations of the augmentation system in the longitudinal case have allowed improvements as a result of the real-time analyses. Specifically, gain redefinition has yielded a better responding system when evaluated by piloted simulation runs. More detailed studies involving the longitudinal axis (especially the HSAS system) need to be undertaken.

The lateral-directional case requires refinement in its augmentation system in order to improve the flying qualities. Addition of a pilot in the loop has changed the flying qualities rating as compared to the analytical results obtained via linear system theory. When a pilot was included in the loop, the lateral augmentation system was not determined to be Level 1 as it was using reference 3 criteria with no pilot. The reasons for this problem, and the corrections to it, will be the subject of future studies.

Generally, using the fixed-base simulator for augmentation system verification has proved very useful. It has identified several areas in which improvement was made to the longitudinal system and has shown the need for some type of compensation to the lateral case. Additional simulation activities will include implementation on a moving base simulator to fully assess the handling qualities of the airplane at landing approach in both axes.

REFERENCES

1. Technology Application Studies for Supersonic Cruise Aircraft. NASA CR-145130 (Douglas Aircraft Report MDC-J4550). November, 1976.

2. Technology Application Study of a Supersonic Cruise Vehicle. NASA CR-159034. March, 1979.

3. Flying Qualities of Piloted Airplanes. MIL Spec. MIL-F-8785B (ASG). August, 1969

TABLE 1

COMPARISON OF DYNAMIC CHARACTERISTICS WITH AND WITHOUT AUGMENTATION ENGAGED

PARAMETER	UNAUGMENTED	AUGMENTED	MIL-F-8785B (LEVEL 1 CRITERIA)
SHORT PERIOD:	Real Roots:		
ω_{SP} (RAD/SEC)	-0.650	0.840	≥ 0.8
ζ_{SP}	-0.258	0.688	≥ 0.35
PHUGOID:			
ω_{PH} (RAD/SEC)	0.119	0.209	--
ζ_{PH}	0.149	0.082	≥ 0.04
ROLL:			
τ_R (SEC)	1.35	0.495	≤ 1.4
SPIRAL:			
t_2 (SEC)	∞	35.5	≥ 20.0
DUTCH ROLL:			
ω_{DR} (RAD/SEC)	0.797	0.583	≥ 0.4
ζ_{DR}	0.074	0.307	≥ 0.08*
$\omega_{DR}\zeta_{DR}$ (RAD/SEC)	0.059	0.179	≥ 0.15

*For $\omega_{DR} > 1.88$ RAD/SEC, this requirement supersedes the $\omega_{DR}\zeta_{DR}$ product requirement.

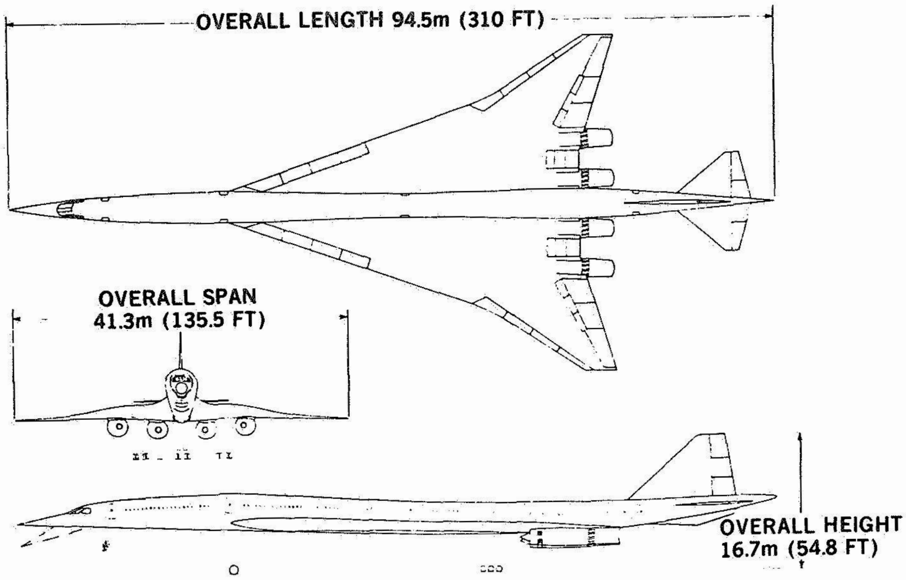

Figure 1.- MDC supersonic cruise vehicle used for active controls simulation purposes.

