

# ANALYSIS OF THE VISTA LONGITUDINAL SIMULATION CAPABILITY FOR A CRUISE FLIGHT CONDITION

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## ABSTRACT

The Variable Stability In-Flight Simulator Test Aircraft (VISTA) is the next generation US in-flight simulator for high-performance aircraft currently being developed by the US Air Force. VISTA is an F-16D in which the cockpit environment, feel, and flying characteristics can be changed to match a wide array of aircraft. While VISTA can simulate a wide range of dynamics, its capabilities are subject to certain practical limitations due to aircraft mass and inertia, available control power, actuator bandwidth, computational delays, structural modes, etc.

The purpose of this analysis is to estimate the range of dynamic response characteristics that the VISTA can simulate for the longitudinal mode of an up-and-away flight condition. The analysis matched the angle-of-attack time response of a Low-Order Model (LOM) to a linear simulation of the VISTA aircraft for a range of feedback gain sets. In the analysis presented here, a frequency-domain matching technique with the equivalent time delay included in the optimization of the match was used. The effects of the feedback gain sets to the VISTA aircraft dynamics will be shown. The result of this analysis will be compared against the VISTA goal.

$\zeta_e$	Equivalent Damping Ratio
HOM	High Order Model
LOM	Lower Order Model
$N_z$	Normal Acceleration at CG
$G_z$	Normal Acceleration Gain
$q$	Pitch Rate
$G_q$	Pitch Rate Feedback Gain
$\lambda_1, \lambda_2$	Negative Roots of Second Order Transfer Function
TPS	Test Pilot School
VISTA	Variable Stability In-Flight Simulator Test Aircraft

## 1. INTRODUCTION

The ability for VISTA to simulate other aircraft is provided by the Variable Stability System (VSS). The VSS is a network of three Rolm Hawk computers which compute control commands to the F-16 actuators to simulate flight characteristics of the vehicle under consideration. This involves interfacing the VSS with the existing F-16 digital fly-by-wire control system. The VSS will use the response-feedback technique to match the motions of the aircraft being simulated. Gain scheduling will be incorporated to account for nonlinearities in the aerodynamics.

VISTA has four primary applications. The first is in-flight simulation for new aircraft development and pre-first flight flying qualities test. The second is training test pilots in the Air Force and Navy test pilot schools. The third is flight control research on flying qualities. The fourth is flight vehicle integration studies of combat maneuvering and avionics/flight control system integration. VISTA is being built by General Dynamics with the Calspan Corp responsible for the development of the VSS.

## List of acronyms

ADPO	Advanced Development Program Office
$G_\alpha$	Alpha Feedback Gain
$G_{\dot{\alpha}}$	Alpha Dot Feedback Gain
$\alpha$	Angle of Attack
$\dot{\alpha}$	Angle of Attack Rate
$\tau_e$	Equivalent Time Delay
$\omega_e$	Equivalent Frequency

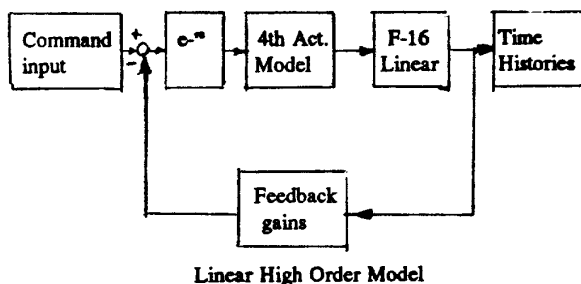
The baseline VISTA simulation envelope is defined to be 80-90% of the F-16D envelope and less than Mach 0.9. This represents a significant increase over the existing US. in-flight simulators. Figure 1 shows the flight envelopes of in-flight simulators.

