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SIMULATION STUDY OF GUST ALLEVIATION IN A TILT ROTOR AIRCRAFT VOLUME I

A. K. AMOS
H. R. ALEXANDER

JUNE 1977

PREPARED UNDER CONTRACT NAS2-8048-4R

FOR

NATIONAL AERONAUTICS AND SPACE ADMINISTRATION
AMES RESEARCH CENTER

BY

BOEING VERTOL COMPANY
A DIVISION OF THE BOEING COMPANY
P. O. BOX 16858
PHILADELPHIA, PENNSYLVANIA 19142

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FOREWORD

The studies summarized in this report were performed by the Boeing Vertol Company for the National Aeronautics and Space Administration, Ames Research Center under NASA Contract NAS2 8048-4. Mr. T. Galloway was the NASA Technical Monitor over the greater part of the program; Mr. G. Callas was the Technical Monitor for a short time at the beginning of the program.

Mr. H. R. Alexander was the Boeing Vertol Project Manager. Dr. Anthony K. Amos was Project Engineer for methodology and dynamic simulation development. Mr. J. P. Magee, Tilt Rotor Program Manager, and M. A. McVeigh, who developed the basic vehicle simulation, also made significant contributions. Very substantial contributions were also made by George Knott and Austin Mollenkoff of the Simulation Staff of Boeing Computer Services.

ABSTRACT

The response to vertical turbulence in cruise of the HTR XV-15 design is studied. This design is a modified version of the XV-15 with a hingeless fiberglass soft-in-plane rotor system. The parameters of a gust alleviation system are determined and the performance of the system is evaluated over a range of cruise velocities and altitudes. The study is performed using simulation techniques and the mathematical model includes detailed dynamic representation of the wing and rotor. Volume I is the summary report of the study, while Volume II contains details of analytical and other data used in the study.

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SUMMARY

This document reports a study of the gust response characteristics and the design of an alleviation system for the HTR XV-15. This tilt-rotor aircraft design is a version of the XV-15 which incorporates a 7.93m (26 foot) diameter soft-in-plane hingeless rotor.

The need for gust alleviation in tilt-rotor aircraft is discussed in Section 1, and the position is taken that it will be necessary for passenger acceptance of the concept because of the relatively low altitude and, therefore, frequent occurrence of turbulence. The need for inclusion of detailed rotor effects is justified on the basis of the low frequency of the rotor regression modes, and the possibility that alleviation of the airframe response might at the same time increase the response of the rotor system. A brief review of recent related work on gust alleviation is given.

Simulation is used as the principal mode of investigation because the contract had been initiated with the intention of including a pilot in the loop for subjective evaluation of the alleviation effectiveness. This necessitated development of the simulator mathematical model to include rotor dynamics (see Volume II) and of analytical methods discussed in Appendix I to process simulator data for system design.

An alleviation system was designed for a representative speed and altitude case and evaluated over a range of cruise altitudes and speeds. The system studied use flap and elevator control activated by a suitably shaped signal from an accelerometer located in the pilot cabin or a device sensing angle of attack. Up to 70% alleviation in cabin normal acceleration can be obtained with relatively simple flap-elevator system characteristics. Rotor response tends to remain approximately constant. Difficulties were experienced when A_1 B_1 cyclic control was added with the intention of reducing the level of rotor response. This can be resolved either by the use of additional sensing, (e.g., regulate rotor response independently of normal acceleration or angle of attack by direct sensing of hub moments) or by more accurate matching of transfer functions calculated from the methodology used in this study.

The present summary volume presents detailed derivation and results for a typical flight cruise condition. Appendix I gives an outline of methodology used to define alleviation system characteristics and Appendix II presents additional response and analysis data for the subject flight condition. Volume II compiles basic response data, and required control characteristics for a range of altitudes and speeds. Volume II also contains details of the analytical approach to the inclusion of rotor dynamic effects in the simulation mathematical model.

1.0 INTRODUCTION

1.1 BACKGROUND

Recent studies of alternative vehicles for short-haul air transportation concepts utilizing rotors (Reference 1) suggest that the tilt-rotor configuration is an economically alternative candidate in this role. These studies showed that the tilt rotor would have wing loadings similar to modern fixed-wing transports because the configuration derives its VTOL or STOL capability from the rotor. Thus, in cruise flight the sensitivity of the tilt rotor to vertical gusts would be of a similar magnitude to that of conventional fixed-wing transports. For several reasons this represents less than a satisfactory ride quality situation.

For example, the tilt-rotor aircraft in short-haul operation will cruise at altitudes in the 3,049-4,573m (10,000-15,000 feet) range and the intensity and probability of occurrence of severe turbulence, is therefore greater than is the case with conventional long range transports which typically cruise at much higher altitudes. In addition, in short-haul operation there is little opportunity to avoid reported turbulence regions by changes of course or altitude.

It therefore seems likely that alleviation of turbulence response will be required since passenger acceptance will be related to the ride experienced in high altitude jet aircraft.

1.2 SEVERITY OF THE PROBLEM AND COMPARISON WITH CONVENTIONAL AIRCRAFT TYPES

Figure 1.1 shows an estimate of gust sensitivity levels for the 100 passenger tilt-rotor transport studied in Phase I of this contract and reported in Reference 1. The gust sensitivity acceleration per unit gust expressed as amplitude (g/ft/sec) varies inversely with gross weight. At the optimum cruise altitude 3811m (12,500 feet) the gust sensitivity is shown as exceeding the level specified by more than 100%. However, these gust sensitivities were derived from equivalent sharp-edged gust calculations as defined in FAA regulations and various military specifications.

A more widely accepted measure of ride quality is RMS response to random turbulence. Figure 1.2 shows the RMS response levels of an advanced version of the XV-15 tilt rotor using a soft-in-plane 7.93m (26-foot) diameter Boeing rotor system and compare it with the responses of several other aircraft. The relationship of these levels to subjective comfort levels are also shown in Figure 1.2. These criteria for degrees of discomfort due to "g" levels are based on experimental work from a number of sources (summarized in Reference 2). Since these criteria are expressed in terms of RMS levels of continuous sinusoidal vibration they may not adequately reflect adverse

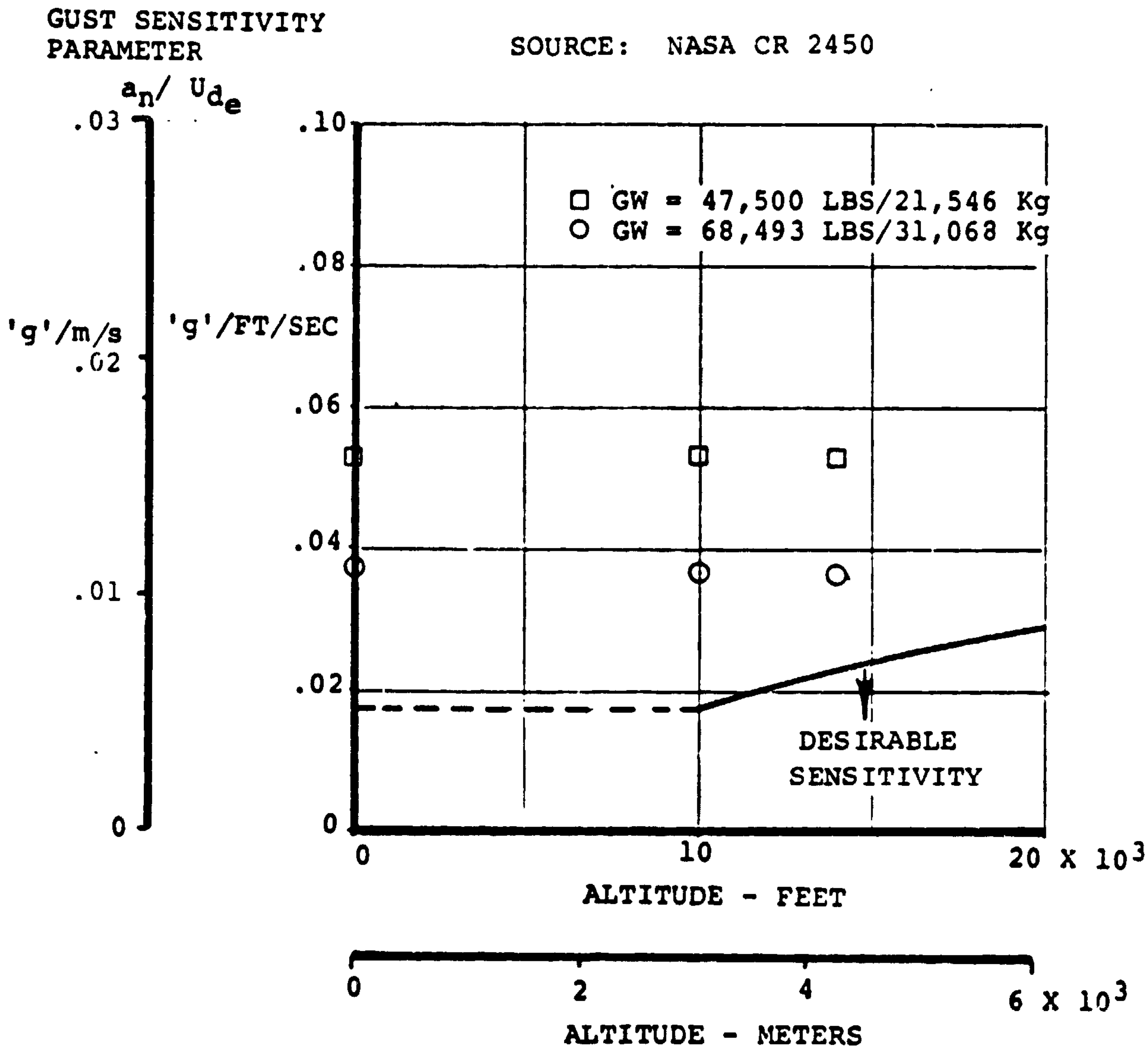

FIGURE 1.1. GUST SENSITIVITY WITHOUT ALLEVIATION OF A LARGE TILT-ROTOR TRANSPORT

HTR XV-15 RMS VERTICAL ACCELERATION IN 6 FT/SEC RMS TURBULENCE AND RELATION TO COMFORT RATINGS DERIVED FROM GROUND SIMULATION

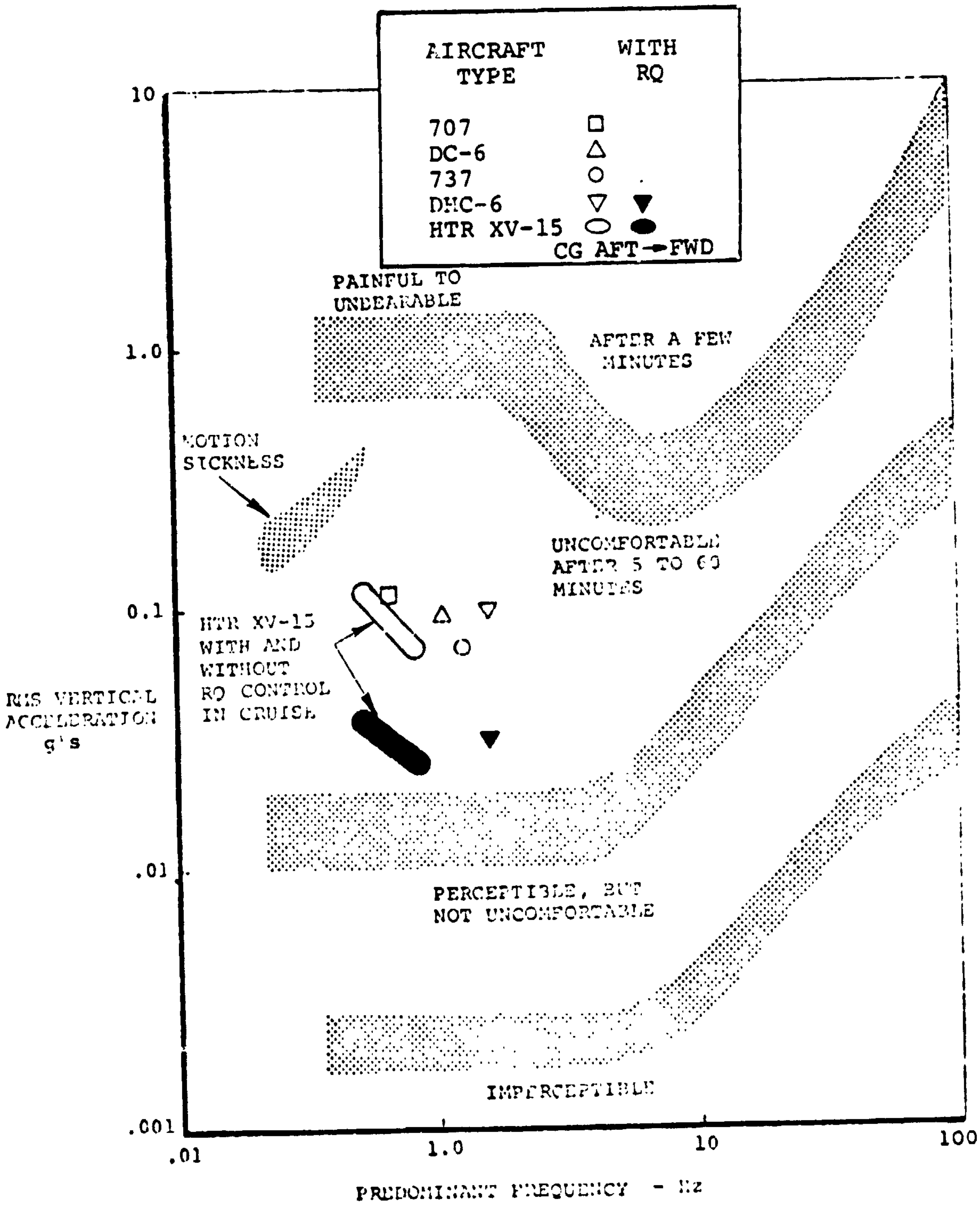

FIGURE 1.2. COMPARISON OF HTR XV-15 PILOT STATION VERTICAL ACCELERATION WITH COMFORT RATINGS AND EXISTING AIRCRAFT.

reaction of passengers to occasional large peaks, and other criteria indicate that levels of less than .11g RMS are desirable.

However, Figure 1.2 shows that the responsiveness of the HTR XV-15 in cruise to random vertical turbulence is approximately the same as that of the DC-6, DHC-6 and Boeing's 707 and 737. The reduction in response level provided by gust alleviation systems is also shown in Figure 1.2 for the HTR XV-15 and DHC-6. The selection of a HTR XV-15 gust alleviation system is discussed in other sections of this report.

As noted above the altitude of operation and consequent frequency of turbulence occurrence makes gust alleviation desirable in the tilt-rotor configuration and DHC-6 while the longer range higher altitude transports are marginally acceptable without alleviation.

1.2.1 Special Features of the Tilt-Rotor Configuration

Gust alleviation has been successfully implemented in a number of commercial passenger aircraft by systems employing main surface and empennage control motions geared to sensors measuring the intensity of the turbulence. It was expected that similar systems would be effective for the tilt-rotor configuration flying in the cruise mode, and such a system has been defined as part of the study undertaken during the subject contract. However, the presence of large rotors with low structural frequencies raised a number of questions about the response of the rotor blades and the potential impact on the gust response of the vehicle. The rotor modal frequencies ($\Omega-\omega\xi$) and ($\Omega-\omega\beta$),(associated with the regressive lead-lag and out-of-plane bending respectively), fall in the frequency range where there is a reduced but still significant level of gust intensity. An additional concern is that these frequencies are not widely separated from the frequency of the short period mode of the aircraft which ranges from about 0.5 Hz in the aft c.g. location at low speeds to frequencies greater than 1.0 Hz in high speed, forward c.g. flight conditions.

1.2.2 Availability of Rotor Cyclic Controls in Tilt Rotor

The presence of rotors and their control system present opportunities as well as potential problems. It may be asked whether cyclic or collective controls may be used to supplement or replace flaps and elevators for gust alleviation. In particular, can the cyclic controls be used effectively to reduce blade structural response in turbulence. Questions to be answered include whether a conventional gust alleviation system will worsen blade response and how are rotor controls to be integrated with a conventional control system to provide an acceptable combination of reduced blade response and improved ride quality.

1.2.3 Potential Worsening of Rotor Response by Use of Conventional Gust Alleviation System

Increased blade response might be anticipated as a result of using direct lift devices such as flaps and spoilers for gust alleviation. Since these systems reduce the normal response of the aircraft which has an alleviating effect on angle of attack, it might be expected that blade response would increase to the point where this would need to be alleviated by the application of rotor controls. This concern has to some extent been removed by the results of the subject study, although the use of rotor controls for general alleviation purposes has been addressed.

1.3 OBJECTIVES OF CURRENT STUDY

As a result of these special features, a study was initiated to address the following issues.

1. Evaluate magnitude of response to random turbulence without alleviation; identify preliminary design parameters of a flap-elevator alleviation system, and evaluate its performance.
2. What level of rotor response will be experienced in turbulence and how significant is it?
3. Will gust alleviation using flaps and elevators worsen the rotor responses

and necessitate additional cyclic control systems to alleviate rotor responses?

4. Conversely, will the performance of a flap-elevator system, designed to reduce cabin response, be adversely affected by uncontrolled rotor response?

5. Investigate preliminary design parameters of a system using cyclic controls in addition to flap and elevator, with objective of alleviating rotor and airframe response.

1.4 RECENT RELATED WORK ON GUST ALLEVIATION

1.4.1 Tilt Rotor Configuration

Recent work on the question of gust responsiveness of tilt-rotor aircraft has concentrated on the behavior of a cantilevered wing, rotor combination. References 3, 4 and 5 give results of experimental and analytical studies performed at the Aeroelastic and Structures Research Laboratory of the Massachusetts Institute of Technology. In References 6 and 7, Johnson and Frick lay down definitive groundwork for the application of optimal control theory to to the problem of prop-rotor/wing response to vertical gusts. In Reference 7, Johnson shows that rigorous application of optimal control requires feedback from almost all the wing/rotor states, and suggests as an alternative, the measurement of the exciting disturbance from which good estimates of the states may be obtained if an accurate model of the system is available. He also shows that a single controller, optimally designed for one speed condition, operated efficiently over the entire cruise speed range. He suggests that some programming of system parameters with nacelle tilt or speed may be necessary for low speed and transition conditions. He proposed as a next step the investigation of the response of a complete model of the aircraft including the rigid body flight modes and detailed representation of the control system.

1.4.2 Other Configurations

A number of studies of gust alleviation have appeared recently for fixed wing and helicopter aircraft. Reference 8 is a study of gust alleviation in short-haul aircraft of fixed-wing configurations designed to field lengths of 610m (2,000 Feet) and 914m (3,000 Feet). The effectiveness of gust load alleviation and ride quality control system and the impact on aircraft gross weight and price is evaluated. This study differentiates between systems designed to alleviate structural loads and those designed to less severe ride quality improvement criteria.

Results for a gust alleviation study of the DHC-6 Twin-Otter are given in Reference 9 and show that substantial improvements in ride quality are obtainable for little additional cost.

Helicopter gust suppression techniques are studied analytically for the CH-53 in Reference 10. These results show that up to seventy-five percent of the gust disturbances may be eliminated by the use of optimally designed feedback system.

1.5 SCOPE OF CURRENT PROGRAM

The investigations of tilt rotor behavior discussed above (Reference 7) apply powerful analytical technology to the prediction of the behavior of the prop-rotor/wing combinations. In the program reported here a simulation approach has been adopted, and the rigid body flight modes of the aircraft have been included in the mathematical model along with wing and rotor blade structural dynamics. The simulation model was based on a detailed full force model of the HTR XV-15 developed under Task I of NAS2-8048-4R contract and described fully in Reference 11. (Preliminary Simulation of an Advanced Hingeless Rotor XV-15 Tilt-Rotor Aircraft", M. A. McVeigh, NASA CR 151950, December 1976). A major part of the current activity was the addition of rotor and wing dynamics as optional features, and of the NASA Ames gust generator for random turbulence along with the capability to include a variety of feedback system parameters and shaping networks. The addition of rotor and wing dynamic effects is discussed in detail in Volume II. A simple approach to the definition of system parameters was developed and this uses frequency response data obtained from the simulation. Among the reasons for the adoption of a simulator approach in this investigation was a requirement to demonstrate the effectiveness of the gust alleviation system with a pilot in the loop: it subsequently became apparent that the cycle time required for wing and rotor dynamics was incompatible with real time simulation.

1.6 PRELIMINARY DISCUSSION OF RESULTS

The 240 Knot, 3,049m (10,000 Feet) condition was selected for initial definition of a flap-elevator alleviation system. The characteristics of the system selected were compared with those estimated for a matrix of condition over the range 200 to 280 Knots from 1524 to 4572m (5,000 to 15,000 Feet) altitude at forward and aft center of gravity locations. It was concluded that the requirements were sufficiently similar over the complete range that one set of system parameters might be expected to alleviate at all conditions. Figures 1.3 and 1.4 show the response of the principal variables without alleviation, while Figures 1.5 and 1.6 shows the same set of variables with the selected alleviation system working.