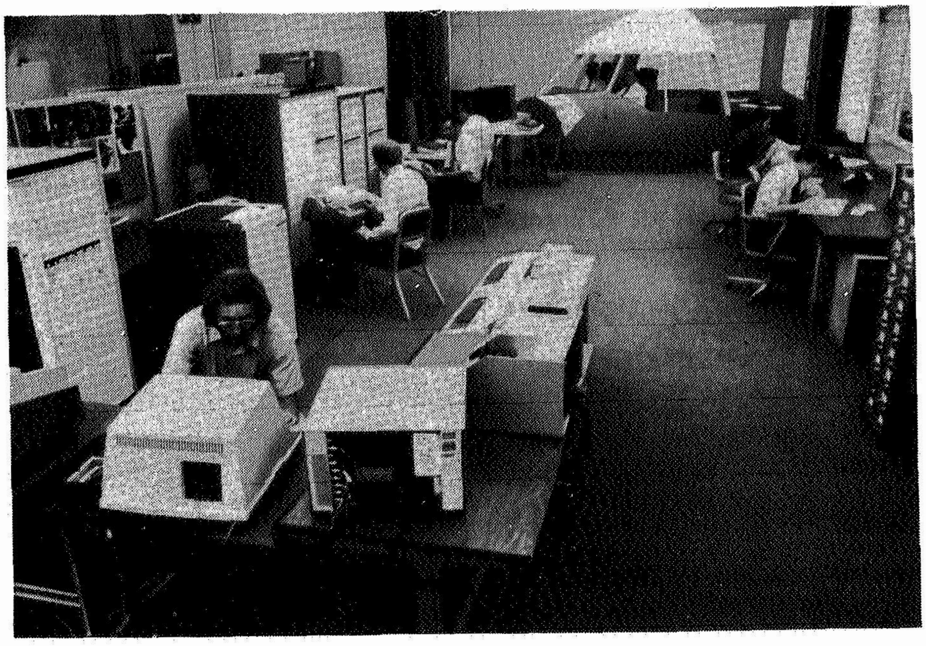

Figure 2.- DETAC simulation facility.

Figure 3.- Cockpit mockup.

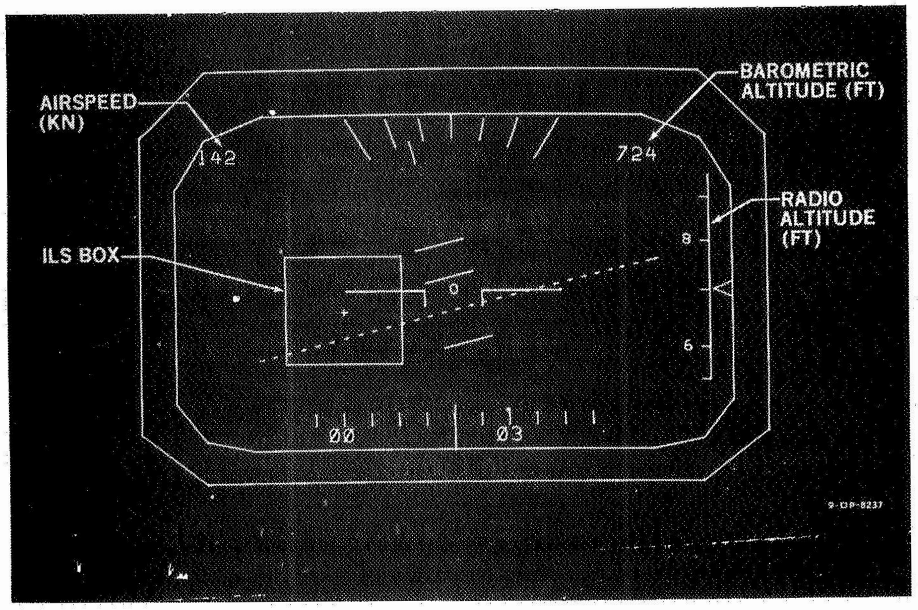

Figure 4.- EADI used for display to pilot.