## 2. ANALYSIS APPROACH

For this analysis, a non-real time, linear, six-degree-of-freedom, High-Order Model (HOM) simulation of the VISTA aircraft using Matrixx, a control design and analysis program, was used to determine the frequency response characteristics for a range of feedback gain sets. For each gain set, a frequency-domain matching program, McFit, was used to obtain a LOM for each set of gains. The range of LOM response characteristics were plotted to graphically illustrate the VISTA simulation capability.

### 2.1 High Order Model

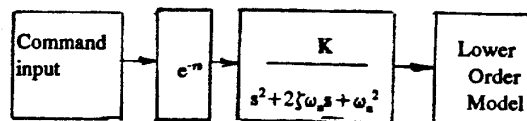
The HOM created with Matrixx consisted of linearized F-16 plant dynamics, fourth-order actuator models, and second-order Pade' approximation for 18 msec system transport time delay ( $e^{-s}$ ). The 18 msec system transport time delay was modelled for the Hawks computation. A block diagram of HOM is shown below. This model was validated with a check case from a nonlinear six-degree-of-freedom simulation. Time histories of the nonlinear simulation (Calspan's HOM) check case and the corresponding Advanced Development Program Office (ADPO) HOM response are shown in figure 2.



For longitudinal dynamics, there are four feedback gains: angle of attack ( $G_a$ ), angle of attack rate ( $G_{\dot{a}}$ ), pitch rate ( $G_p$ ), and normal acceleration ( $G_{\ddot{z}}$ ). The dynamics of VISTA can be altered by adjusting the feedback gains. For this analysis the range of values used for each feedback gain was limited to those used by Calspan in their analysis. The  $G_a$  was fixed at 0.0. The  $G_{\dot{a}}$  ranged from 0.0 to 6.0. The  $G_p$  ranged from 0.0 to 0.6. The  $G_{\ddot{z}}$  ranged from 0.0 to 0.1. The limits of these feedback gains were based on the Calspan experience. Different combinations of these feedback gains were set in the HOM on Matrixx. For combinations of these feedback gains, the transfer function of the delta elevator command to angle of attack response was determined.

### 2.2 Lower Order Model

Once the dynamic characteristics of the HOM were established for a given set of feedback gains, the McFit program was used to find the LOM which most closely matched the HOM transfer function. The form of the LOM used in this analysis is shown in the block diagram below. The LOM parameters were the equivalent time delay ( $\tau_e$ ), the equivalent damping ratio ( $\zeta$ ), the equivalent frequency ( $\omega_n$ ), and the equivalent transfer function gain ( $k$ ). Occasionally, the LOM denominator found by McFit consisted of two real roots instead of a complex pair. In such cases the denominator was described by  $(s + \lambda_1)(s + \lambda_2)$ .



Linear Low Order Model

### 2.3 Matching Technique

The McFit program was developed by the McDonnell Aircraft Company to be used to determine equivalent lower order models of highly augmented aircraft. It is frequently used by the Flight Dynamics Directorate and the Aeronautical Systems Division to determine compliance of such aircraft with the US military flying qualities specifications.

McFit will match, in the frequency domain, a high order transfer function or frequency response data with an equivalent reduced order model. It uses a weighted least-square optimal match of a high order frequency response in amplitude and phase angle at up to fifty frequencies in a user-specified frequency range. The program adjusts the parameters of the reduced-order equivalent system in an iterative multivariable search until a cost function is minimized. The cost function used in McFit is:

$$\text{Cost} = (20/n) \sum_{\omega_i} [( \text{gain}_{\text{HOM}} - \text{gain}_{\text{LOM}} )^2 + .01745 ( \text{phase}_{\text{HOM}} - \text{phase}_{\text{LOM}} )^2]$$

where: gain is in dB  
 phase is in degrees  
 $\omega$  is the input frequency  
 n is the number of discrete frequencies

For this analysis, the LOM was matched to the HOM at 30 frequencies in the frequency range from 0.1 to 15 rad/sec. Guidance in the flying qualities standard, MIL-STD-1797, recommended a frequency range of interest from 0.1 to 10.0 rad/sec unless the equivalent short-period frequency was greater than 10.0

rad/sec. In this analysis, there were several LOMs with equivalent short-period frequencies greater than 10.0 rad/sec. Therefore, 15 rad/sec was used as the upper frequency range limit for all matches done in this analysis. By doing this, the cost function would be the same for all matches. All of the parameters of the LOM were freed. That is, the search routine could adjust all of the parameters, including  $\tau_e$ , in the optimization of the match.