FLIGHT CONDITION: 240 KNOTS, 10,000 FEET, (3,049m), FORWARD CG

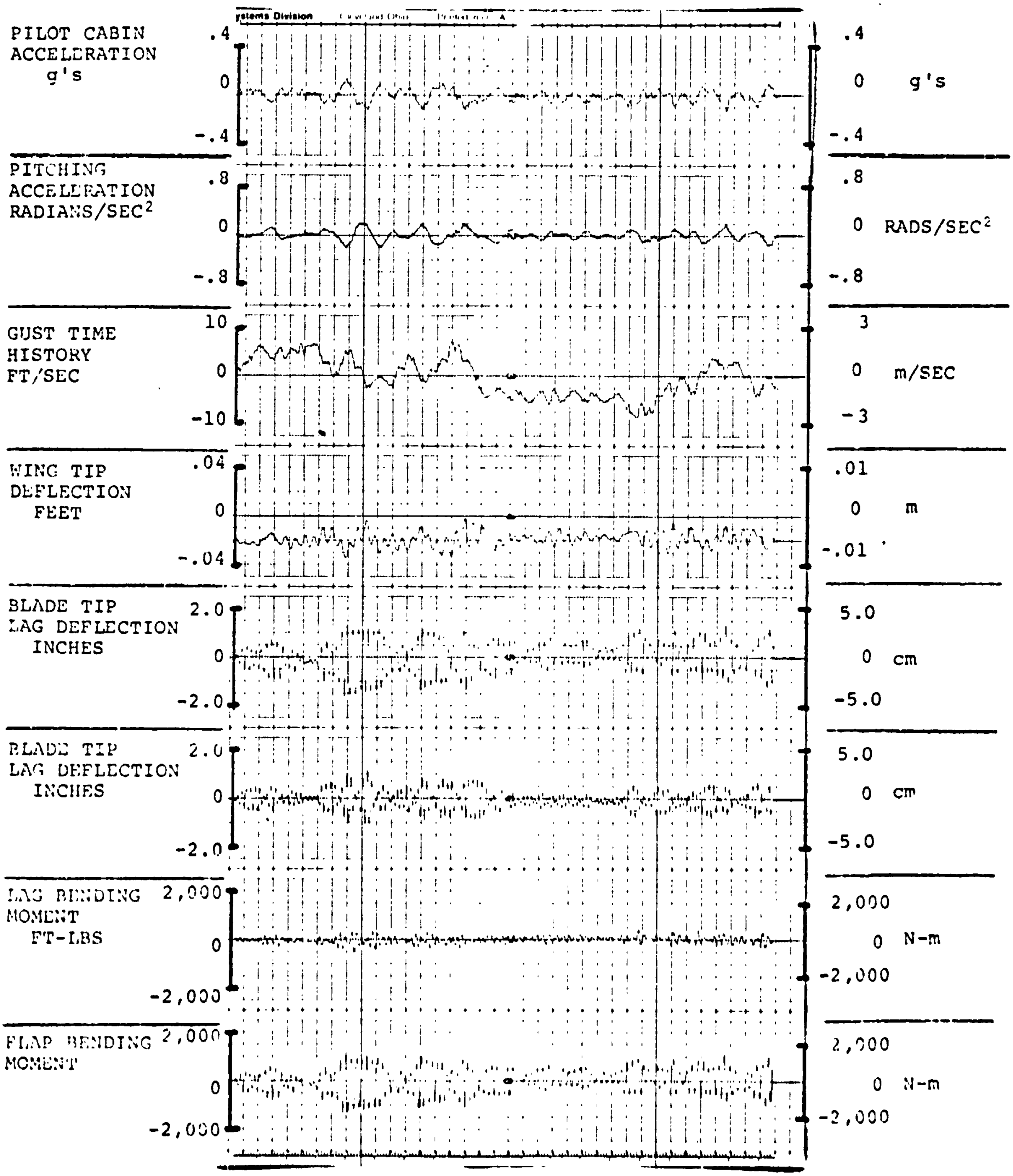

FIGURE 1.3. RESPONSES FOR GAIN F = 0, GAIN E = 0

FLIGHT CONDITION: 240 KNOTS, 10,000 FEET, (3,049m), AFT CG

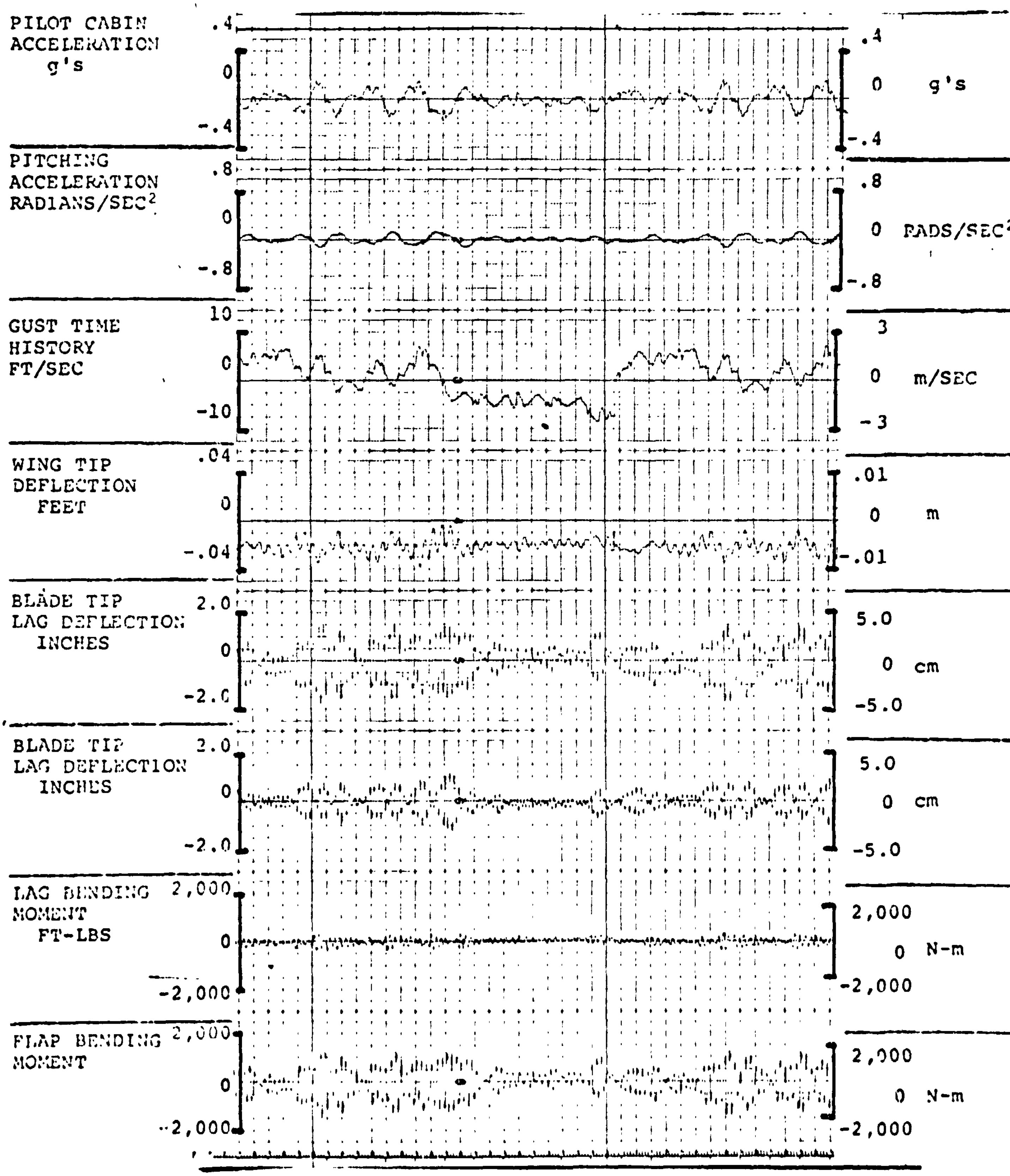

FIGURE 1.4. RESPONSES FOR GAIN F = 0, GAIN E = 0

FLIGHT CONDITION: 240 KNOTS, 10,000 FEET, (3,049m), FORWARD CG

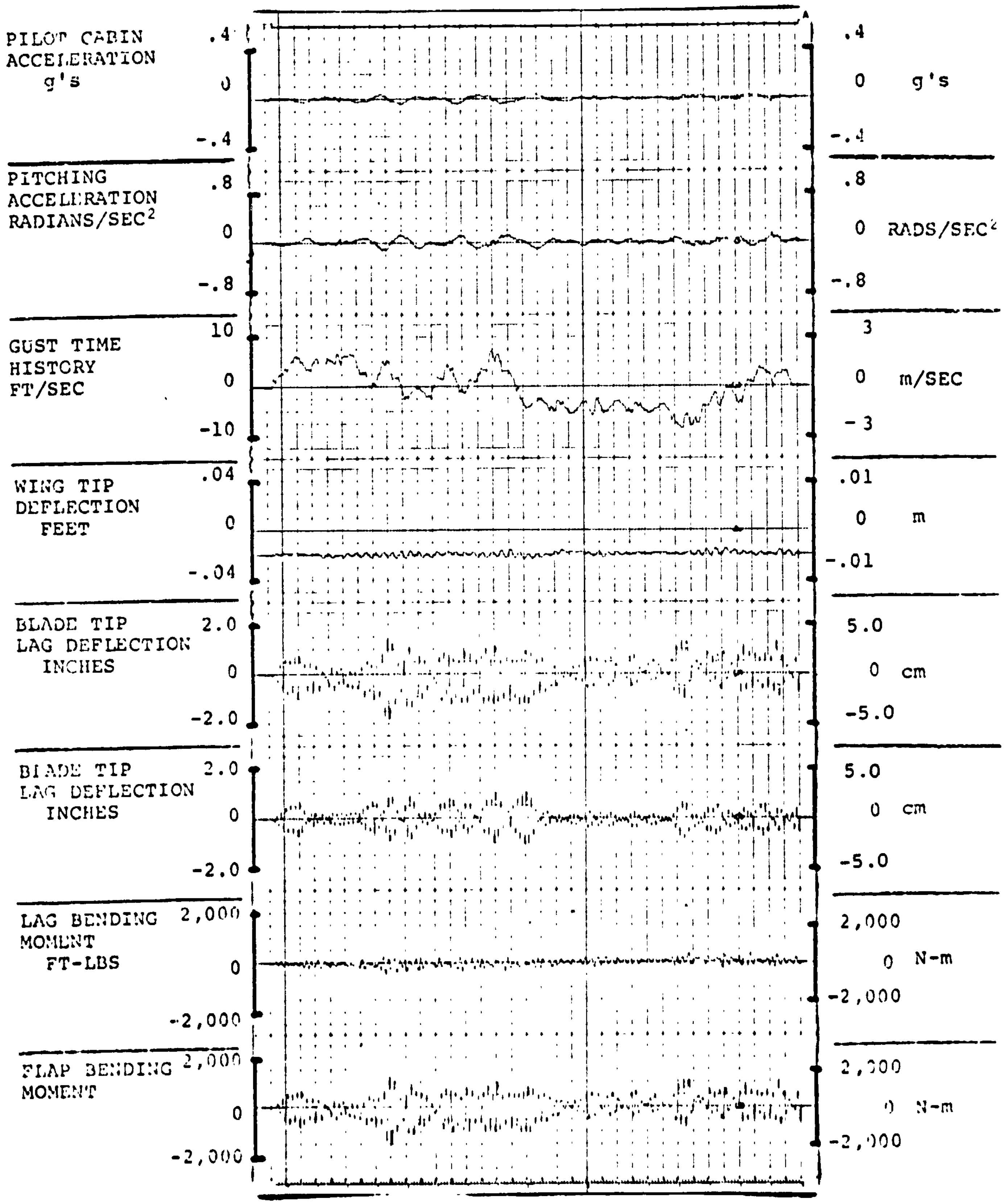

FIGURE 1.5. RESPONSES FOR GAIN F = 4.0, GAIN E = .6

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FLIGHT CONDITION: 240 KNOTS, 10,000 FEET, (3,049m), AFT CG

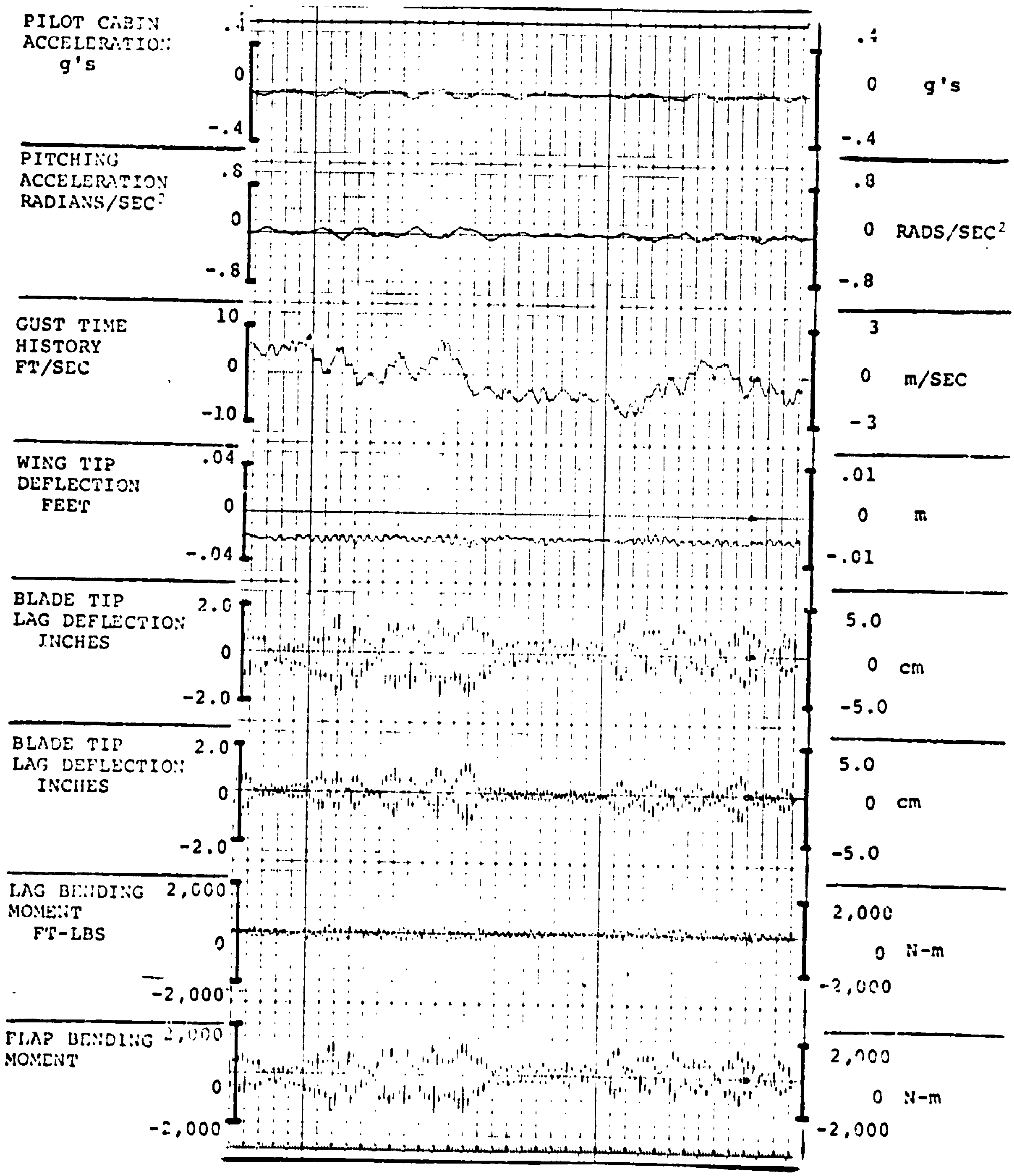

FIGURE 1.6. RESPONSES FOR GAIN F = 4.0, GAIN E = .6

A very high level of alleviation is achieved in cabin normal acceleration. Pitching acceleration is reduced by a lesser amount because the elevator gain $\delta E/g$ was restricted by stability considerations; at the aft c.g. condition, a long period instability develops at elevator gain levels approaching those needed to provide equal attenuation in pitching and normal acceleration response. Improved shaping of the elevator feedback signal would eliminate this restriction. The presence of the gust alleviation system does not produce an appreciable difference in the levels of blade loads or deflections. This is significant. Earlier intuitive discussions of gust alleviation by the use of flap for direct lift control envisioned increased blade loads. It was thought that these would occur as a result of the higher angles of attack which would be caused by restraining vertical acceleration. This reduces the natural alleviation of gust angles of attack associated with velocity of response in the vertical direction. The simulation showed this would occur if the aircraft is constrained in pitch; however, when account is take of the pitching response of the aircraft, the blade loads tend to remain at a fairly constant level.

Cabin normal acceleration alleviation factors attained by the flap-elevator system selected are shown in Tables IA and IB. Table IA shows factors for peak accelerations

TABLE IA. ATTENUATION OF PEAK NORMAL ACCELERATIONS WITH SELECTED SYSTEM

SPEED KNOTS	CG LOCATION	ALTITUDE 1,524m 5,000 FT	3,049m 10,000 FT	4,573m 15,000 FT
200	FWD	.70	.64	.62
	AFT	.69	.69	.67
240	FWD	.70	.69	.67
	AFT	.72	.69	.68
280	FWD	.81	.77	.72
	AFT	.71	.76	.67

TABLE IB. REDUCTION FACTOR ON RMS NORMAL ACCELERATION IN CABIN

SPEED KNOTS	CG LOCATION	ALTITUDE 1,524m 5,000 FT	3,049m 10,000 FT	4,573m 15,000 FT
200	FWD	.68	.60	.58
	AFT	.68	.64	.61
240	FWD	.68	.70	.63
	AFT	.71	.71	.66
280	FWD	.76	.73	.67
	AFT	.73	.72	.63

while RMS levels are listed in Table IB. In this system cabin acceleration is sensed and used as a feedback signal which drives the flaps and elevators. Suitable shaping is introduced so that the system does not interfere with normal maneuvering commands, while providing specified levels of alleviation. An alternative system sensing fuselage angle of attack was examined for a limited number of flight conditions and was found to give similar results. Rotor response was not found to be a problem and satisfactory alleviation of cabin acceleration was demonstrated using only flap and elevator controls. Nevertheless, the use of A_1 and B_1 cyclic controls in conjunction with flap and elevator was explored with a view to providing specified reductions in rotor hub moments and blade bending, along with improved vehicle response. This investigation was pursued even though blade response turned out to be less of an issue than preliminary reasoning had indicated, because it is believed that the use of rotor controls will play an important part in the suppression of lateral direction and assymetric turbulence. In the lateral case rotor cyclic control may be envisioned as providing the side force equivalent of direct lift control. That is to say, A_1, B_1 cyclic and rudder would serve a similar purpose in the lateral case to that of flap and elevator in the vertical. However, the integration of all four controls, flap, elevator, A_1 and B_1 cyclic brought to light a number of difficulties which are discussed in Section 2.

In summary, preliminary design for a gust alleviation system has been successfully accomplished for a tilt-rotor aircraft with a hingeless soft-in-plane rotor system. The technical approach successfully identified a system which provides satisfactory attenuation of cabin normal and pitching acceleration responses: further work is required on the use of cyclic controls for the suppression of blade transient response and for vehicle gust alleviation in a general turbulence environment. Feedback signal shaping may be refined to maximize stability margins and provide additional attenuation of pitching response, if this is considered necessary.

2.0 TECHNICAL DISCUSSION

The problem addressed in this study is how the existing controls of the aircraft may be used to provide a specified attenuation of the response of selected aircraft variables. This was attempted at two levels. First, flap and elevator controls only are considered with the objective of reducing cabin normal acceleration and pitching acceleration; second, flap, elevator and the cyclic controls together were applied with the objective of reducing rotor hub pitching and yawing moments as well as the aircraft accelerations.

Assuming that the transfer function of each of the selected variables with respect to the gust and control inputs are known, it is possible to derive the control combination required to produce the desired effects in the selected variables. These controls may in turn be expressed in terms of some measure of the external disturbance. This arrangement is shown schematically in Figure 2.1. The response of the aircraft to a random disturbance U, pilot commands U_P and alleviates system control input V_A is governed by an equation of the form

$$[A]\ddot{q} + [B]\dot{q} + [C]q = F_o\, U + H_o\, (V_P + V_A)$$

$$\text{or } [G(s)]q = F_o\, U + H_o\, (V_P + V_A)$$

where A, B, C and matrices of coefficients describing the vehicle dynamics.