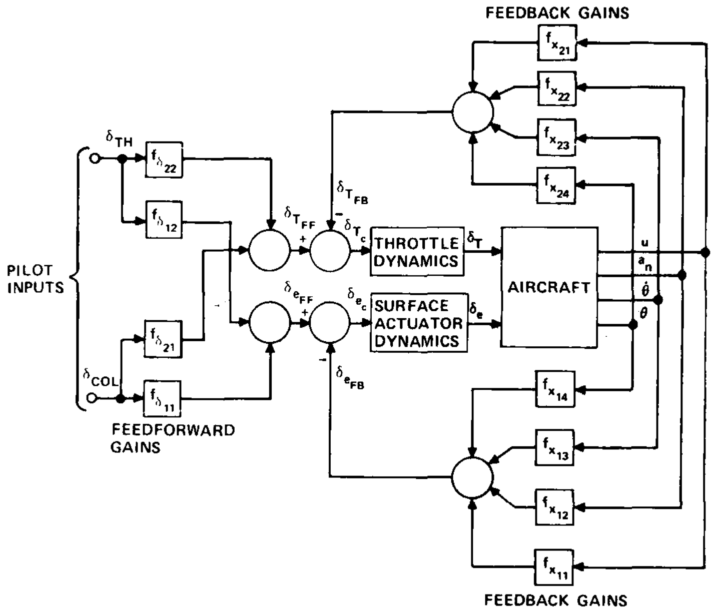

Figure 5.- Longitudinal augmentation system.

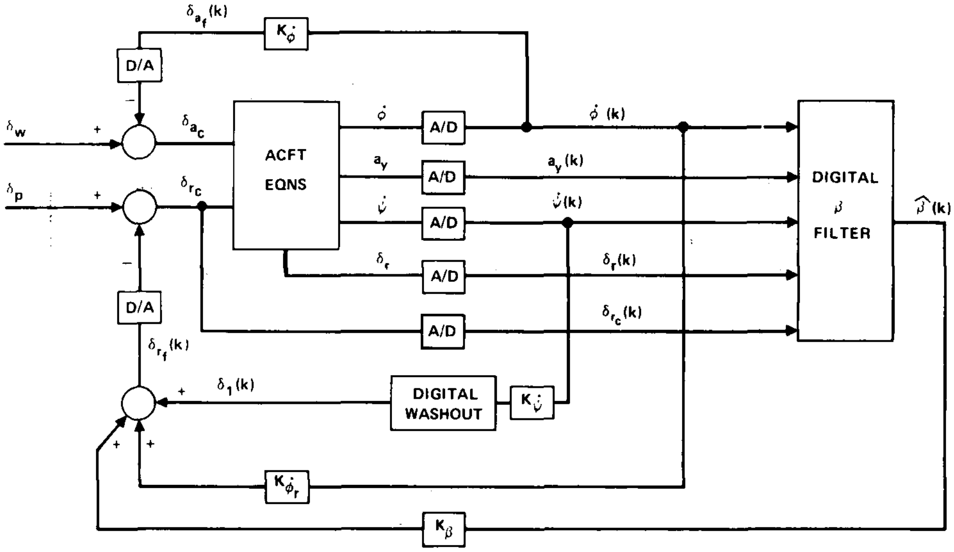

Figure 6.- Lateral augmentation system.