### 3. ANALYSIS RESULTS

The analysis effort concentrated on determining the VISTA simulation boundary in the longitudinal axis for the following cruise flight condition:

$V_i = 350$  kts (indicated air speed)  
Mach = 0.78  
Gear and Flap up  
Altitude = 20,000 feet above sea level

#### 3.1 VISTA Short-Period Simulation Boundaries

The predicted VISTA short-period simulation boundary is graphically depicted in figure 3. This figure requires some explanations to assist interpretation. The scale across the bottom is  $2\zeta_e\omega_e$  or  $\lambda_1 + \lambda_2$ . The scale on the right-hand is  $\omega_e^2$  or  $\lambda_1\lambda_2$ . The scale of the left-hand side is  $\omega_e$  or square root of  $\lambda_1\lambda_2$ . The parabolic lines represent lines of constant equivalent damping ratio,  $\zeta_e$ . This form allows plotting of complex pairs and real pairs on the same plot. The thick lines indicate the boundaries of VISTA short-period simulation capabilities as a function of equivalent time delay. The bottom boundary is the  $G_a = 0.0$  limit. The top boundary is the  $G_a = 6.0$  limit. The left most boundary is the  $G_q = 0.0$  limit. The boundary in the upper left corner is the  $G_q = 0.6$  limit. The  $\tau_e = 80$  msec line is the second line from the left. Any points on this line can be simulated with no less than 80 msec of equivalent time delay. For this flight condition, the VISTA aircraft could not simulate dynamics with less than 70 msec of equivalent time delay. The boundary on the far right is the  $\tau_e = 120$  msec line. Of course, the VISTA aircraft can simulate dynamics with higher time delay than 120 msec. However, the VISTA ADPO did not have enough points to describe the VISTA simulation boundary beyond this line.

The  $\tau_e$  boundary lines indicate that it requires a higher equivalent time delay to simulate higher equivalent short-period frequencies or damping ratio. For example, looking at figure 3 it requires approximately 85 msec of equivalent time delay to simulate an airplane with  $\omega_e = 5$  rad/sec and  $\zeta_e = .2$ . It requires approximately 94 msec of equivalent time delay to simulate an aircraft with  $\omega_e = 5$  rad/sec and  $\zeta_e = .6$  rad/sec. It requires approximately 114 msec of equivalent time delay to simulate an aircraft with  $\omega_e = 10$  rad/sec and  $\zeta_e = 0.6$ . Using category A flying qualities in the standard handbook, MIL-STD-1797, the  $\tau_e$ ,  $\omega_e$ ,  $\zeta_e$  boundary lines also describe the VISTA simulation capabilities in terms of flying qualities in figure 4. Figure 5 shows the predicted VISTA short-period simulated boundary overlaid with the VISTA goal.

#### 3.2 Relationship Between Feedback Gains and LOM Dynamics

Figures 6-9 show the relationships between the feedback gains and

equivalent dynamics of the LOMs. Figure 6 shows a short period frequency as a function of  $G_q$  and  $G_a$ . While holding the  $G_a$  and  $G_z$  constant and increasing  $G_q$ , the frequency will increase respectively. Figure 7 shows a short period damping ratio as a function of the  $G_a$  and  $G_q$  with the  $G_z$  fixed at 0.0. The damping ratio increased faster at a low  $G_a$  than a higher  $G_a$  with higher  $G_q$ . Figure 8 shows an equivalent time delay as a function of the  $G_a$  and  $G_q$  with the  $G_z$  fixed at 0.0. The equivalent time delay increased faster at a low  $G_a$  than a higher  $G_a$  with higher  $G_q$ .