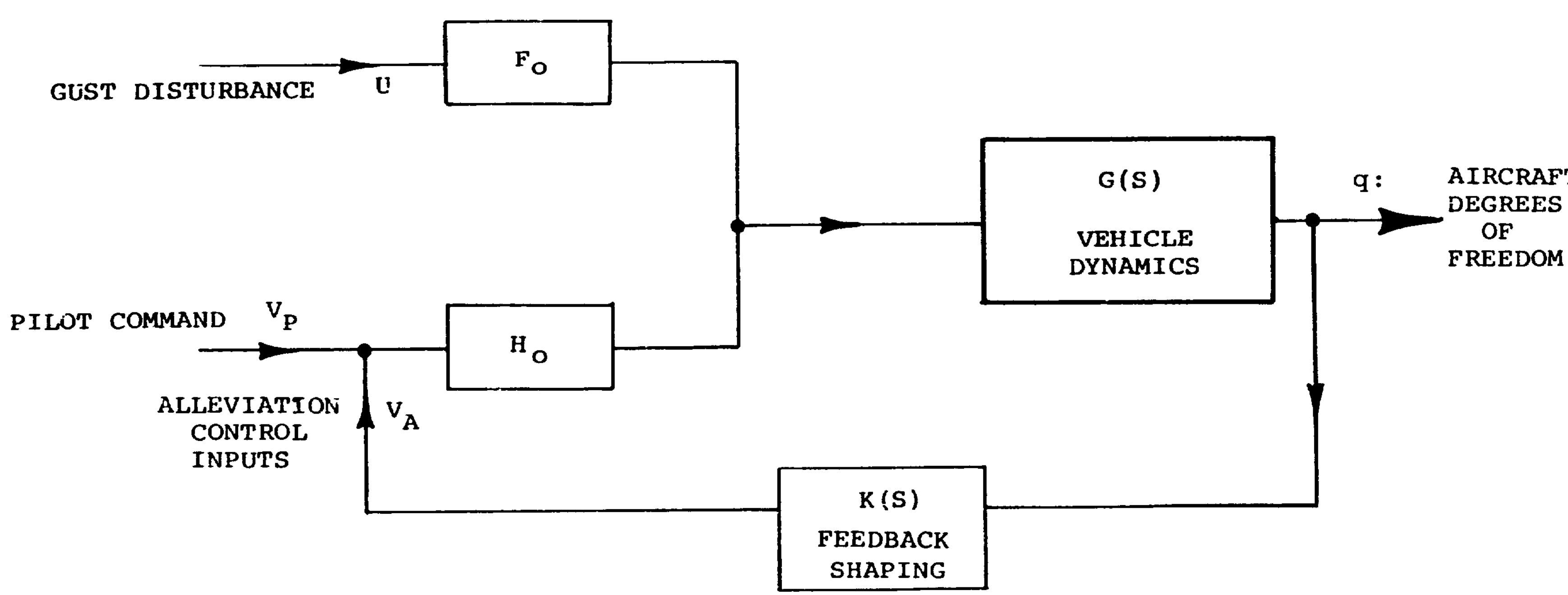

FIGURE 2.1. CONCEPTUAL SCHEMATIC OF ALLEVIATION SYSTEM.

F_o and S_o are matrix connecting inputs to generalized forces in the aircraft variables, and

$$[G(s)] = [As^2 + Bs + C].$$

The task of an alleviation system is to automatically provide control input V_P such that the behavior of the basic aircraft

$$q/u = 1/G$$

is modified to give a desired response characteristic

$$q/u = 1/G.^*$$

The problem then develops into one of identifying a suitable feedback transfer function $[K(s)]$.

In principle, this may be done analytically by algebraic manipulation of the transfer functions. However, when we are dealing with a multi-variable system and multiple controls it seems preferable to solve arithmetically for the control amplitudes and phases by repeated calculation at discrete frequencies. These may subsequently be converted to transfer function form. This method is discussed in detail in Appendix A.

2.1 RESPONSE DATA ACQUISITION

In order to effect this identification of control requirements, the frequency responses of the aircraft variables of interest were determined by forcing the simulation with sinusoidal inputs of gust flap elevator, A_1 and B_1.

Apart from the gust response, this is how one might acquire much information during a flight development program. The experience of handling data of this type was valuable because it displayed many of the features which we would expect to be present in data reduced from flight test records.

For example, errors in processing and scatter and other anomalies, had to be resolved expeditiously and with a minimum number of reruns.

Response data was generated for a matrix of speed, altitude and center of gravity conditions and resulted in data of the type shown in Figure 2.2 through 2.4.

Figure 2.2 shows for the forward center of gravity case, cabin normal acceleration and aircraft pitching acceleration due to sinusoidal gusts on the frequency range .2 to 5.0 Hz. Figures 2.3 and 2.4 show the response of these variables to flap and elevator inputs over the same frequency range.

Appendix B contains the complete set of 240 Knot data for forward and aft center of gravity locations including center of gravity, angle of attack and hub moment response to cyclic control inputs.

2.2 INFLUENCE OF GUST SPECTRUM; AND PERFORMANCE REQUIRED BY ALLEVIATION SYSTEM

The gust responses shown are for continuous sinusoidal turbulence of constant amplitude. When the frequency

240 KNOTS, 3049M (10,000 FEET), FORWARD CG
$\omega_g = \pm 5$ FT/SEC

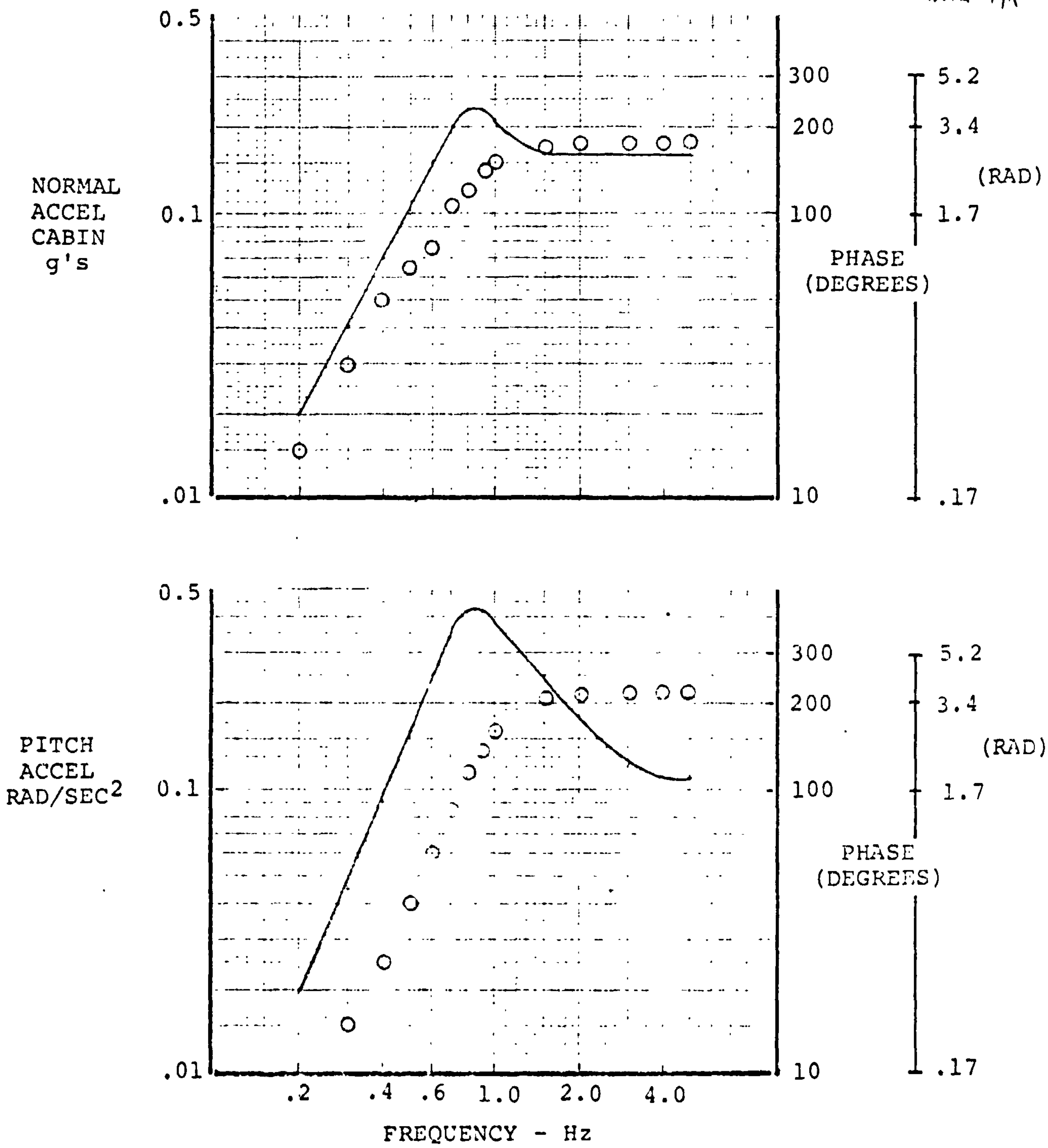

FIGURE 2.2 . FREQUENCY RESPONSE OF CABIN NORMAL AND PITCH ACCELERATIONS DUE TO VERTICAL GUST (240 KNOTS, 3049 METERS, FORWARD CG)

240 KNOTS, 3049M (10,000 FEET), FORWARD CG

$\delta_F = \pm 1.0°$

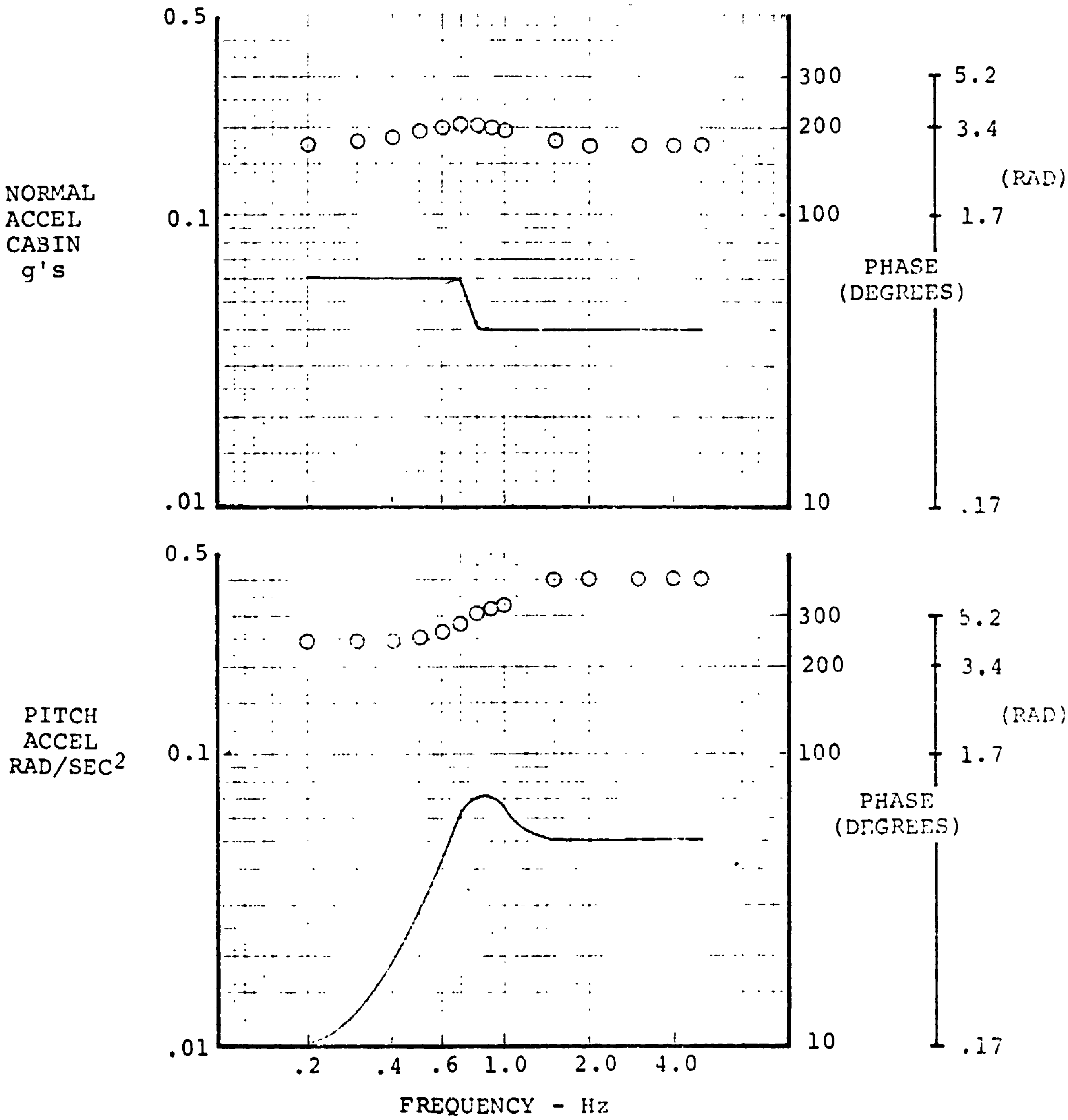

FIGURE 2.3 . FREQUENCY RESPONSE OF CABIN NORMAL AND PITCH ACCELERATIONS DUE TO δ_F (240 KNOTS, 3049 METERS, FORWARD CG)

240 KNOTS, 3049M (10,000 FEET), FORWARD CG

$\delta_e = \pm .5°$

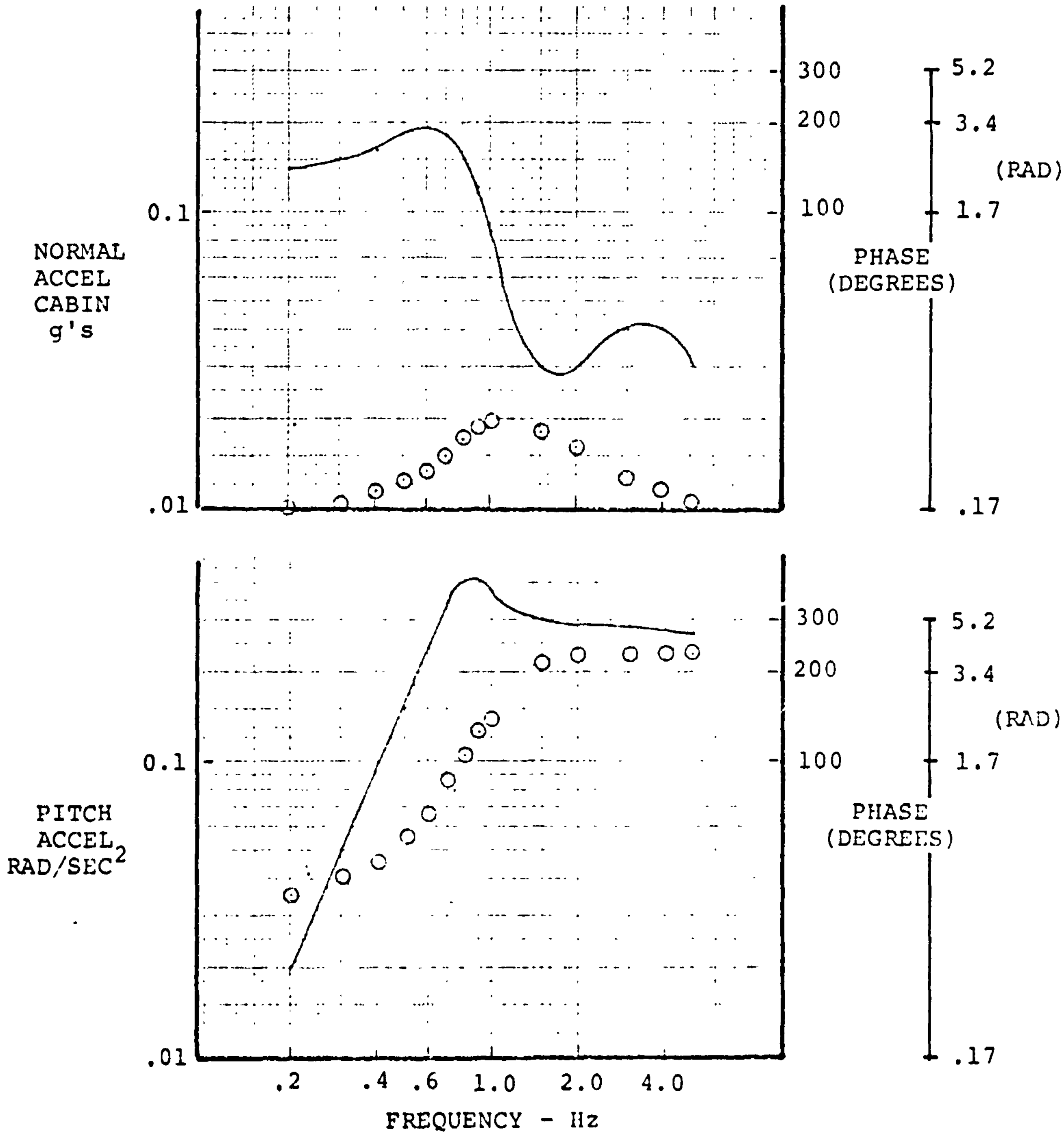

FIGURE 2.4 . FREQUENCY RESPONSE OF CABIN NORMAL AND PITCH ACCELERATIONS DUE TO δ_e (240 KNOTS, 3049 METERS, FORWARD CG)

spectrum of gust intensity is also considered the gust response is modified as shown in Figure 2.5. This is based on clear air turbulence (Dyden Scale) as defined in MIL-F-8785B(ASG) of the form

$$\Phi_{w_g}(\Omega) = \sigma_w^2 \quad \frac{L_w}{\pi} \quad \frac{1 + 3\ (L_w\Omega)^2}{[1 + (L_w\Omega)^2]^2}$$

This suggests that the system needs to operate at maximum efficiency over a fairly narrow frequency range. The peak for the forward CG conditions occurs around 0.70 Hz, so the alleviation goals selected were as follows:

- Constant from 0.5 to 0.7 Hz.
- Reduced effectiveness above 0.7 Hz inversely proportional to frequency.
- Reduced efficiency below 0.5 Hz proportional to frequency.

2.3 FEEDBACK CONTROL CHARACTERISTICS

Solving for the control inputs and feedback characteristics required to provide the above alleviation characteristics by the method outlined in Appendix A we arrive at a system definition for flap and elevator feedback shown in Figure 2.6. The complete set of solutions for the forward and aft center of gravity positions, with and without A_1, B_1 participation are given in Appendix B.

240 KNOTS, 3049M (10,000 FEET), FORWARD AND AFT CG

w_g FOR DRYDEN SCALE TURBULENCE

σ_w = 1.67 M/SEC (5.5 FT/SEC): L_w: 533M (1750 FEET)

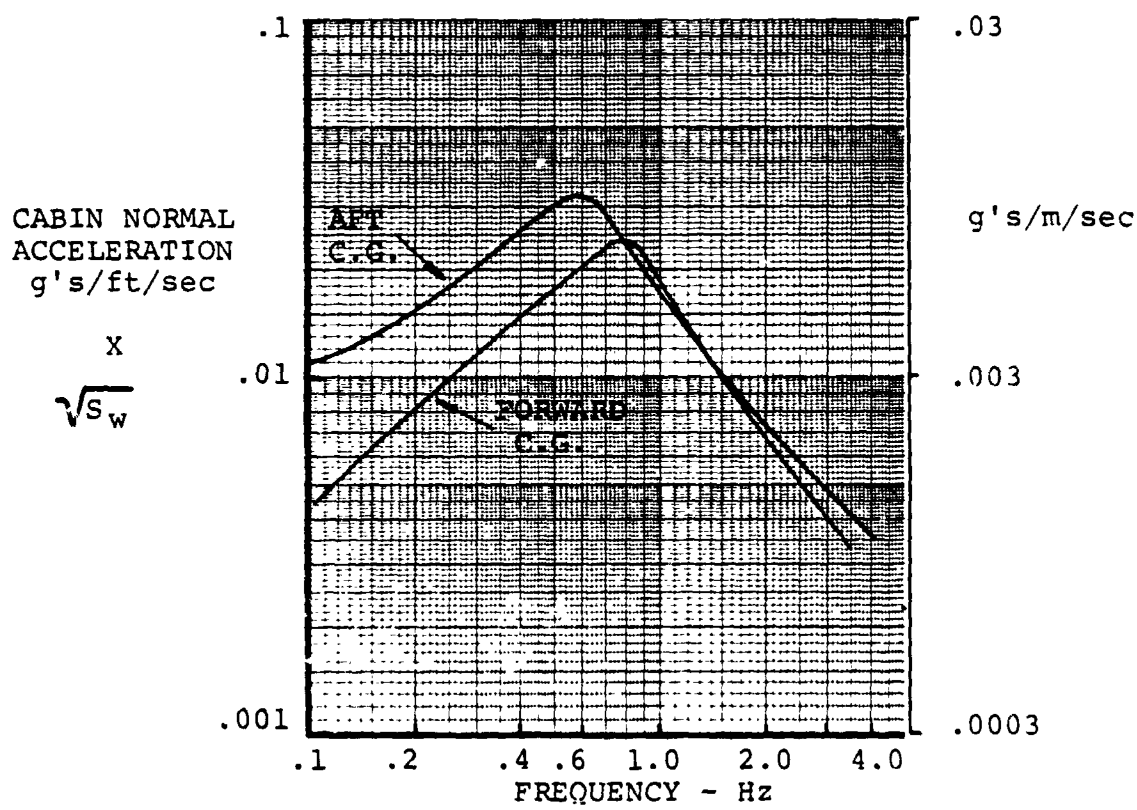

FIGURE 2.5. CABIN FREQUENCY RESPONSE MODULATED BY GUST SPECTRUM.