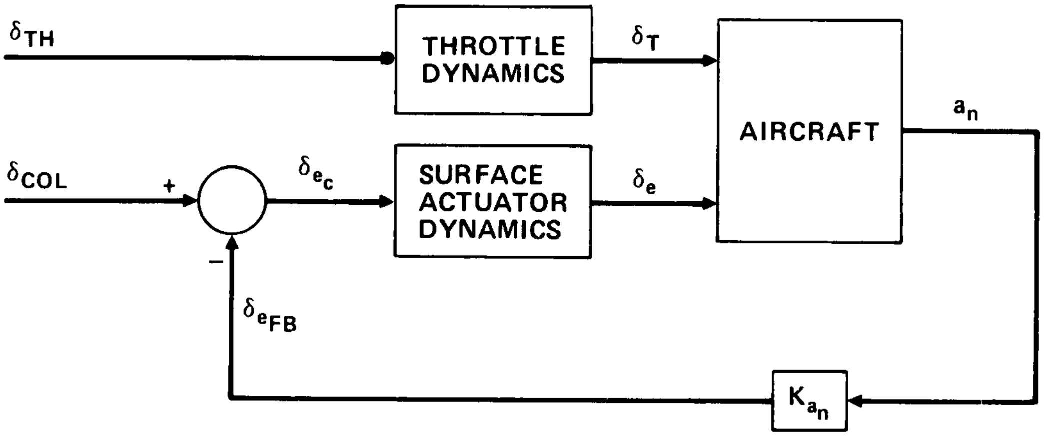

Figure 7.- Hard stability augmentation system for longitudinal axis.

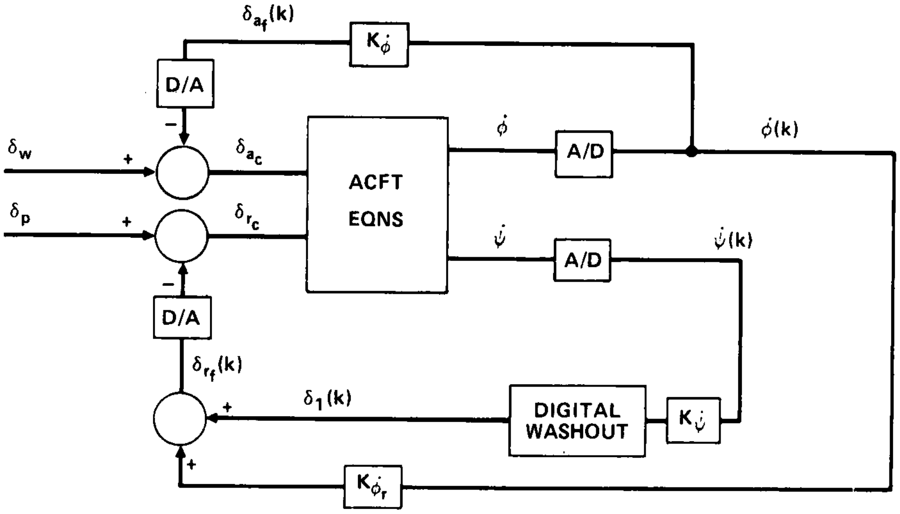

Figure 8.- Hard stability augmentation system for lateral axis.