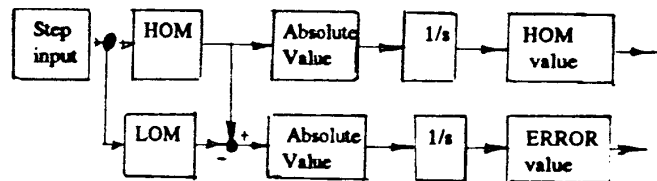
#### 3.3 Time Integral Error Model

The analysis described in this paper measures the LOM match to the HOM by the cost function as described above. To comply with one of the VISTA statement of work requirements, this analysis used the following equation for the time integral error.

$$\frac{1}{\Delta} \int_{t_1}^{t_2} |X_{\text{model}} - X_{\text{vista}}| dt \leq .15 \quad \frac{1}{\Delta} \int_{t_1}^{t_2} |X_{\text{model}}| dt$$

Where:  $X_{\text{model}}$  is the model representing the HOM  
 $X_{\text{vista}}$  is the model representing the LOM  
 $t_1$  is the beginning of the time interval of interest  
 $t_2$  is the end of the time interval of interest  
 $\Delta = t_2 - t_1$

The block diagram below represents the above equation.



For this analysis, the  $X_{\text{model}}$  was the ADPO's linear model on Matrixx for each of the five gain sets. For each linear model, the corresponding  $X_{\text{vista}}$  was determined from McFit. A step input with a magnitude of one was used, and the time interval of interest was from 0 to 4 seconds. The following table contains the result of LOM matches for five selected gain sets:

EQUIVALENT LOM						GAIN SETS		
conf. no.	$\xi$	$\omega$ (rad/sec)	Time delay (msec)	Cost	%integ. Error	$G_x$	$G_y$	$G_z$
1	0.04	5.8	83	4.0	3.2	2.0	0.1	0
2	0.15	6.3	88	5.6	2.2	2.0	0.2	0
3	0.58	5.4	97	7.6	1.2	1.0	0.3	0
4	0.31	10.31	109	16.9	2.2	3.0	0.5	.05
5	0.68	12.2	123	19.9	1.6	2.0	0.6	0

#### 4. OBSERVATIONS

Based on this analysis, the VISTA simulation boundary was formed for the longitudinal axis. There are couple of things to remember:

4.1 The LOM match ignored the phugoid mode of the HOM.

4.2 Compare the LOM time history with the HOM time history respectively to check the model fidelity by using the time integral error criterion.

4.3 Sometimes, the McFit matching program did not match the HOM very well for the case where the HOM had overdamped characteristics. In other words, the HOM has two real roots instead of two complex roots. It can be matched better with the first order LOM instead of the second order LOM.

4.4 The analysis found that there was a slight difference in the dynamic response for the pitch rate HOM match compared to the alpha HOM match. Some of the pitch rate HOM matches did not pass the time integral error criterion of the statement of work, while the alpha HOM matches did. Both HOMs used the same feedback gains. The difference between the LOMs was the damping ratio. The plots of the pitch rate and the alpha HOM match are shown in figures 9a and 9b respectively.

#### 5. CONCLUSION

The analysis presented in this paper indicates that the VISTA aircraft does not meet the goal for up-and-away short-period mode. VISTA does not meet the requirement for having less than 70 msec of equivalent time delay between the model and VISTA aircraft response for an aircraft with no time delay. This will have less affect in practice because all modern aircraft have time delay due to actuators and computations from hardware and software. It

should be pointed out that the goals for the VISTA simulation dynamics were based on the incorporation of high bandwidth actuators. Instead, baseline VISTA will use the existing F-16 actuators with resulting decreasing performance capability. Although not validated by the VISTA ADPO, Calspan's analysis demonstrates that the VISTA aircraft meets the goal for power approach short-period modes. It also meets the goal for the lateral-directional modes for both up-and-away and power approach flight conditions.