FEEDBACK REQUIRED FOR SPECIFIED ALLEVIATION IN CABIN

240 KNOTS, 10,000 FEET (3049M), FOREWARD CG

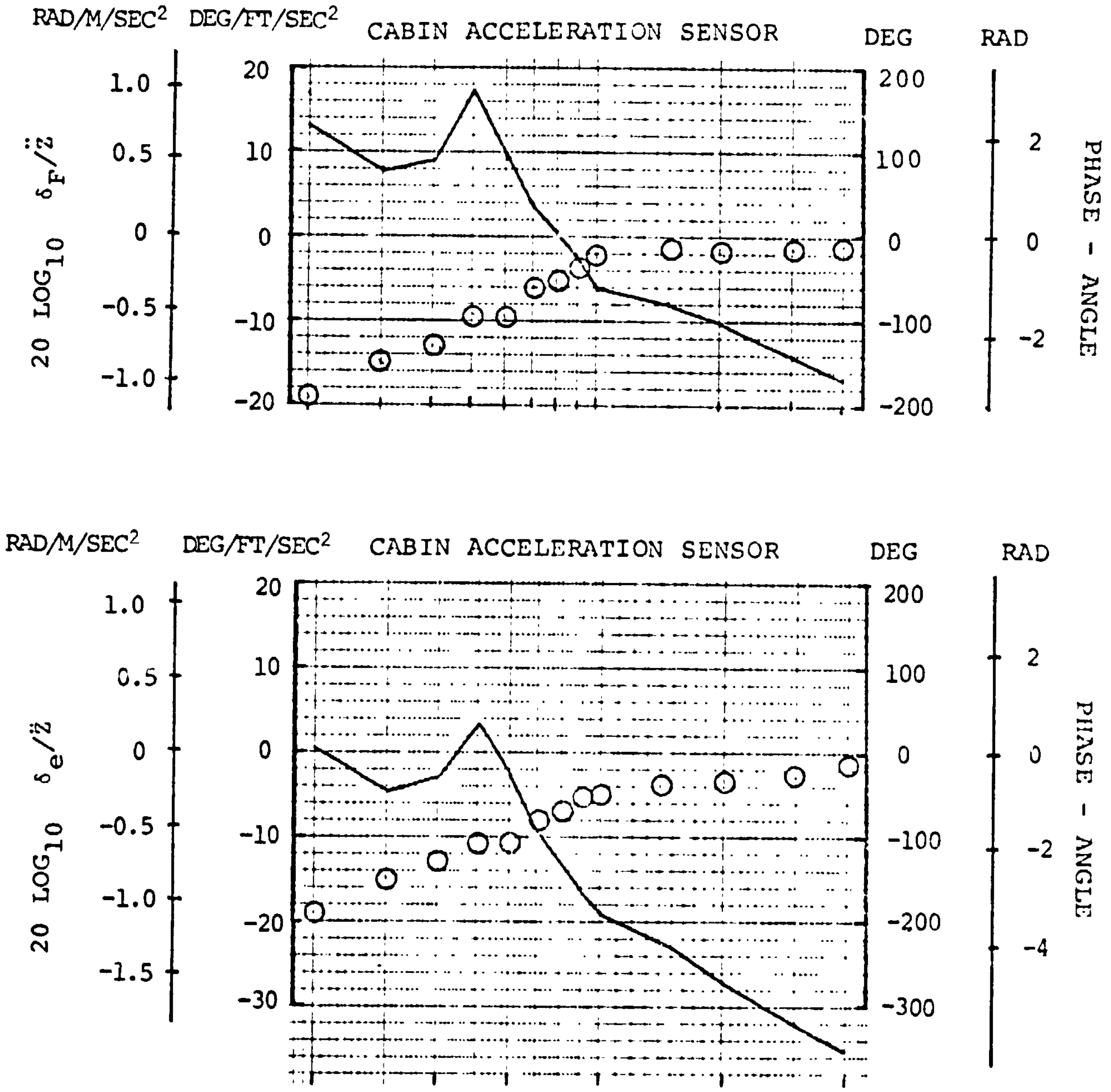

FIGURE 2.6. FLAP & ELEVATOR FEEDBACK REQUIRED WITH CABIN ACCELERATION SENSING, 240 KNOTS, 3049 METERS, FORWARD CG, NO A_1, B_1 FEEDBACK

2.4 APPROXIMATIONS TO IDEAL CHARACTERISTICS

The alleviation effectiveness variation defined above is reasonable. However, higher levels of effectiveness may be tolerated and this makes easier the task of providing acceptable approximations to the ideal control characteristics. The procedure which was adopted was to provide the gain levels calculated for 0.5 Hz which typically demands the highest gain setting, and to provide a good match of phase over the frequency range 0.5 - 0.8 Hz using as simple a shaping network as possible. This usually means that a higher-than-planned level of alleviation is provided at other frequencies. However, since these levels were the subject of a reasonable, but nevertheless arbitrary decision, this does not present a problem unless the stability margins become too low.

Several considerations prompted this procedure.

(i) A simple system will be more easily translated into hardware.

(ii) A limited library of simulation networks was available, and highly specialized networks would have required development of new algorithms.

(iii) There are practical limits to what can be realistically represented by digital simulation.

In defining shaping networks, account was also taken of the need to wash out the system at low frequencies so that it would not fight pilot input steady commands for acceleration during maneuvers. This can also be accomplished by providing a bias to the control system using a stick pickoff signal. However, in the present study the washout approach was used. Account was also take of the characteristics imposed by control actuator rate limits. It was considered that the actuator rate limit would override the theoretical small perturbation corner frequencies which are typically in excess of 10 Hz. Hence, actuator dynamics were represented by a first order lag, $1/1 + \tau S$ with τ = .05 selected to represent a rate limit in the range .69 to .87 radians per second (40 to 50 degrees per second).

2.5 SHAPING FOR SYSTEM USING FLAP AND ELEVATOR CONTROL

The transfer function for the flap and elevator systems are, therefore, expressible in the general form

$$\frac{\partial F}{\ddot{z}} = \left\{\begin{matrix}\text{LOW FREQUENCY}\\ \text{WASHOUT}\end{matrix}\right\} \times \left\{\begin{matrix}\text{SHAPING}\\ \text{FUNCTION}\end{matrix}\right\} \times \left\{\begin{matrix}\text{ACTUATOR}\\ \text{DYNAMICS}\end{matrix}\right\}$$

and assuming a second order washout function this becomes

$$\frac{\partial F}{\ddot{z}} = \left\{\frac{S^2}{S^2 + 2\xi_1 \omega_1 S + \omega_1^2}\right\} \times \left\{\frac{\text{SHAPING}}{\text{FUNCTION}}\right\} \times \left\{\frac{1}{1 + \tau S}\right\}.$$

The shaping functions must adjust the total phase between the sensed signal, and the flap and elevator to the values shown in Figure 2.6 for cabin acceleration feedback. The 240 Knot forward center of gravity case of 3049m (10,000 feet) was selected for investigation and it was found that a shaping function of the form

$$-\frac{1}{S^2}\left\{S^2 + 2\xi_2\omega_2 S + \omega_2^2\right\}$$

will provide the required phase characteristics. However, since this effectively eliminates the effectiveness of a second order washout, as shown above, a higher order washout function is required. This was provided by two second order washouts in cascade with corner frequencies ω_1 = .025 Hz and damping coefficients ξ = .60. This leads to a transfer function for the flap:

$$\frac{\delta F}{\ddot{Z}} = -\left\{\frac{S^2}{S^2 + .188S + .0246}\right\}^2\cdot\left\{\frac{S^2 + 1.427S + 9.86}{S^2}\right\}\cdot\left\{\frac{K_F}{1 + .05S}\right\}$$

or

$$\frac{\delta F}{\ddot{Z}} = -\left\{\frac{S^2}{S^2 + .188S + .0246}\right\}\cdot\left\{\frac{S^2 + 1.427S + 9.86}{S^2 + .188S + .0246}\right\}\cdot\left\{\frac{K_F}{1 + .05S}\right\}$$

approximately 20° more phase lag is indicated for the elevator and this was provided by a longer time constant (τ = .075) in the actuator transfer function.

For 90% reductions in normal and pitching accelerations the values calculated for K_F and K_E (nominal flap and elevator system gains respectively) are 6.0 and 0.8.

The acceleration feedback system defined in this report was evaluated over a matrix of speed and altitude conditions with the aircraft at forward and aft center of gravity limits. The results of this study are discussed in Section 3.

2.6 α FEEDBACK SHAPING

Aircraft angle of attack, as the signal sensed to activate the alleviation controls, has the advantage of not being reduced by a direct lift control system alleviating normal accelerations so that high levels of alleviation do not imply high loop gains. Also, since perturbations in angle of attack are the primary cause of acceleration responses it might be expected that the need for heavy signal shaping would be reduced. Figures 2.7 and 2.8 show angle of attack response to gust, flap and elevator inputs to the aircraft system.

The characteristics of feedback systems using α as the sensed signal were evaluated in the same way as were those for acceleration sensing, and the system requirements for the 3049m (10,000 feet) 240 Knot, forward center of gravity case are presented in Figure 2.9. As expected the phase requirements present less difficulty. Flap and elevator control applications are required to be phased approximately 180° and 200° respectively, with respect to the α signal over the frequency range of interest.

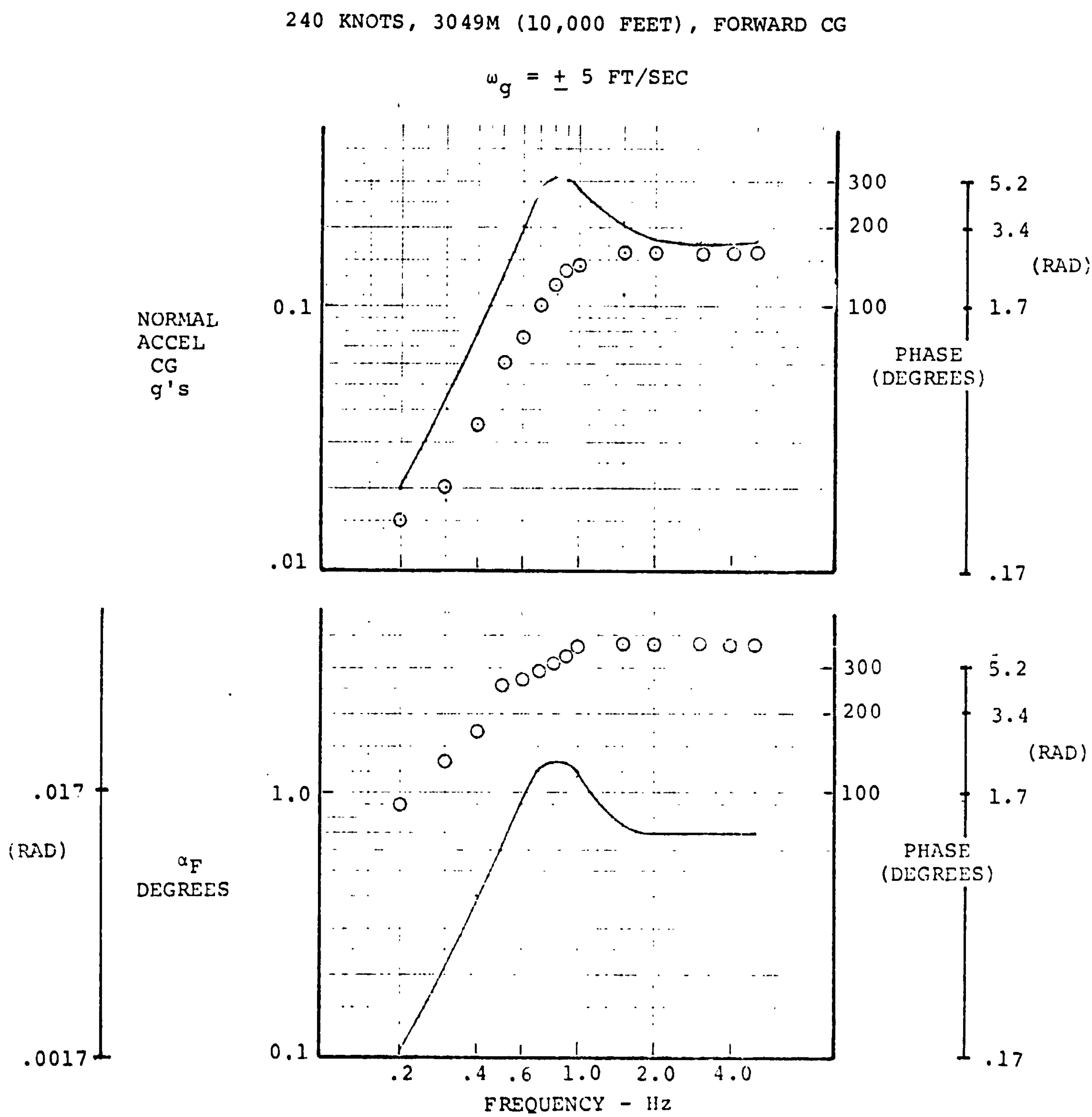

FIGURE 2.7 . FREQUENCY RESPONSE OF NORMAL ACCELERATION AT CG AND FUSELAGE ANGLE OF ATTACK DUE TO VERTICAL GUSTS (240 KNOTS, 3049 METERS, FORWARD CG)

240 KNOTS, 3049M (10,000 FEET), FORWARD CG

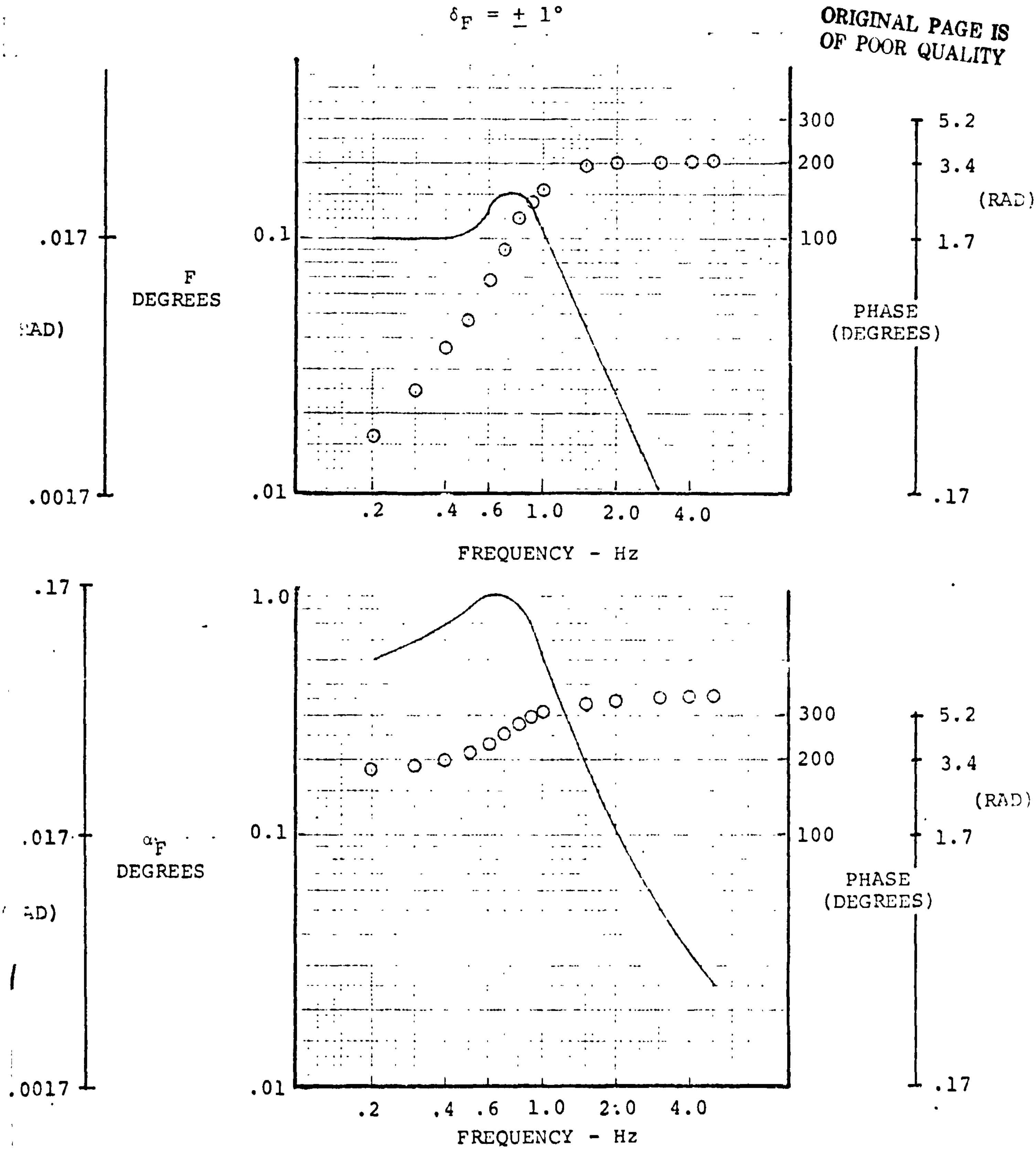

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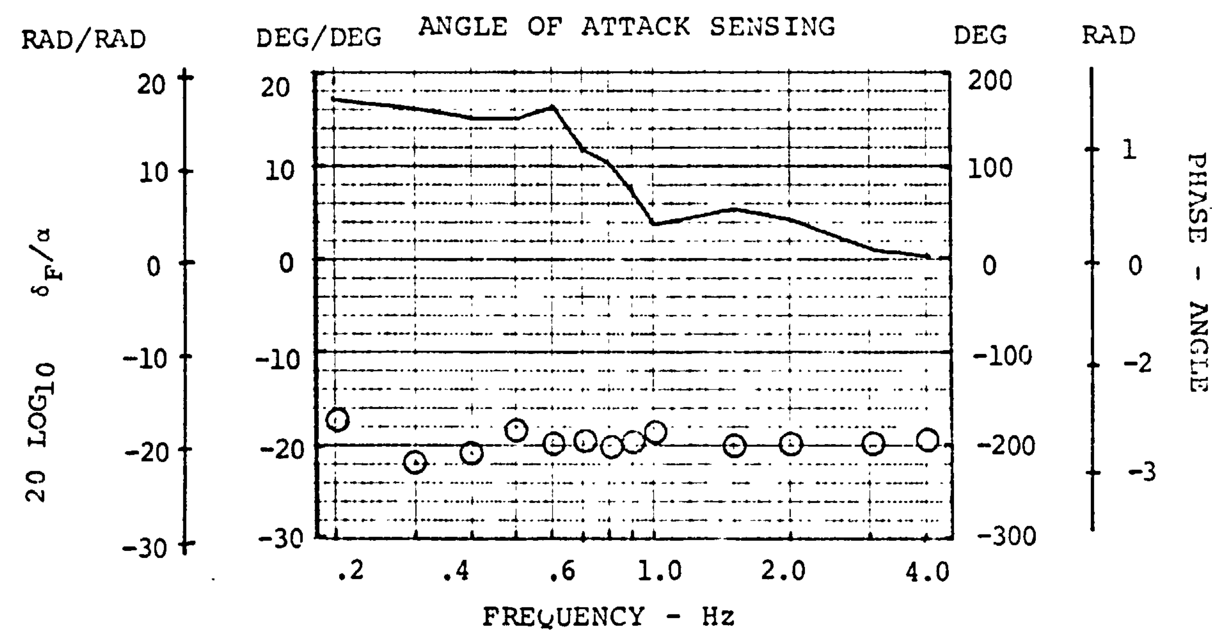
FIGURE 2.8. FREQUENCY RESPONSE OF FUSELAGE ANGLE OF ATTACK DUE TO SINUSOIDAL FLAP AND ELEVATOR APPLICATION

FEEDBACK REQUIRED FOR SPECIFIED ALLEVIATION IN CABIN

240 KNOTS, 10,000 FEET (3049M), FORWARD CG



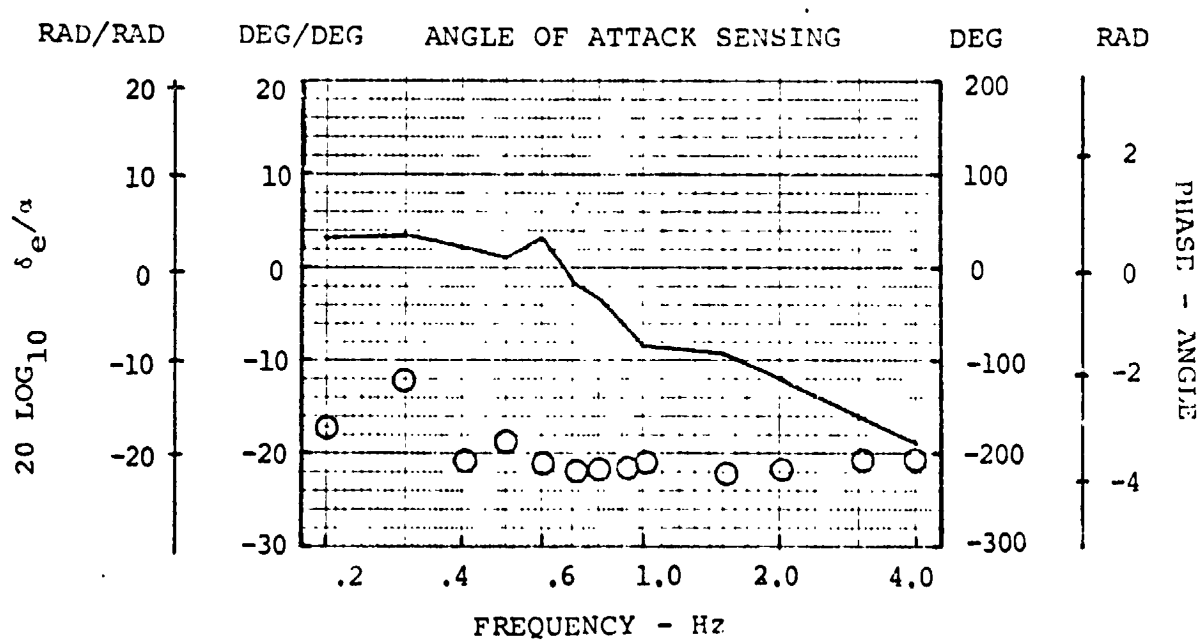


FIGURE 2.9. ELEVATOR FEEDBACK REQUIRED WITH ACCELERATION AND α SENSING RESPECTIVELY, 240 KNOTS, 3049 METERS, FORWARD CG, NO A_1, B_1 FEEDBACK

This leads to transfer function of the form

$$\frac{\delta F}{\alpha} = \left\{\frac{S^2}{S^2 + 2\xi_1\omega_1 S + \omega_1^2}\right\} \cdot \left\{\begin{matrix}\text{SHAPING}\\ \text{FUNCTION}\end{matrix}\right\} \cdot \left\{\frac{1}{1 + \tau S}\right\}$$

For the purposes of the α feedback study a higher corner frequency washout was selected. At this stage of the investigation it was suspected that the frequencies adopted for the acceleration feedback case might be too low and could interfere with reasonable inputs from the pilot. Accordingly a much heavier washout with a 0.3 Hz corner frequency was adopted.