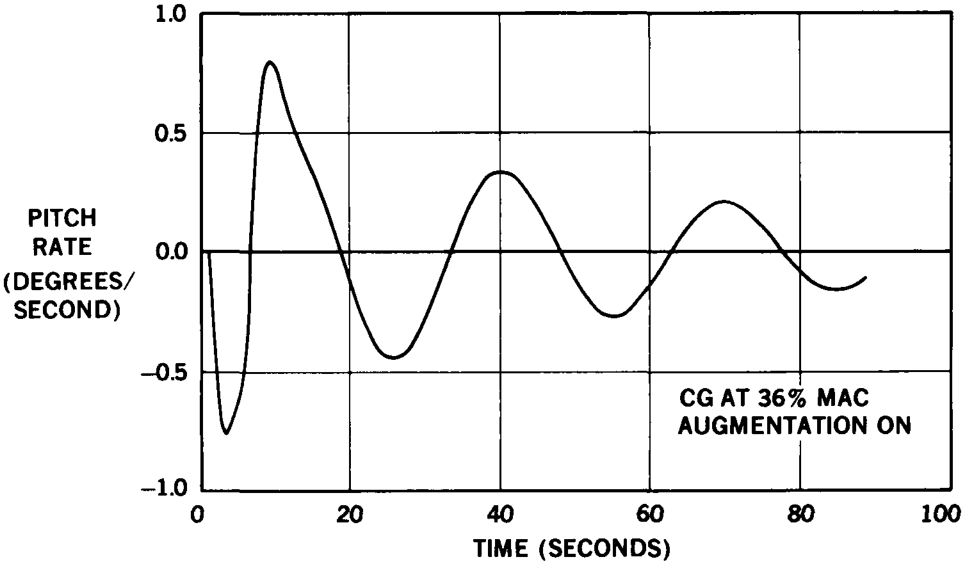

Figure 9.- Pitch rate response to a 1.0-degree step column command.

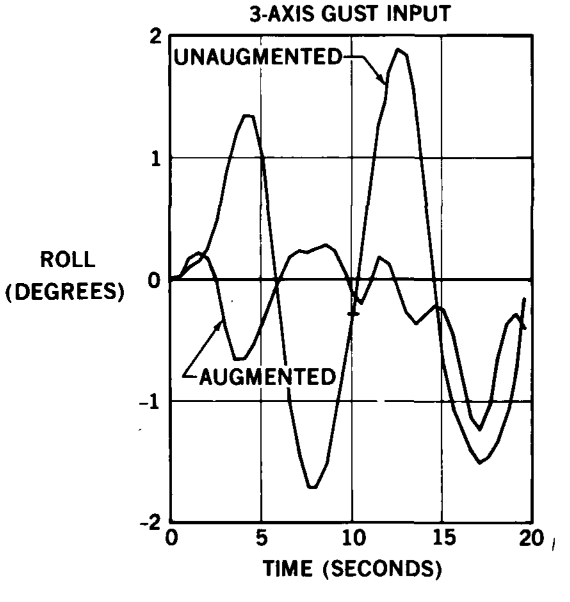

Figure 10.- Augmentation system reduction of wind gust inputs.

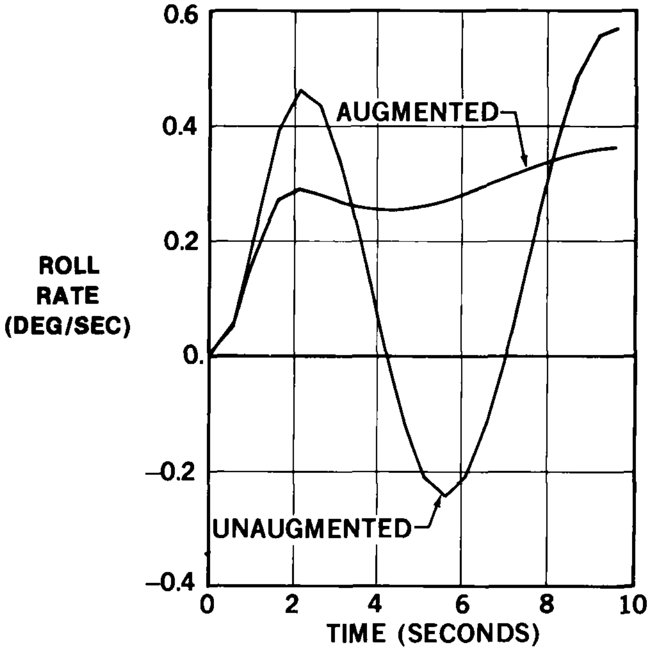

Figure 11.- Roll response to a 1.0-degree step wheel command.