#### References

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- [3] General Dynamics, 'Class II-1 Modification Document for VISTA,' Preliminary Document, March, 1989.
- [4] General Dynamics, 'Critical Design Review Viewgraphs,' VISTA CDR, October, 1989.

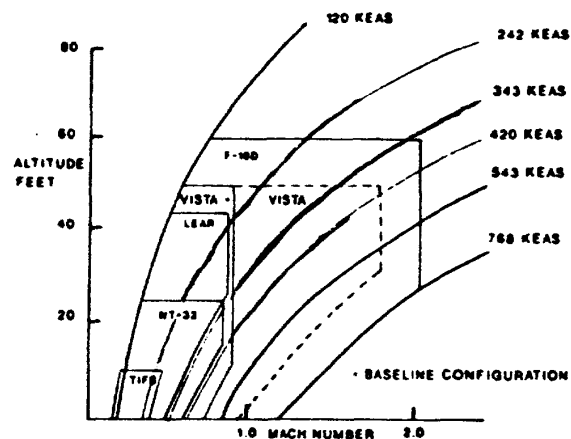
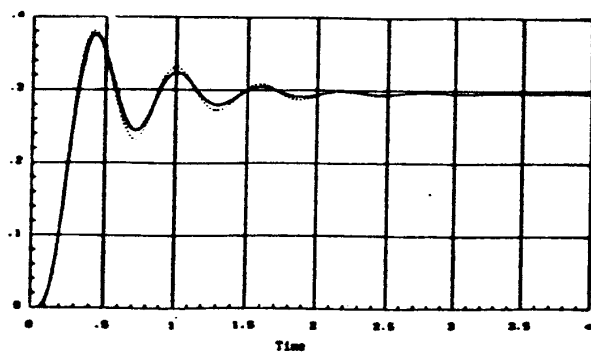