The net transfer function derived for the flap is

$$\frac{\delta F}{\alpha} = \left\{\frac{S^2}{S^2 + 1.884S + 3.549}\right\} \left\{\frac{S^2 + 3.363S + 9.1211}{S^2 + 1.884S + 3.549}\right\} \left\{\frac{K_F}{1 + .05S}\right\}$$

and a similar function with a .075 time constant was used for the elevator.

The results using this system were similar to those obtained with acceleration feedback and are discussed in Section 3.

2.7 INCLUSION OF A_1 AND B_1 CONTROLS

Several attempts were made to include A_1 and B_1 controls in the alleviation system with the objective of reducing hub pitching and yawing moments, and blade loads concurrent with alleviation in cabin normal and pitching acceleration.

This was initially attempted using acceleration feedback without success. It was observed that the phasing requirements associated with all controls involved less shaping in the case of α feedback, and a further attempt was made to include the cyclic controls. Figures 2.10 and 2.11 show gain and phase requirements for A_1 and B_1 controls for acceleration and α feedback at 240 Knots, 3049m (10,000 feet) forward CG. Inspection of the basic frequency response data led to the phase requirements being interpreted as leads rather than lags and transfer functions were provided as follows:

$$\frac{A_1}{\alpha} = \left\{\frac{S^2}{S^2 + 5.028\, S + 10.662}\right\}^2 \cdot \left\{\frac{.8227}{1 + .05S}\right\} \cdot \left\{K_A\right\}$$

$$\frac{B_1}{\alpha} = \left\{\frac{A_1}{\alpha}\right\} \quad .312 \quad \left\{\frac{1 + .6429S}{1 + .1103S}\right\}^2 \cdot \left\{K_B.\right\}$$

NOTE: Unit values of K_A and K_B provide the 0.5 Hz gain levels and ratios of A_1/B_1 shown in Figures 2.10 and 2.11.

The flap and elevator transfer functions are the same as discussed in the preceding paragraph.

This system did not work successfully. A number of possible explan ions exist.

FEEDBACK REQUIRED FOR SPECIFIED ALLEVIATION IN CABIN

240 KNOTS, 10,000 FEET (3049M), FORWARD CG

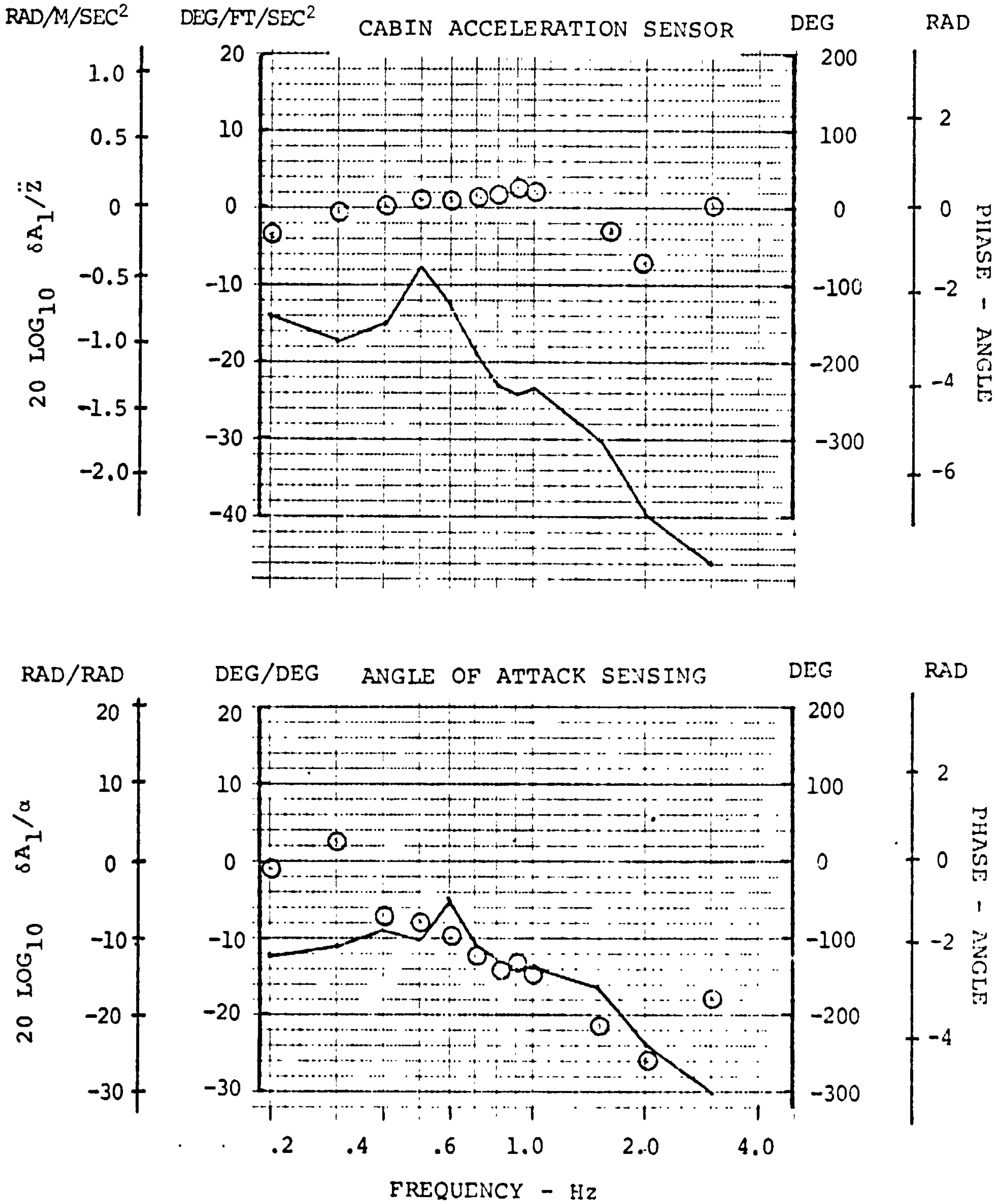


FIGURE 2.10. A_1 FEEDBACK REQUIRED WITH ACCELERATION AND α SENSING RESPECTIVELY, 240 KNOTS, 3049 METERS, FORWARD CG

FEEDBACK REQUIRED FOR SPECIFIED ALLEVIATION IN CABIN

240 KNOTS, 10,000 FEET (3049M), FORWARD CG

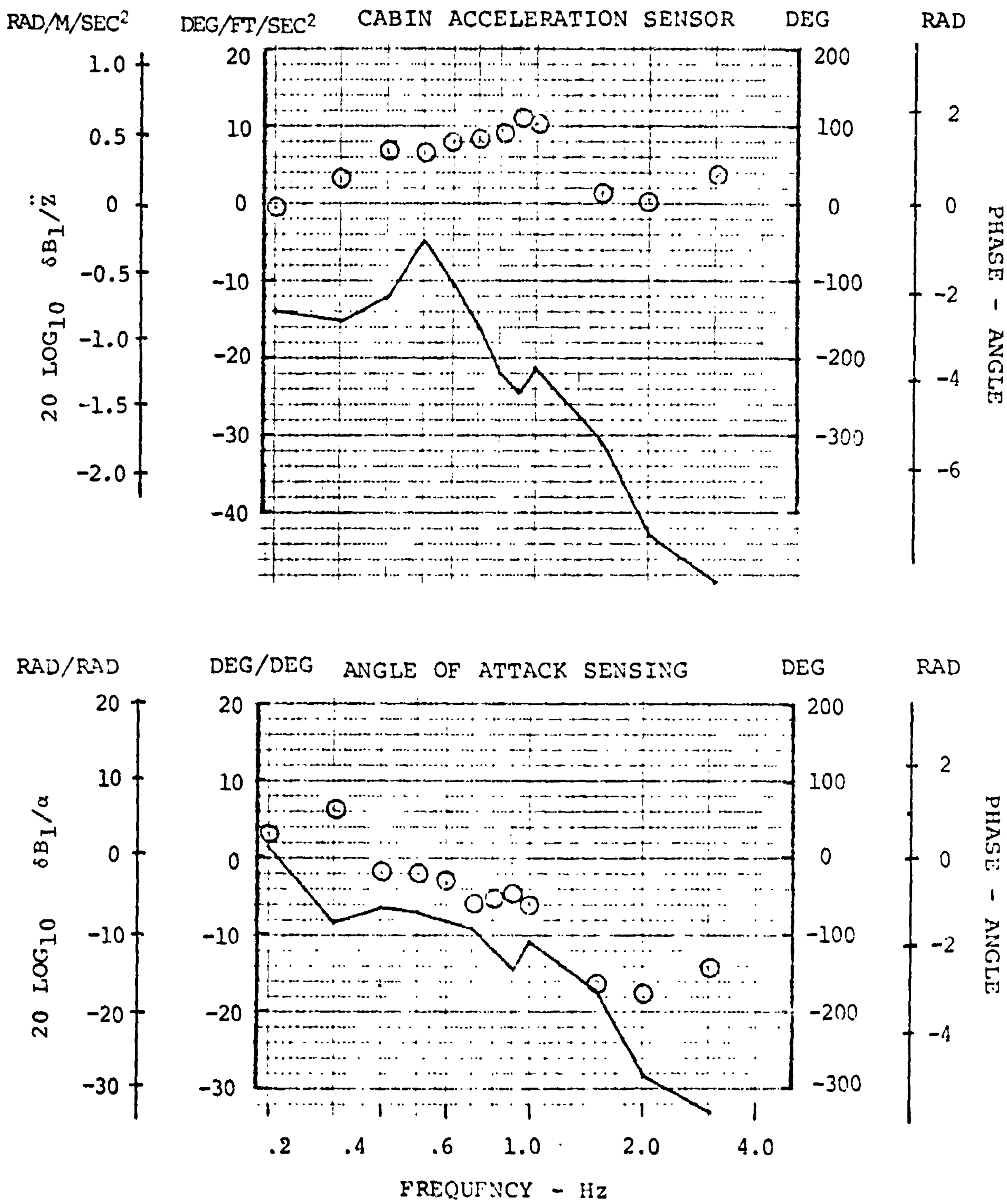


FIGURE 2.11. B_1 FEEDBACK REQUIRED WITH ACCELERATION AND α SENSING RESPECTIVELY, 240 KNOTS, 3049 METERS, FORWARD CG

1. Rapid differential changes in gain are associated with the above transfer functions and this degrades performance at other than the nominal frequencies.
2. The large phase angles associated with the rotor response to control input means that it is fundamentally more difficult to control transient response due to external excitation.
3. The open loop phase and gain margins with the above system may be too small at frequencies away from the design frequency.
4. As more control loops are added the gain ratios between the circuits probably become more critical.

Additional work will be required to determine the exact causes.

2.8 ALTERNATIVE APPROACH TO REGULATION OF ROTOR RESPONSE

There is a high degree of confidence that, given sufficient care the current approach which uses a single sensing device may be made to work satisfactorily. However, an alternative is to regulate the rotor using a direct measure of its response such as hub moment. This would modify the aircraft response characteristics and the flap and elevator system would then be designed to alleviate the resulting aircraft behavior.

3.0 DISCUSSION OF RESULTS

The flap and elevator system defined in Section 2 was evaluated over a matrix of flight conditions from 200 to 240 knots, forward and aft center of gravity location, and at 1524,3049, and 4573m (5,000,10,000 and 15,000 feet). These results are summarized in Tables I.A and I.B. These show that better than 70% reductions in cabin normal acceleration are achieved in most cases. These results are presented as reductions in peak acceleration as well as RMS acceleration.

The results in Tables I.A and I.B were obtained using a system defined for 240 Knots, 3049m (10,000 feet) with the center of gravity forward. This system was designed to bring about an 80% reduction in both normal and pitching accelerations. The gain settings of $K_F = 6.0$ and $K_E = 0.8$ calculated to produce this result, had to be restricted for stability reasons. At gain setting $K_E =$ 0.7, 0.8, the system develops a low frequency instability in the aft CG case. This results in the reductions in pitch accelerations listed in Tables IIA & IIB. At 240 knots, 3049m (10,000 ft) the factors on RMS accelerations range from .26 (aft) to .35 (fwd), compared with RMS normal acceleration factors of .70 & .71 for the same flight conditions. At 1524m (5,000 feet), in the forward CG condition where higher elevator gains can be used, the attenuation of both normal acceleration and pitch approached the specified value of 0.8.

TABLE IIA. ATTENUATION OF PEAK PITCHING ACCELERATIONS WITH SELECTED SYSTEM

SPEED KNOTS	CG LOCATION	ALTITUDE 1,524m 5,000 FT	3,049m 10,000 FT	4,573m 15,000 FT
200	FWD	.36	.50	.44
	AFT	.25	.14	.34
240	FWD	.22	.35	.39
	AFT	.55	.19	.10
280	FWD	.26	.24	.45
	AFT	.50	0	.06

TABLE IIB. REDUCTION FACTOR ON RMS AIRCRAFT PITCHING ACCELERATION

SPEED KNOTS	CG LOCATION	ALTITUDE 1,524m 5,000 FT	3,049m 10,000 FT	4,573m 15,000 FT
200	FWD	.28	.44	.48
	AFT	.28	.28	.30
240	FWD	.34	.35	.34
	AFT	.11	.26	.40
280	FWD	.28	.28	.45
	AFT	0	0	---

3.1 RESULTS FOR ACCELERATION FEEDBACK AT DESIGN FLIGHT CONDITIONS

Basic response data for fifteen aircraft variables is shown in Figures 3.1 and 3.2 for the flight condition chosen for design of the alleviation system. Figure 3.3 shows RMS variation with time for seven of the more important variables. These include cabin acceleration, pitching acceleration and resultant blade bending moments. In Figures 3.4, 3.5 and 3.6, the equivalent data for the same variables are shown with the alleviation system working. Marked reductions are observed in cabin acceleration, pitching acceleration and wing bending deflections, and the overall level of blade bending moments and hub moment response shows little change although differences in the detailed transient of the time histories are apparent. The peak values of flap angle required at the nominal level of turbulence intensity, are less than ± 4 degrees with rates less than 10.0 degrees per second. The associated amounts of elevator are of the order of ± 0.5 degrees.

3.2 α FEEDBACK AT DESIGN FLIGHT CONDITION

Results for angle of attack feedback are shown in Figures 3.7, 3.8 and 3.9. Similar effectiveness in the reduction of cabin normal and pitching accelerations are attained, however, the wing response and flap and elevator control traces indicate reduced damping at a frequency of

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FLIGHT CONDITION: 240 KNOTS, 10,000 FEET, (3,049m), FORWARD CG

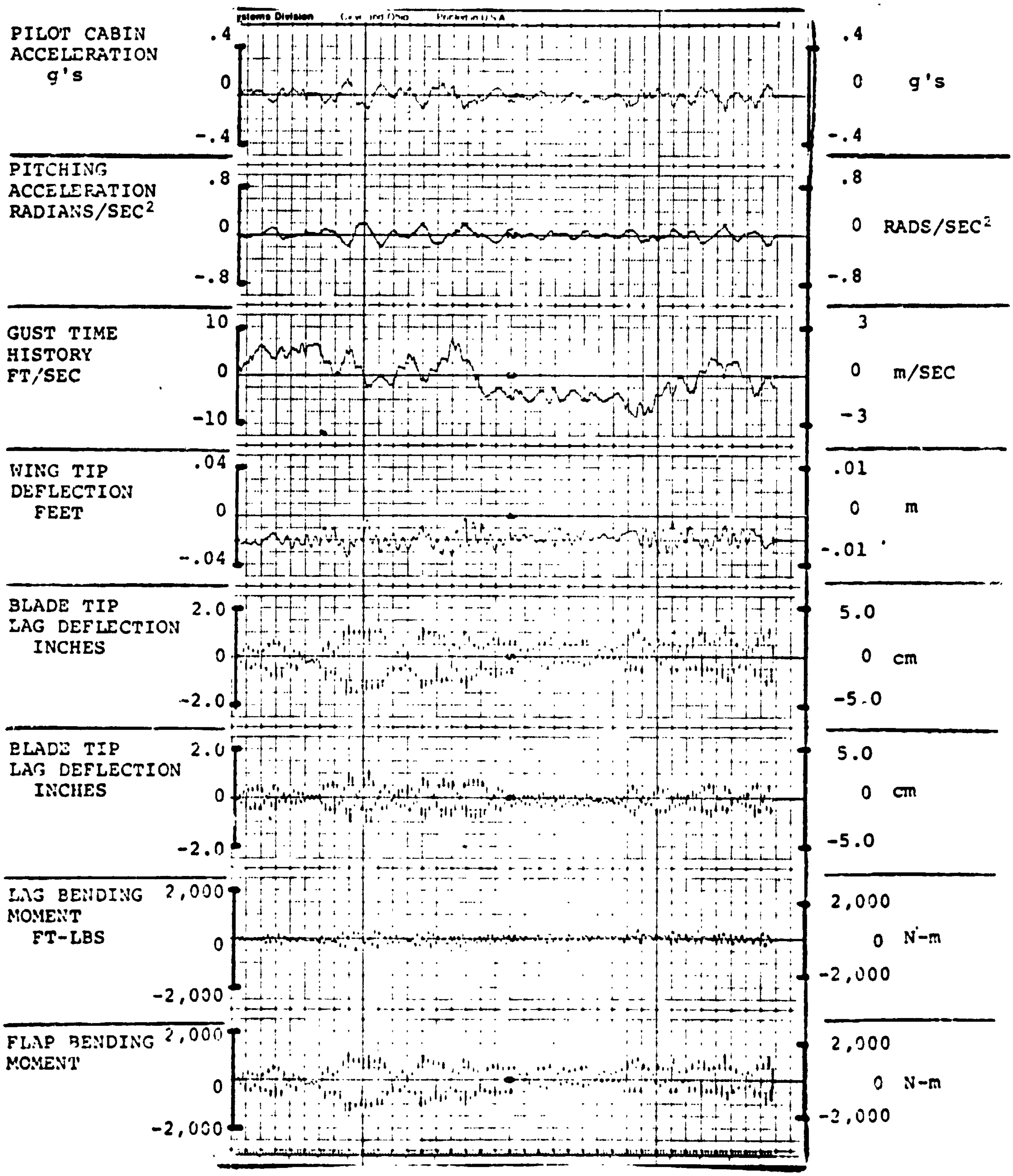

FIGURE 3.1. RESPONSES FOR GAIN F = 0, GAIN E = 0

FLIGHT CONDITION: 240 KNOTS, 10,000 FEET, (3,049m), FORWARD CG

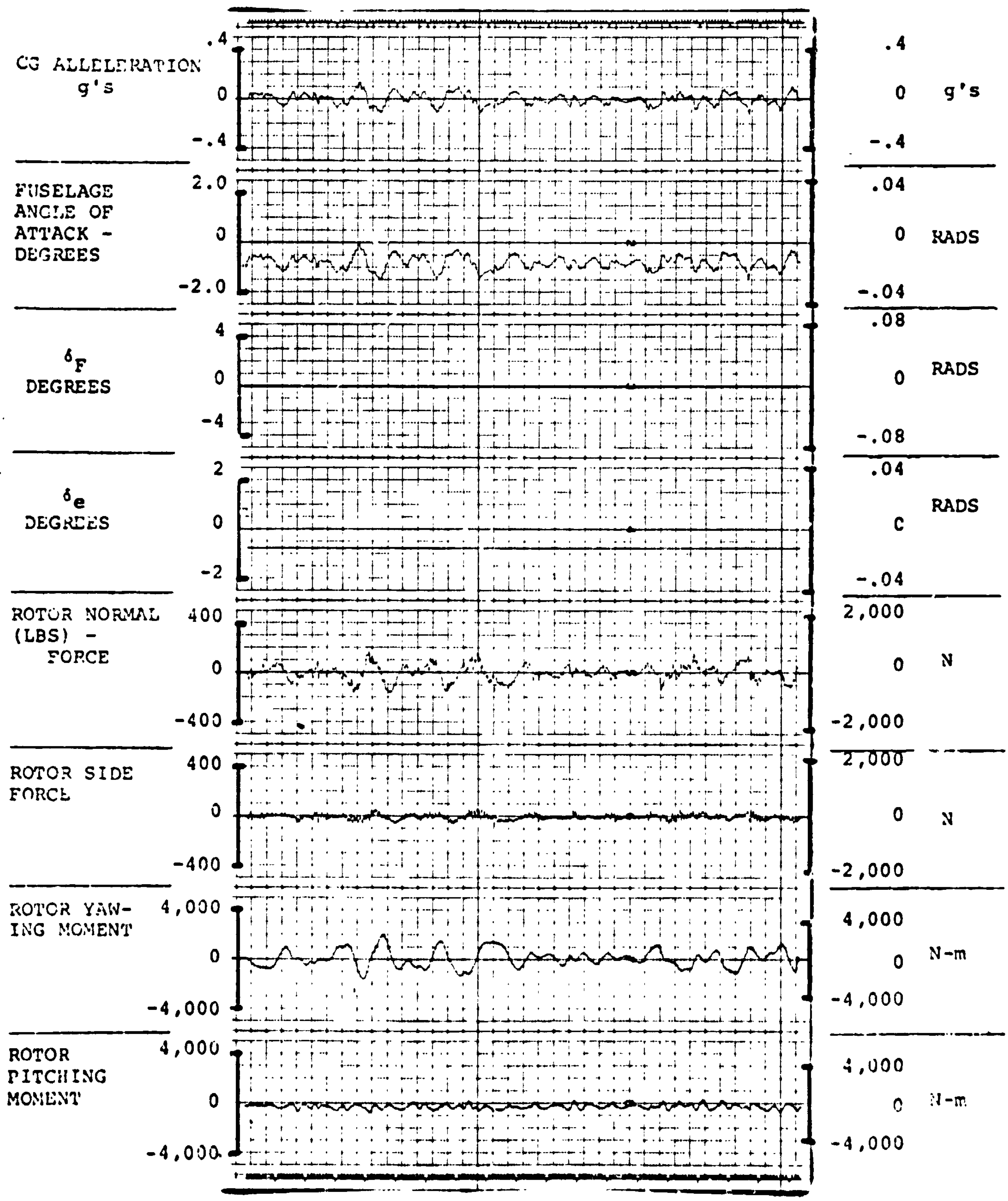

FIGURE 3.2. RESPONSES FOR GAIN F = 0, GAIN E = 0

FLIGHT CONDITION: 240 KNOTS, 10,000 FEET, (3,049m), FORWARD CG

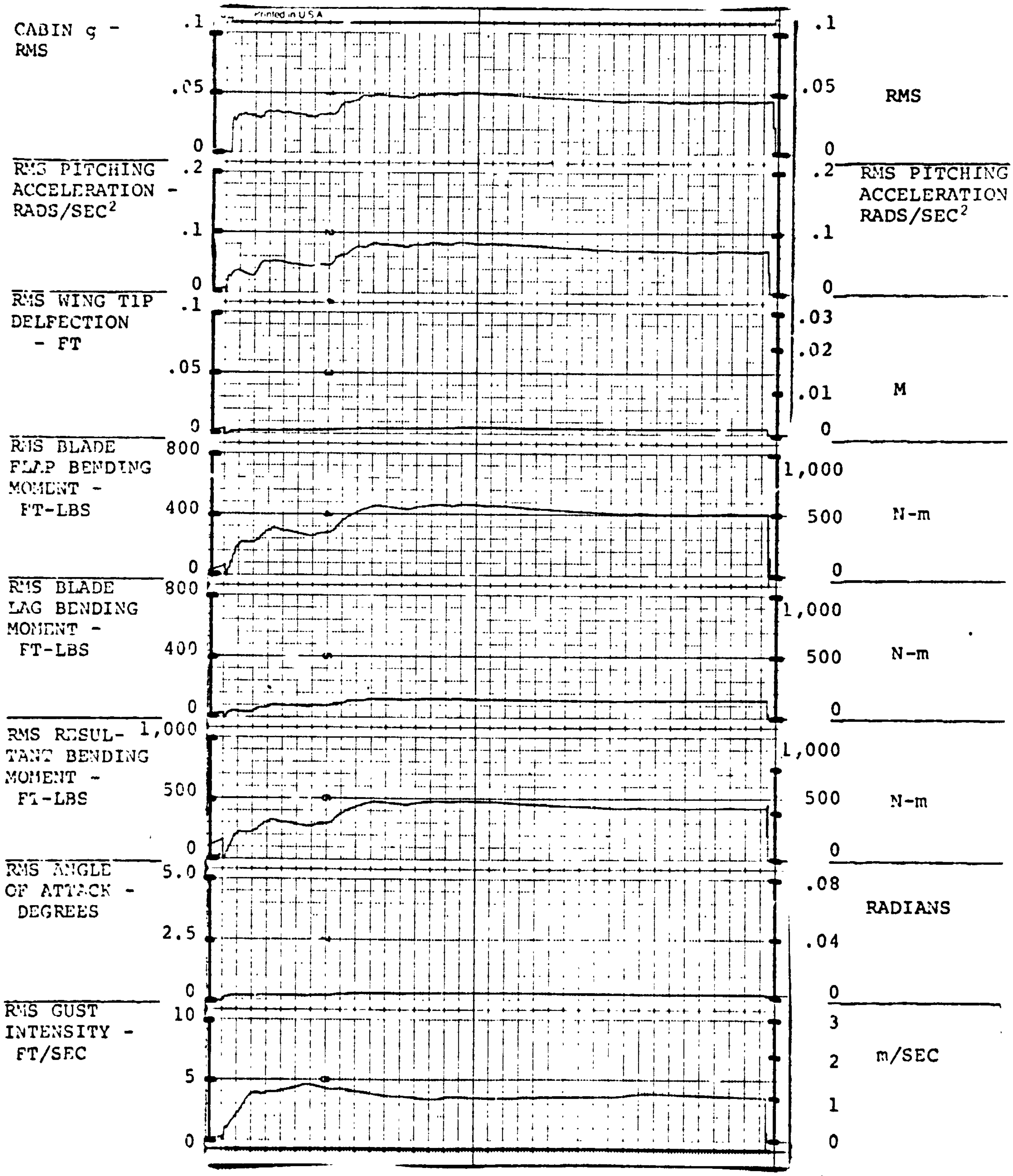

FIGURE 3.3. RESPONSES FOR GAIN F = 0, GAIN E = 0

FLIGHT CONDITION: 240 KNOTS, 10,000 FEET, (3,049m), FORWARD CG

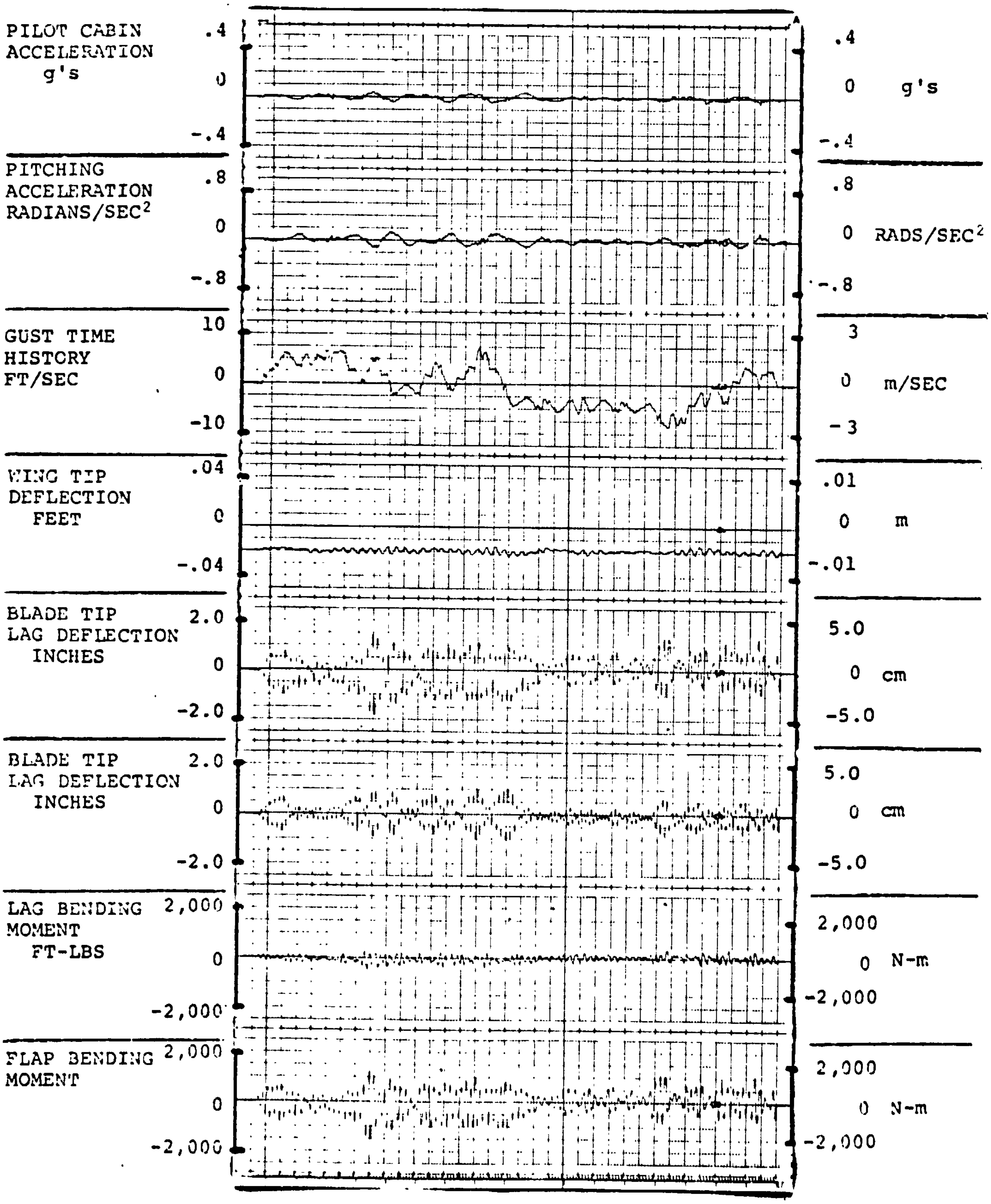

FIGURE 3.4. RESPONSES FOR GAIN F = 4.0, GAIN E = .6

FLIGHT CONDITION: 240 KNOTS, 10,000 FEET, (3,049m), FORWARD CG

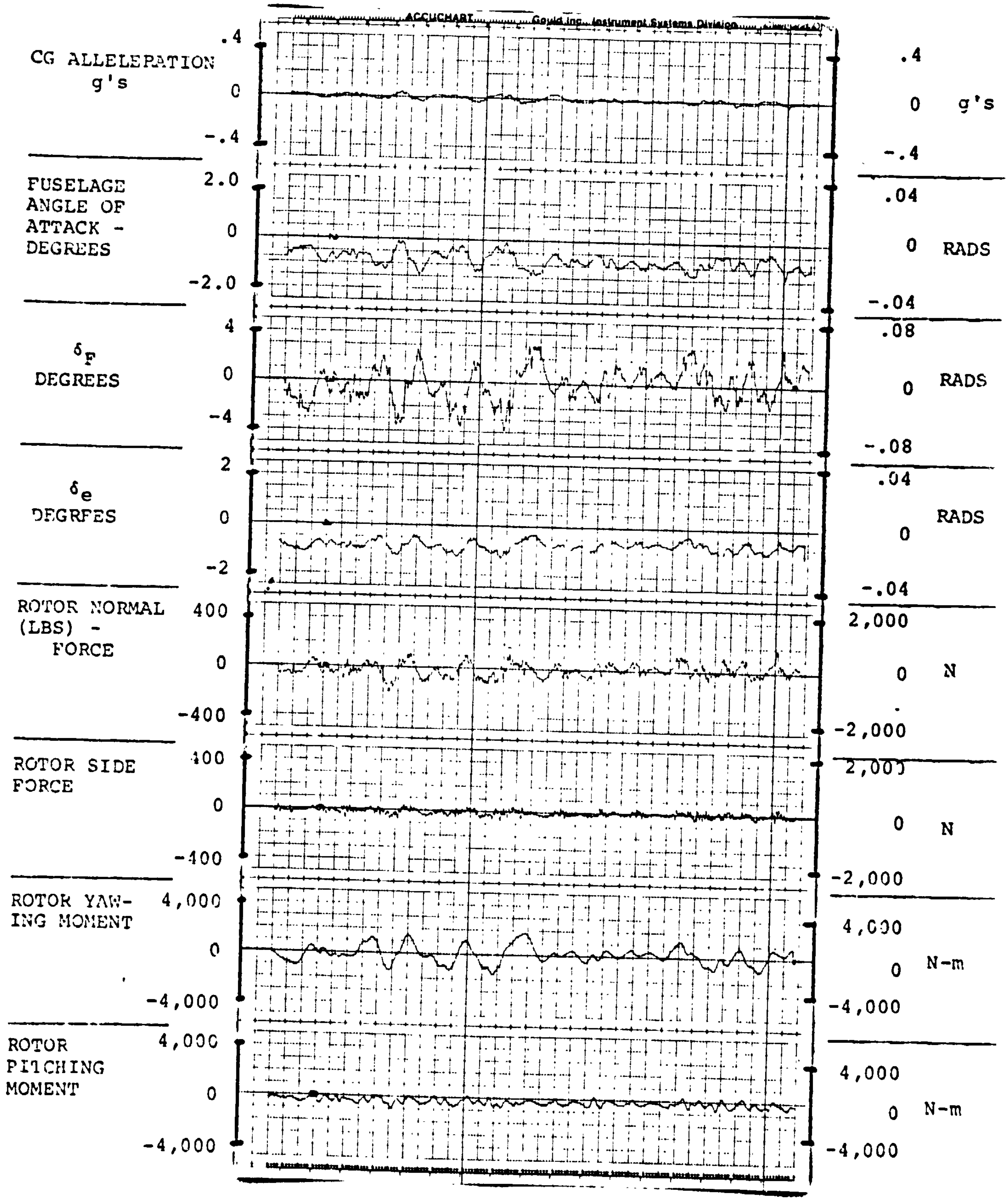

FIGURE 3.5. RESPONSES FOR GAIN F = 4.0, GAIN E = .6

FLIGHT CONDITION: 240 KNOTS, 10,000 FEET, (3,049m), FORWARD CG

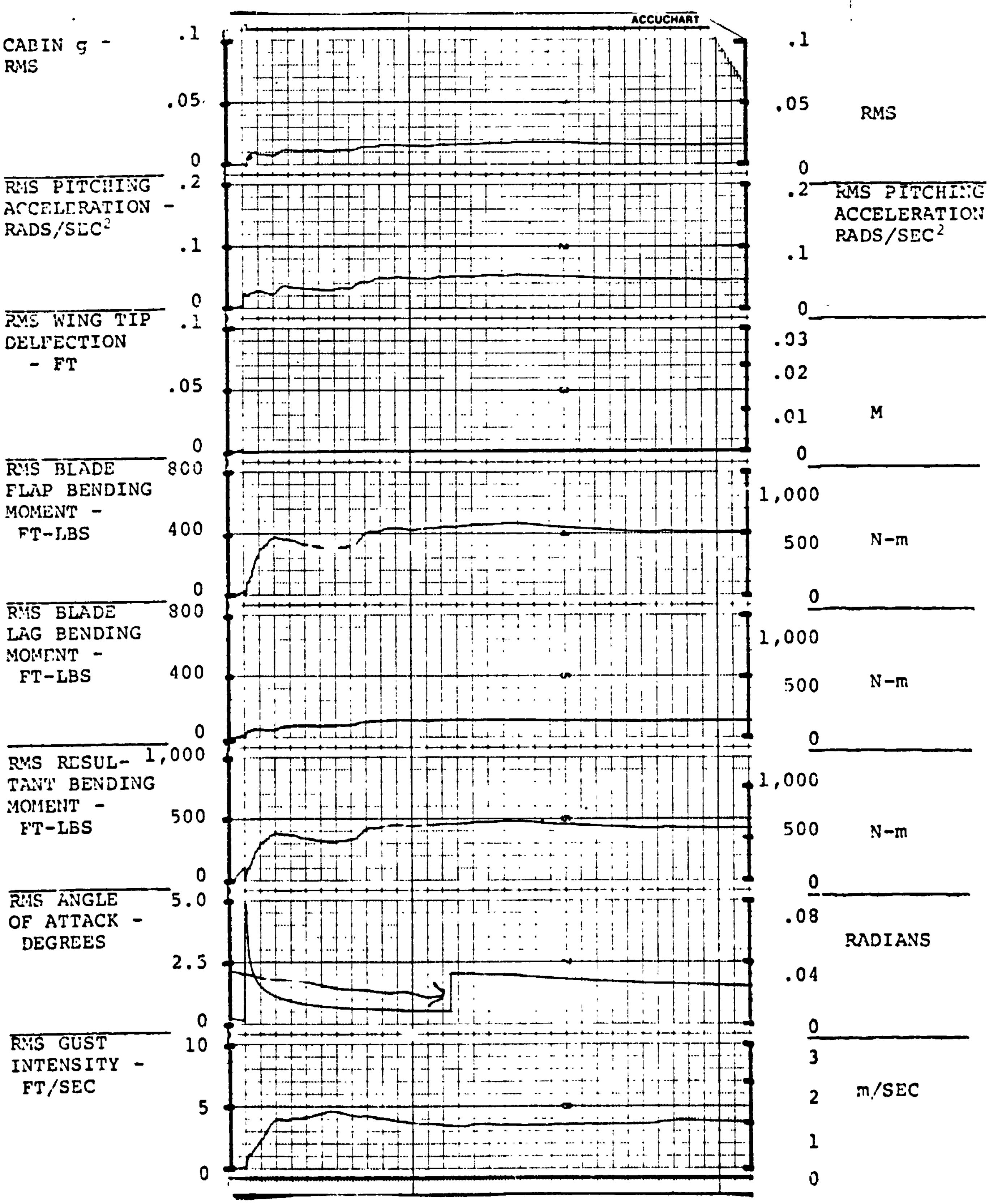

FIGURE 3.6. RESPONSES FOR GAIN F = 4.0, GAIN E = .6

FLIGHT CONDITION: 240 KNOTS, 10,000 FEET, (3,048m), FORWARD CG
α FEEDBACK

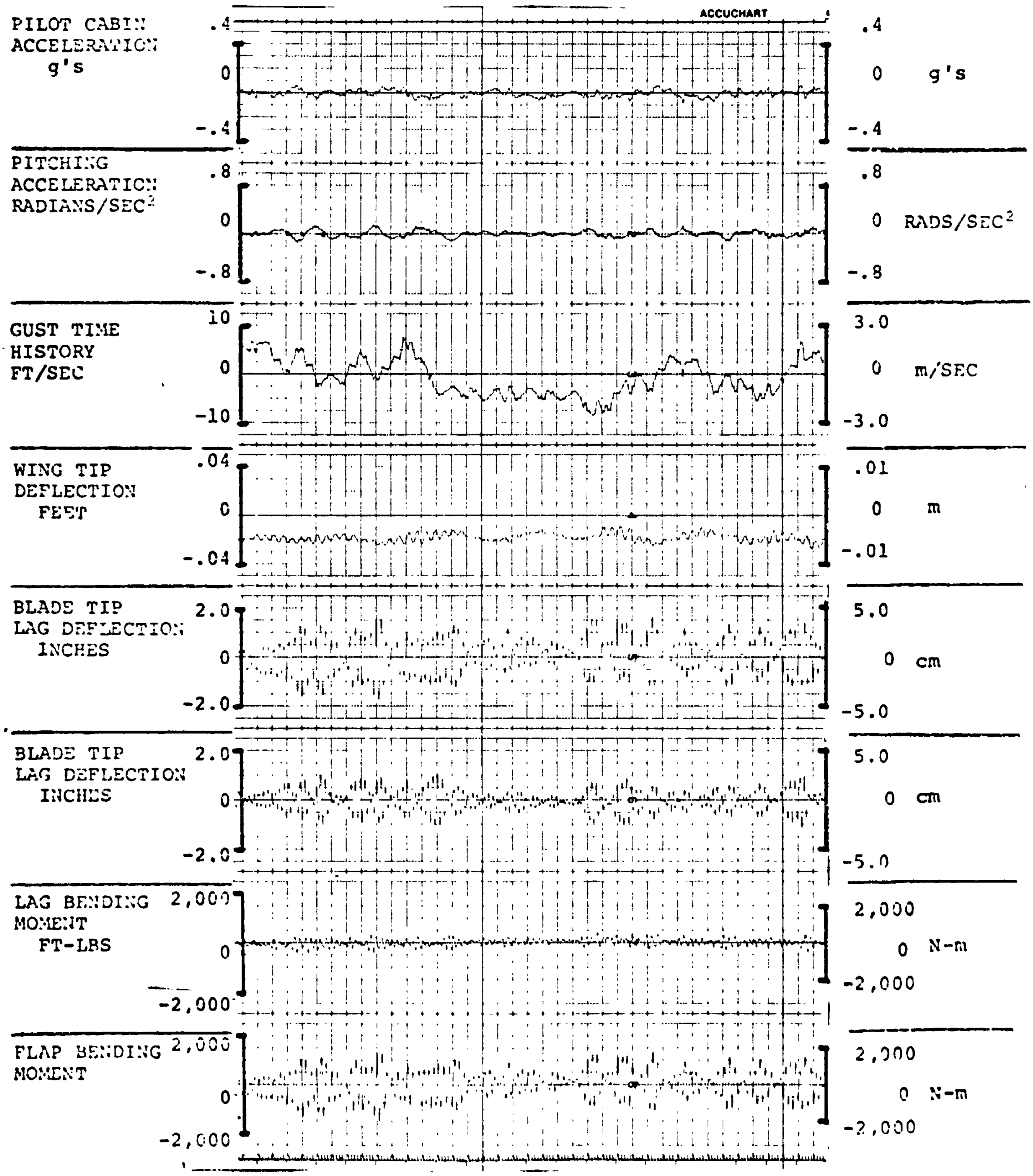

FIGURE 3.7. RESPONSES FOR GAIN F = 4.0, GAIN E = .6

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FLIGHT CONDITION: 240 KNOTS, 10,000 FEET, (3,049m), FORWARD CG
α FEEDBACK