Fig. 1 U.S. Simulators Performance Envelopes

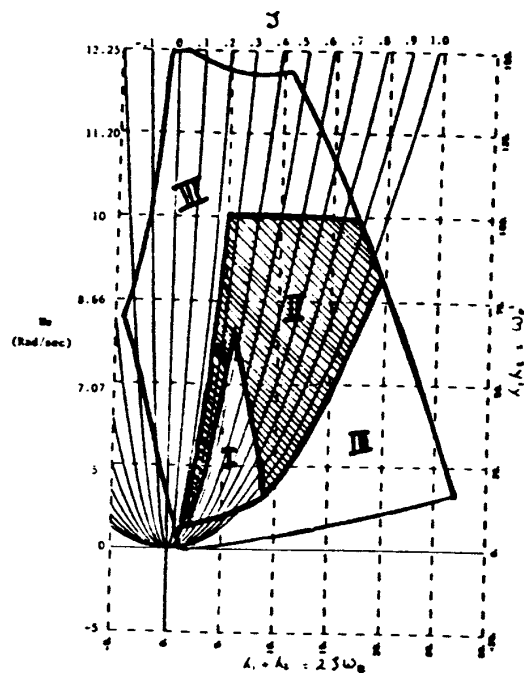
# ALPHA TIME RESPONSE



$$G_A = 3.0 \quad G_A' = 0.05 \quad G_A = 0.5$$

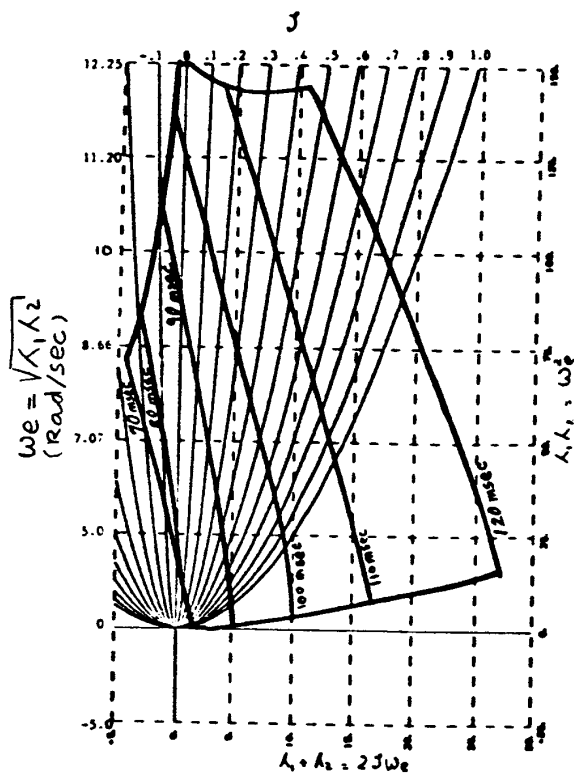
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Fig. 2



Longitudinal Mode (Short Period Frequency)

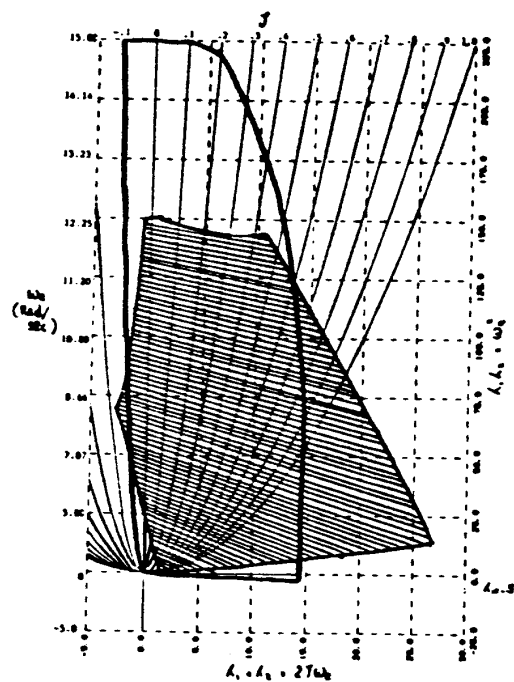
Mach = 0.78      Altitude = 20,000 ft



Longitudinal Mode (Short Period Frequency)

Mach = 0.78      Altitude = 20,000 ft

Fig. 3



Longitudinal Mode (Short Period Frequency)