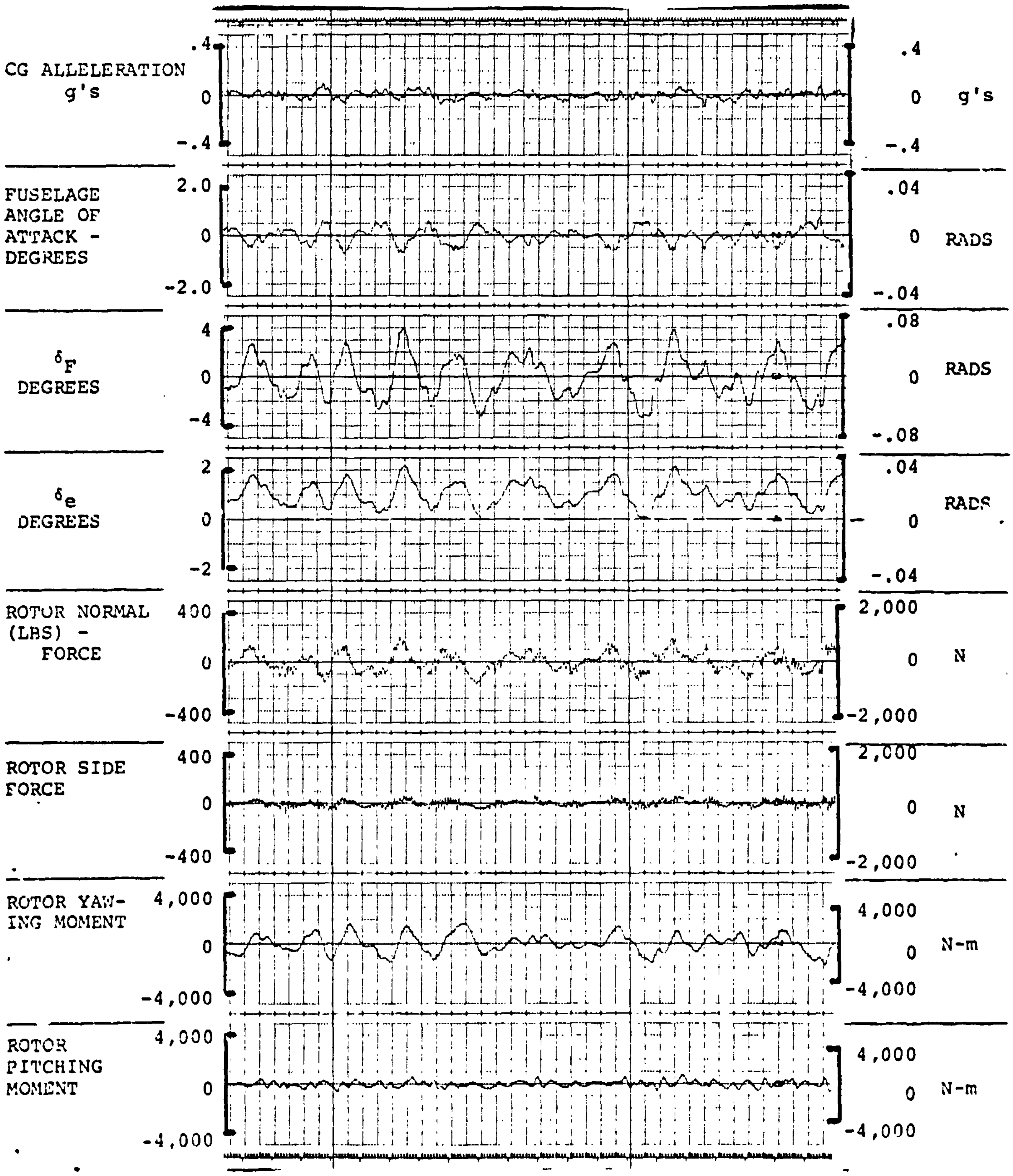

FIGURE 3.8. RESPONSES FOR GAIN F = 4.0, GAIN E = .6

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FLIGHT CONDITION: 240 KNOTS, 10,000 FEET, (3,049m), FORWARD CG, α FEEDBACK

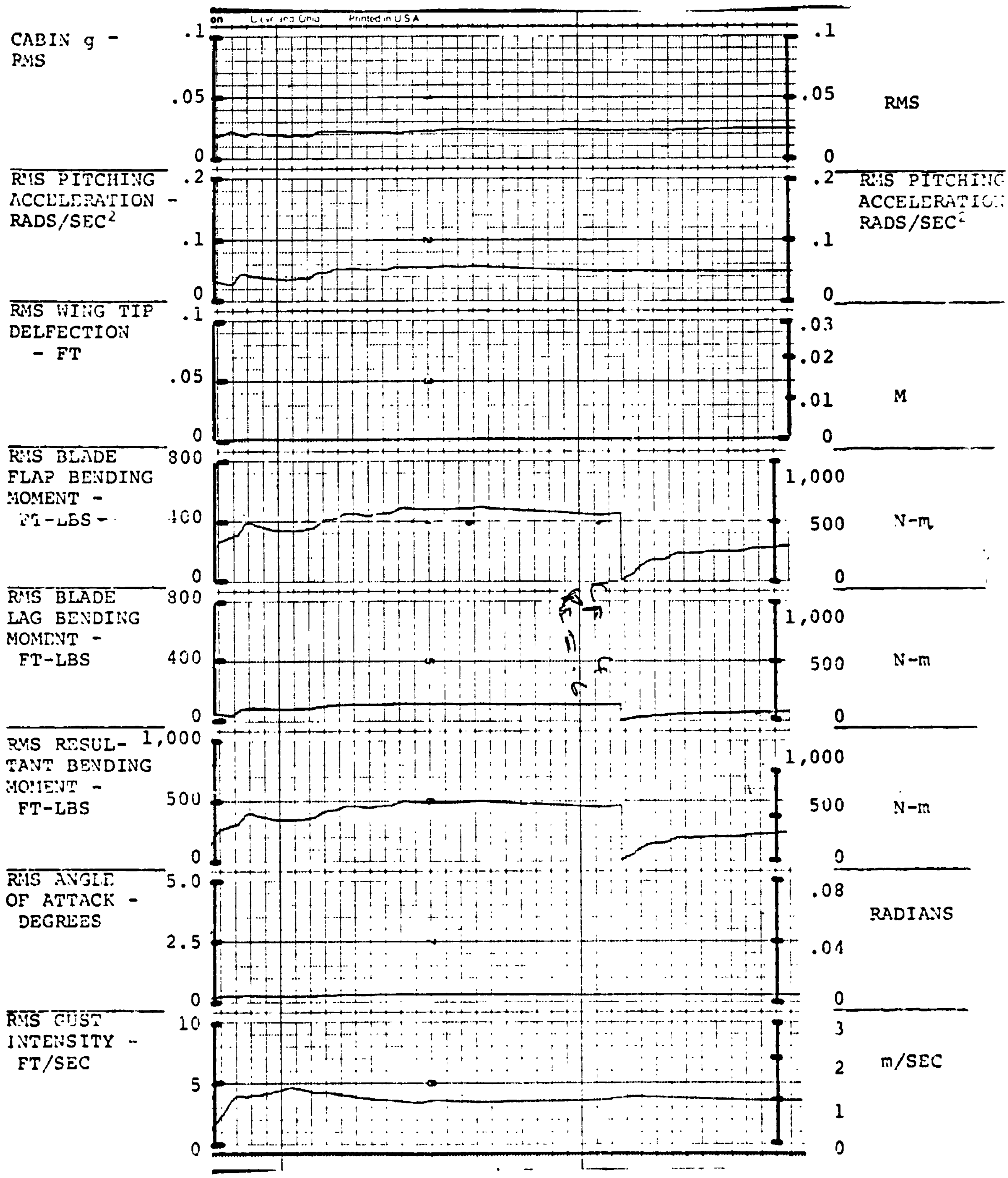

FIGURE 3.9. RESPONSES FOR GAIN F = 4.0, GAIN E = .6

approximately 0.3 Hz. The flap excursions are still less than ± 4 degrees while elevator trace is up to ± 1 degrees. The reduced damping indicates the need for further tailoring of the feedback transfer functions to ensure adequate stability margins.

3.3 ACCELERATION FEEDBACK WITH AFT CENTER OF GRAVITY

Basic aircraft time histories data for the aft center of gravity condition is presented in Figures 3.10 and 3.11, and RMS data in Figure 3.12. The effect of the attenuation system is shown in Figures 3.13, 3.14 and 3.15. The alleviation of cabin normal acceleration is substantially the same for the forward center of gravity case (.69 reduction for peak and .70, .71 reductions for RMS). There is, however, a much reduced level of effectiveness in the alleviation of pitching response, which becomes 0.19 for peaks and 0.26 for RMS.

3.4 ALTERNATIVE PRESENTATION OF SYSTEM PERFORMANCE

In order to facilitate comparison of basic aircraft response and effectiveness of the gust alleviation system with other short-haul aircraft studies, the HTR XV-15 response is presented in the format shown in Figure 3.16. This is adapted from Reference 8 in which vertical accelerations and pitch rates are given for cruise, descent and approach flight at levels of turbulence intensity considered appropriate for these phases of operation. Data for a preconversion speed of 160 Knots is given

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FLIGHT CONDITION: 240 KNOTS, 10,000 FEET, (3,049m), AFT CG