Mach = 0.78      Altitude = 20,000 ft

Shaded Area - Analysis Results

Fig. 5

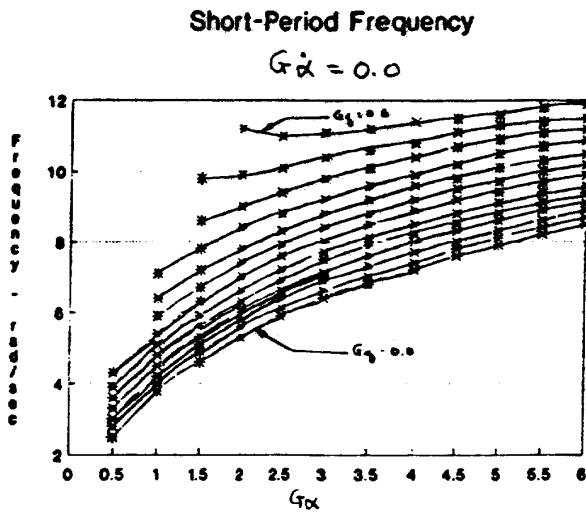


Fig. 6

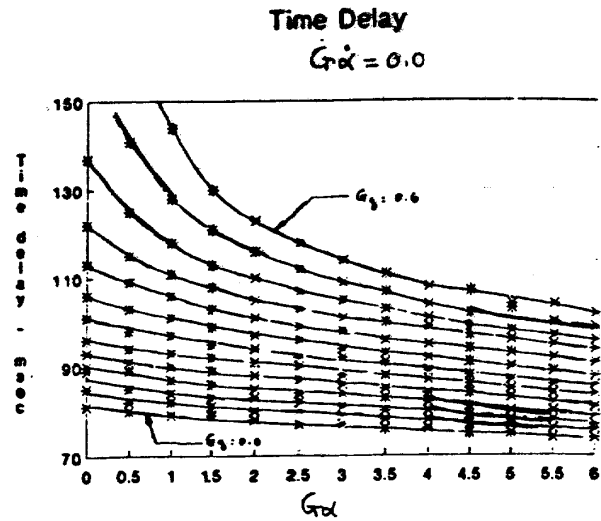


Fig. 8

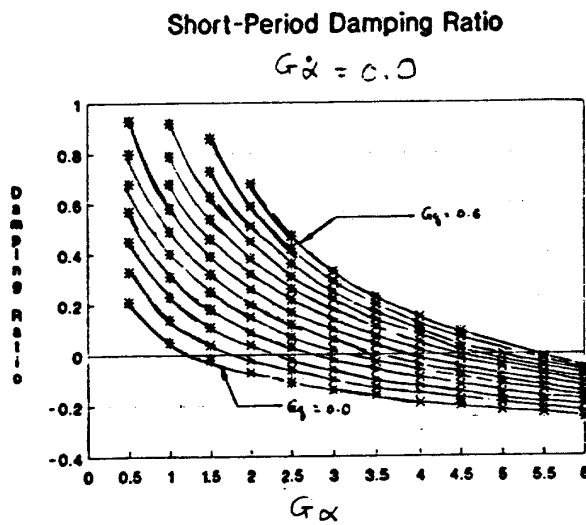


Fig. 7

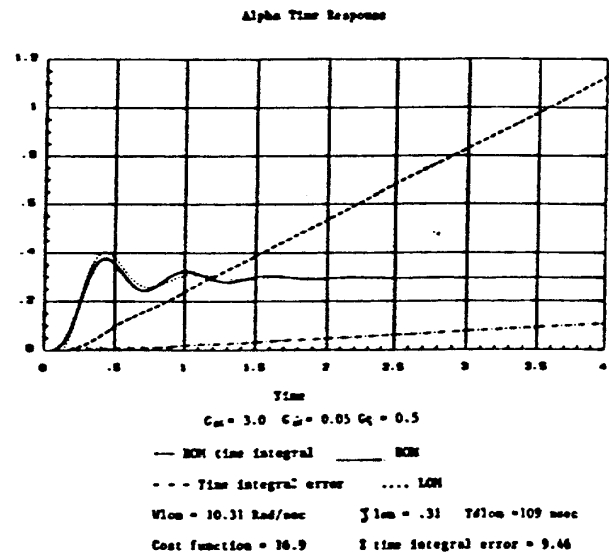


Fig. 9a

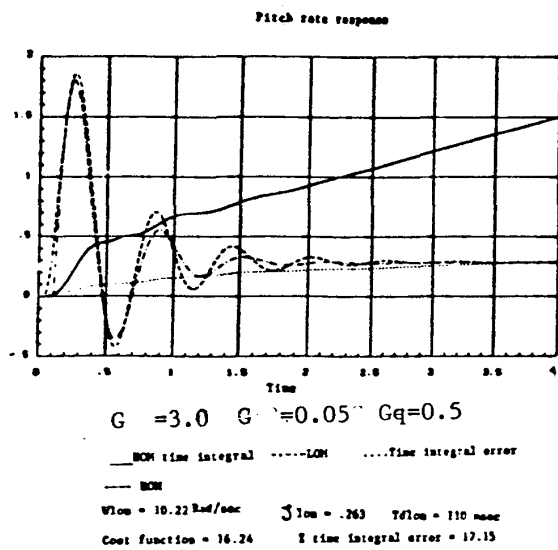


Fig. 9b