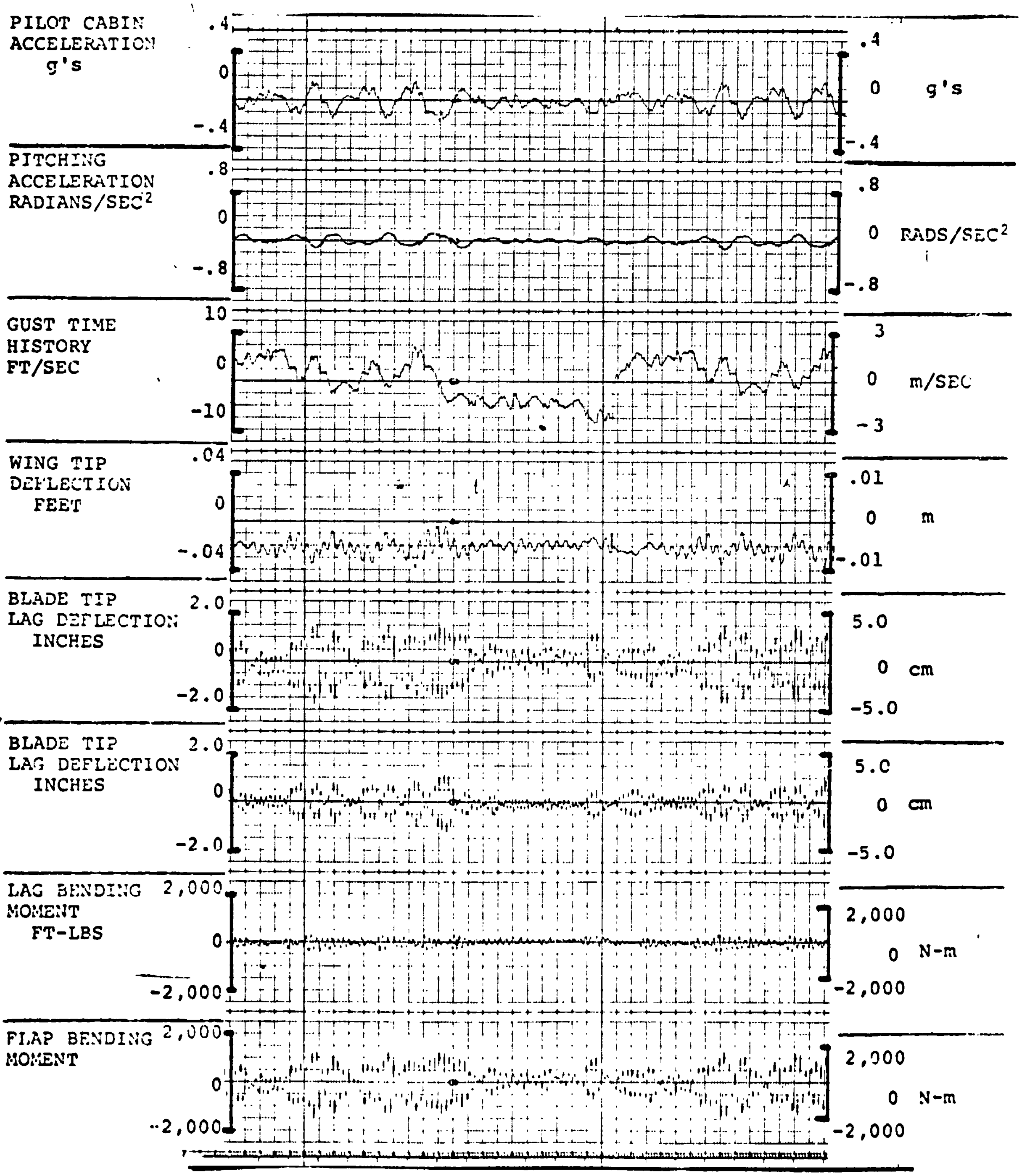


FIGURE 3.10. RESPONSES FOR GAIN F = 0, GAIN E = 0

FLIGHT CONDITION: 240 KNOTS, 10,000 FEET, (3,049m), AFT CG

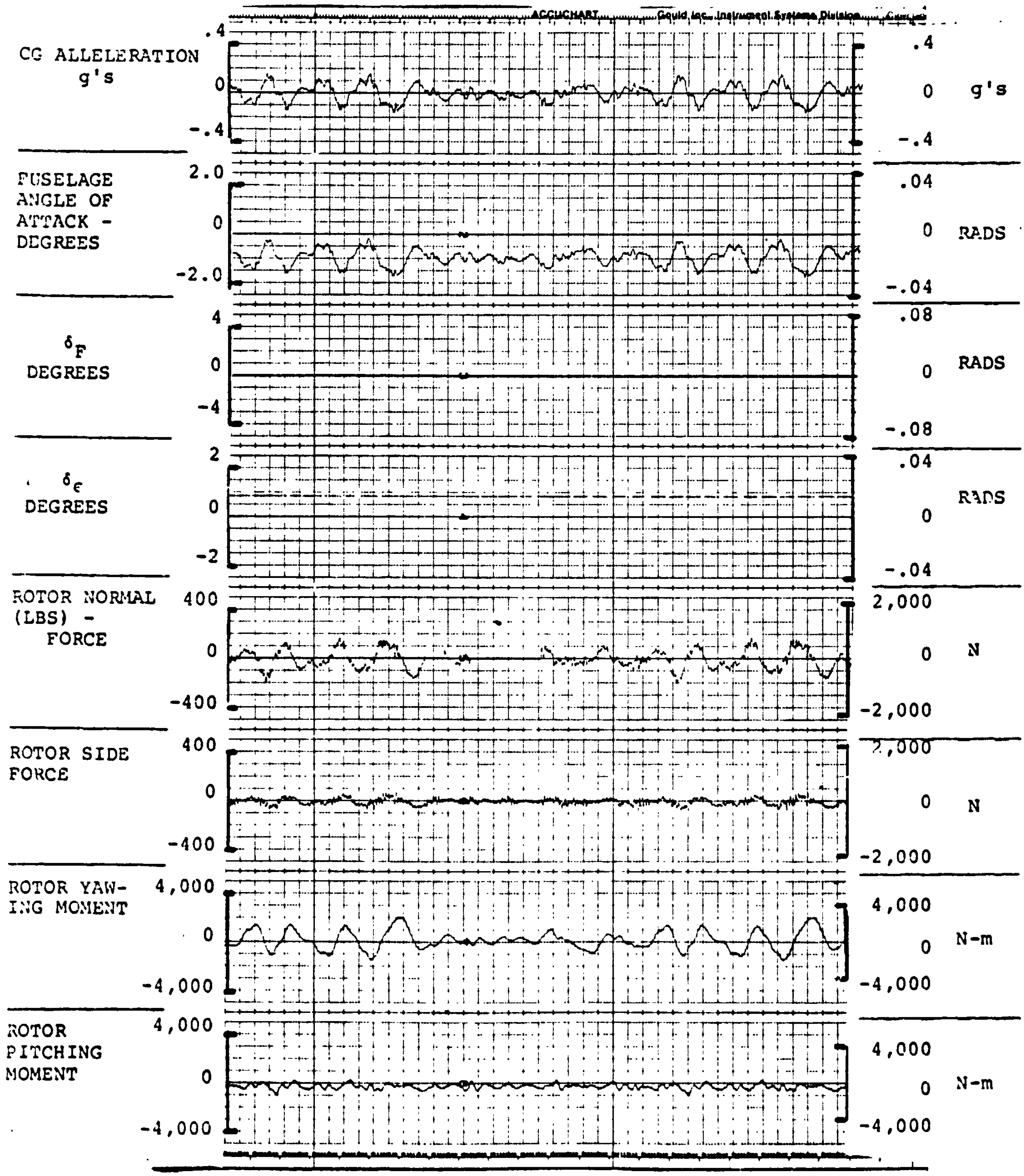


FIGURE 3.11. RESPONSES FOR GAIN F = 0, GAIN E = 0

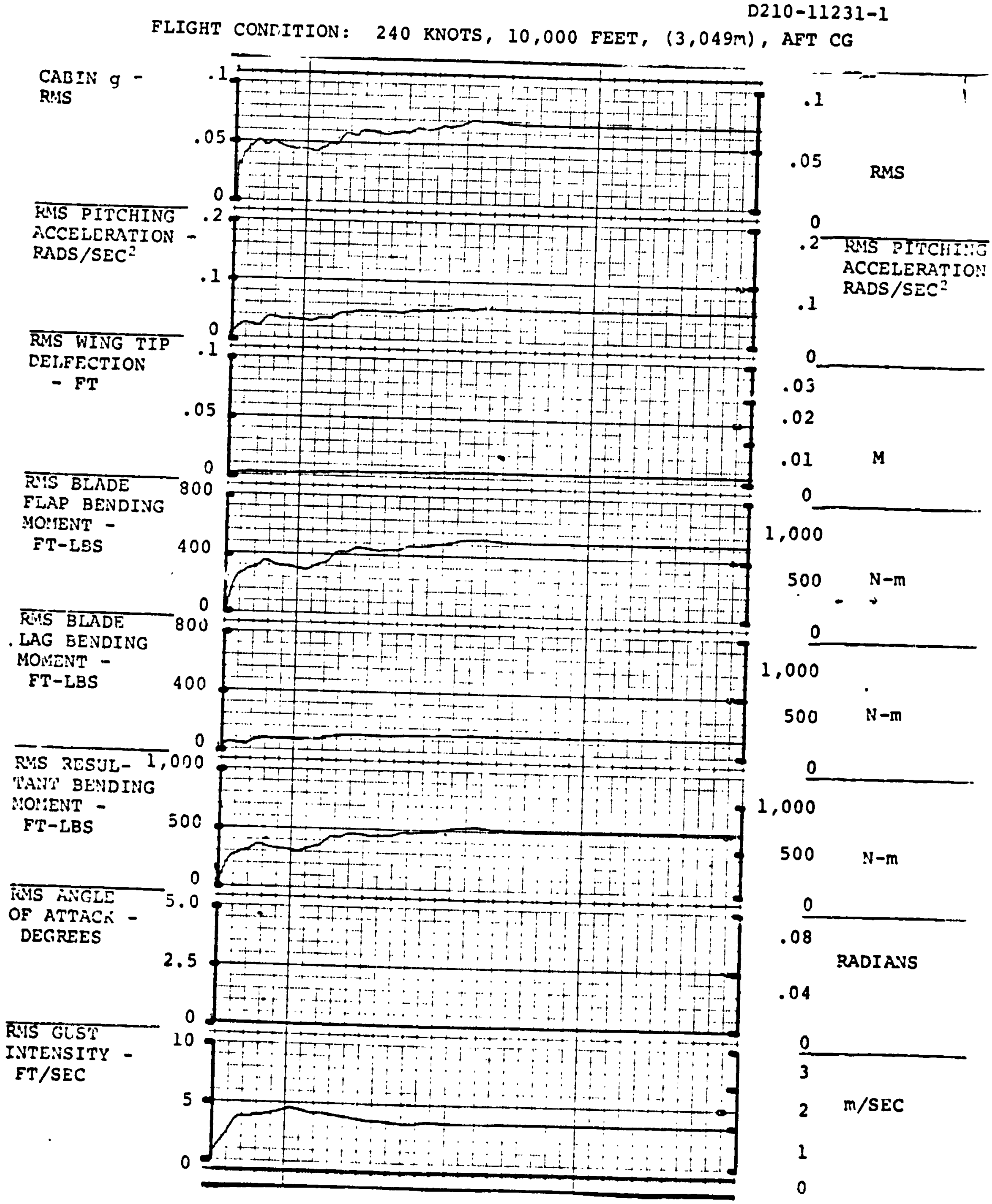


FIGURE 3.12. RESPONSES FOR GAIN F = 0, GAIN E = 0

FLIGHT CONDITION: 240 KNOTS, 10,000 FEET, (3,049m), AFT CG

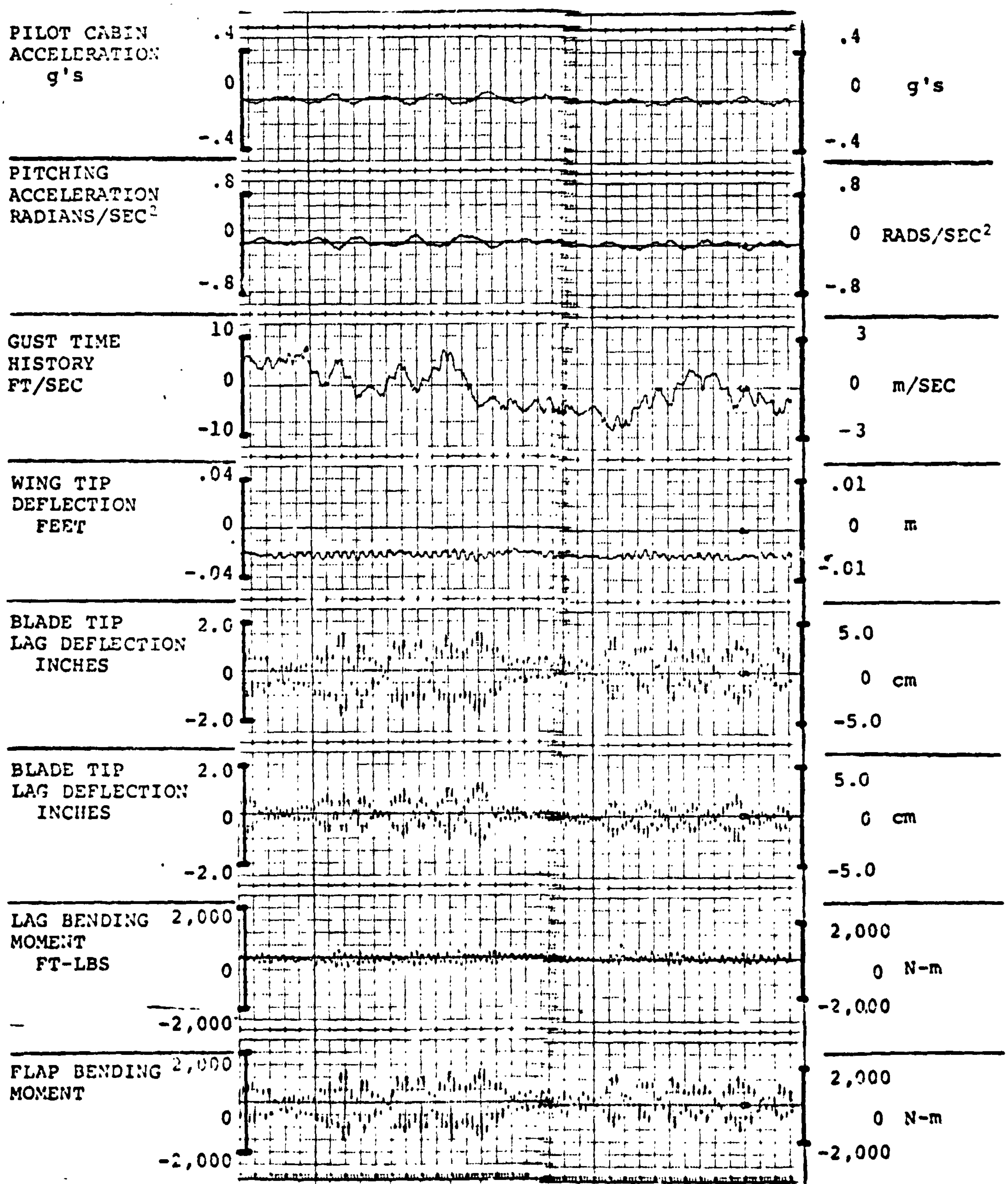


FIGURE 3.13. RESPONSES FOR GAIN F = 4.0, GAIN E = .6

FLIGHT CONDITION: 240 KNOTS, 10,000 FEET, (3,049m), AFT CG

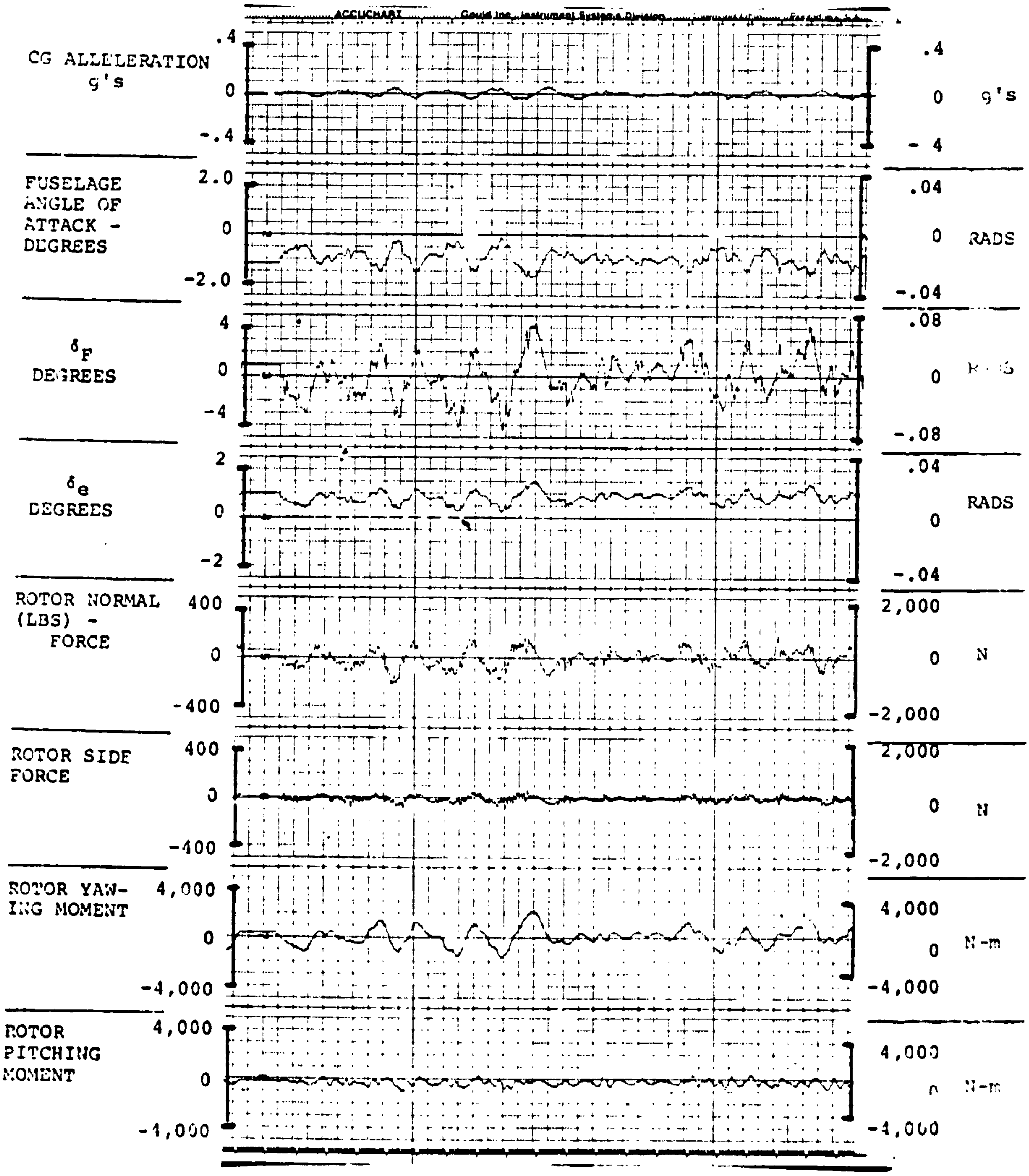


FIGURE 3.14. RESPONSES FOR GAIN F = 4.0, GAIN E = .6

FLIGHT CONDITION: 240 KNOTS, 10,000 FEET, (3,049m), AFT CG

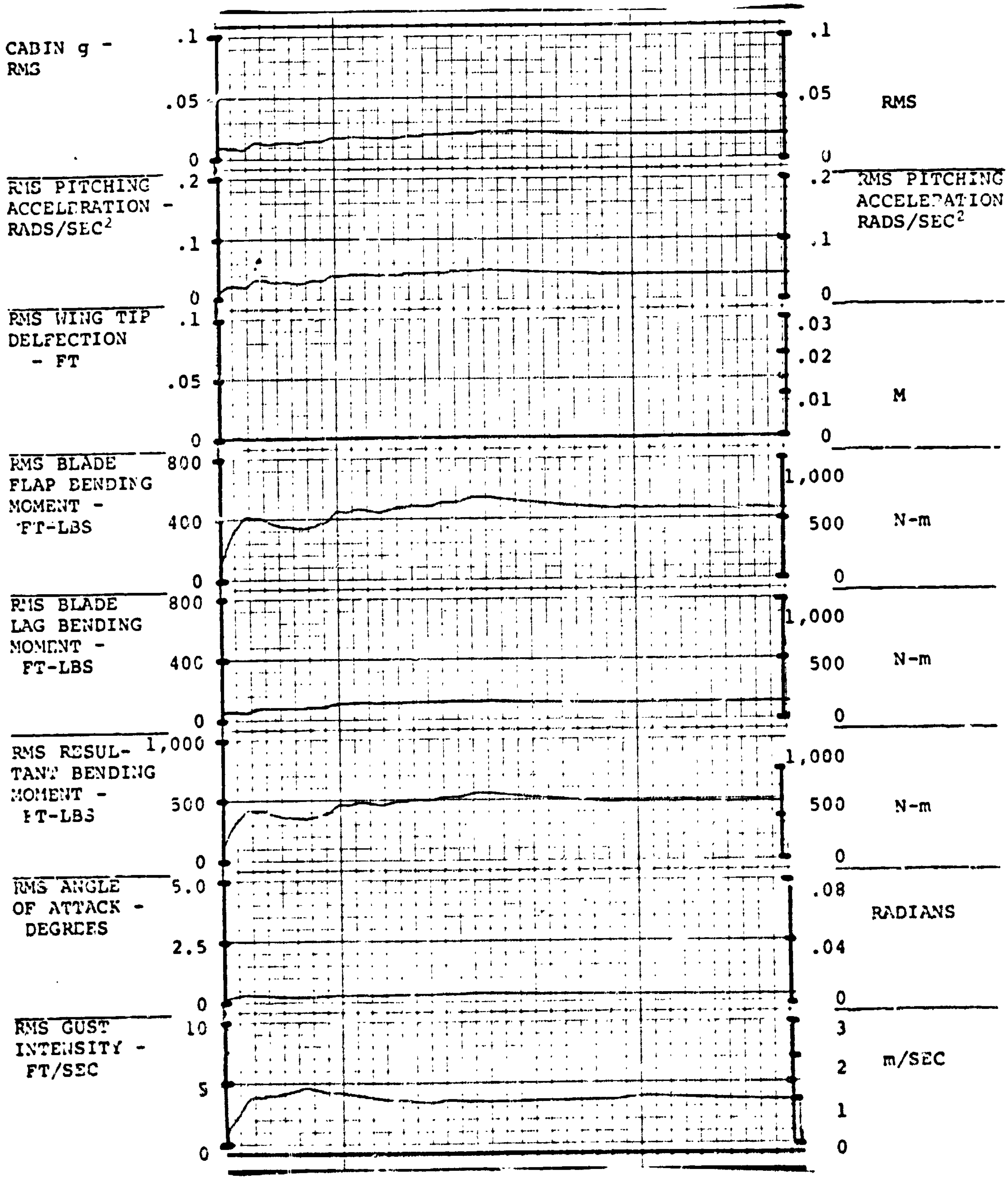
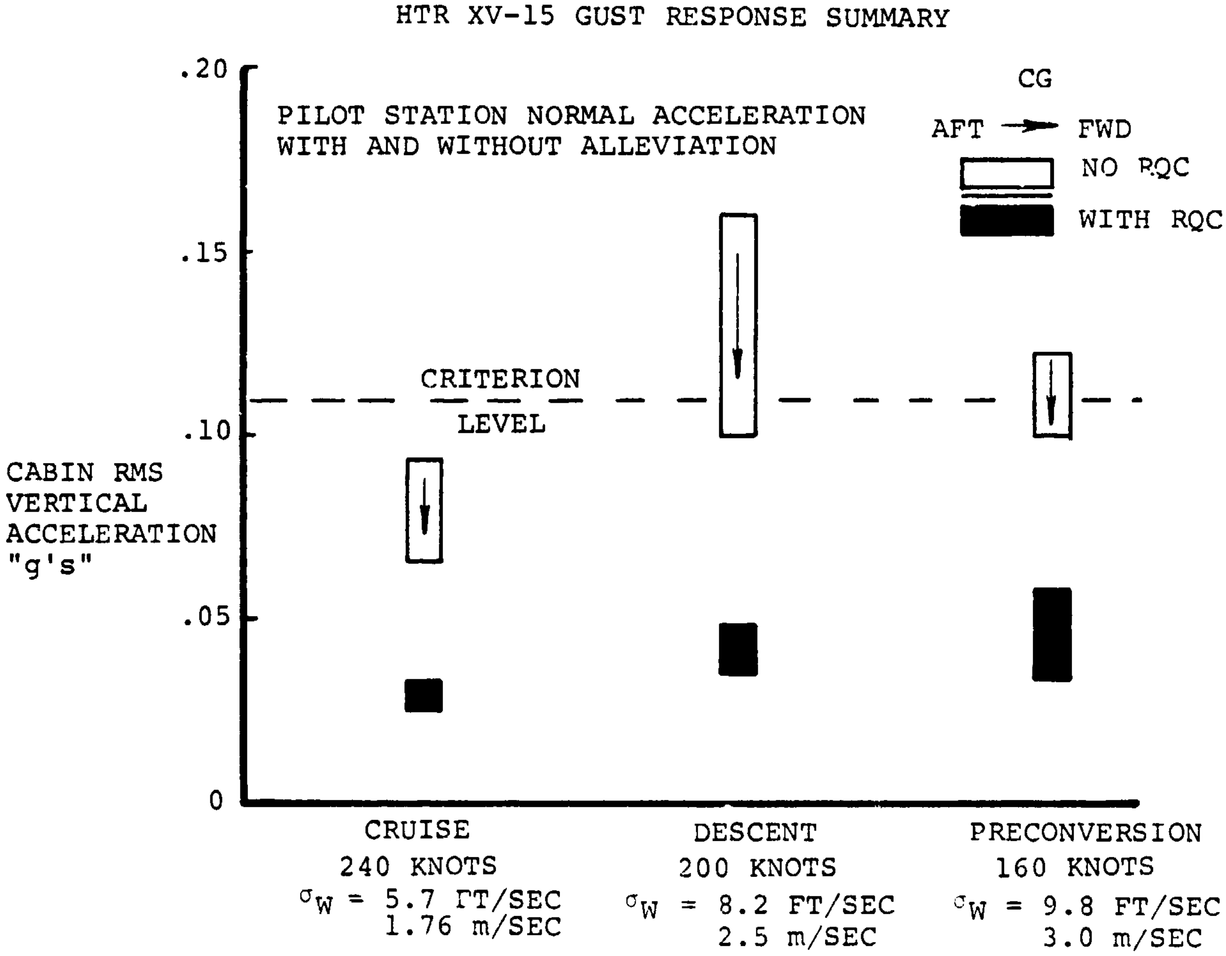


FIGURE 3.15. RESPONSES FOR GAIN F = 4.0, GAIN E = .6



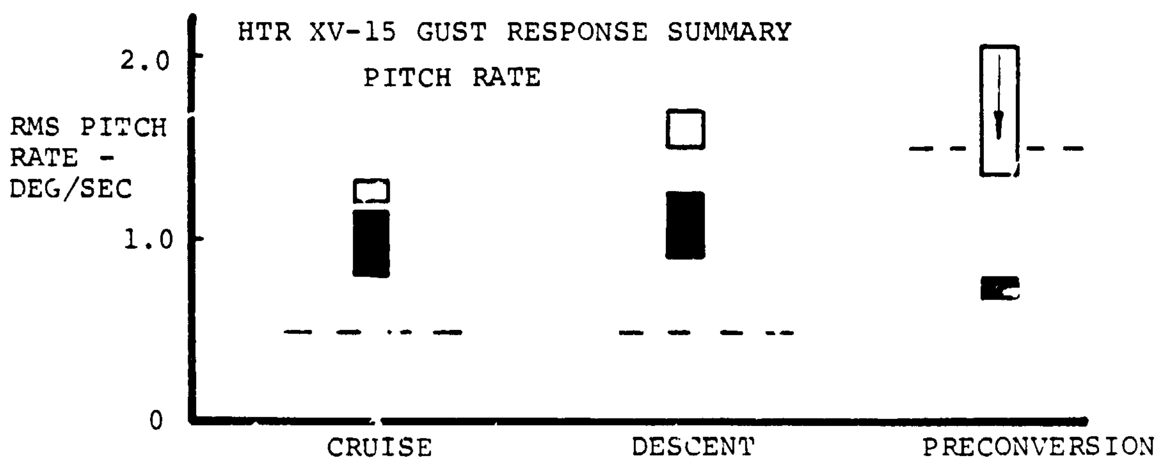


Figure 3.16. Cabin Normal Acceleration and Pitch Rates for Three Flight Conditions.

as an approximate equivalent to an approach condition.

Presented in this manner it is seen that the criterion level of .11g RMS vertical acceleration is met in turbulence of 1.76 m/sec (5.7 ft/sec) RMS intensity, over the complete range of aircraft center of gravity. The alleviation system reduces the response to around 25% of the acceptable criterion level.

At 200 Knots and a gust intensity of 2.5 m/sec (8.2 ft/sec) the basic aircraft normal acceleration response exceeds the .11g RMS level by as much as 50%, and is reduced to approximately 35% with the gust alleviation system active. At 160 Knots and 3.0 m/sec RMS turbulence the basic response level approximates the criterion, and is reduced to a mean level of around 35% by the alleviation system. Pitch rate with and without alleviation exceeds the levels specified in Reference 8, except at 160 Knots where the alleviation system provides 50% of the criterion level. The pitch rates specified in Reference 8 are referenced to levels associated with acceptable passenger comfort provided by contemporary short/medium haul aircraft such as the Boeing 737. In these, pitch response may cause substantial variation of normal acceleration depending on passenger location and this is not an issue in the HTR XV-15 tilt rotor.

3.5 RESULTS INCLUDING ROTOR CONTROLS

Attempts to include rotor control in the alleviation system were not successful. The objective was to reduce blade flapping response and hub moments along with normal and pitching accelerations. It was found that the interactions of the four controls through the sensed variable were sufficiently strong that additional work will be needed to define an acceptable system.

The difficulty stems from the fact that rotor cyclic pitch in cruise is as powerful a control from the aspect of aircraft response as flap or elevator. The initial approach had been to control normal acceleration with direct lift control via the flap; to reduce pitch response by corrective amounts of elevator; and to alleviate hub moments and blade response using A_1 and B_1 cyclic. It was implicitly assumed that there was descending order of magnitude in their impact on vehicle response, however, the data on aircraft response and hub force and moment response shows that levels of cyclic which reduce hub moments by a significant amount, also produce normal and pitching aircraft accelerations of similar magnitude to the accelerations which were the subject of the flap-elevator alleviation system.

Hence, the iterative approach of working on normal acceleration, pitching acceleration and hub moments in succession, is not viable and a direct concurrent solution for all four controls is needed. However, it was not possible and was not considered necessary to match the results for such solution over more than a narrow frequency band, and this is a probable cause of the difficulties with a system using all four controls concurrently.

3.6 GENERAL REMARKS ON ROTOR CONTROLS

As discussed in Section 2, the use of specific sensors for rotor effects might eliminate many of the problems experienced in designing a system for vertical turbulence. However, there are well known difficulties in providing dependable long term signals from either blade motion or hub moments, and this was one of the reasons why the study concentrated on the use of normal acceleration or angles of attack as measures of gust intensity.

In the context of vertical symmetrical turbulence in cruise,the inclusion of rotor effects tends to be academic because its levels of response are not critical and it is probably wiser to ignore the rotor controls. In the alleviation of aircraft response to lateral turbulence, rotor controls are expected to play a primary role and this will represent a fresh challenge.

4.0 CONCLUSIONS AND RECOMMENDATIONS

The study has shown that the HTR XV-15 aircraft has basically about the same level of gust sensitivity in cruise as existing fixed-wing transports such as the Boeing 707,DC6 and 737. Differences in wing loading and lift curve slope appear to be approximately compensated by cruise velocities. Passenger carrying tilt rotor aircraft for the short-haul market may be considerably less gust sensitive than either the HTR XV-15, (wing loading 351 Kg/m^2 (71.8 lb/sq ft)) or fixed-wing STOL designs which rely on low wing loading for short field operation. For example in Reference 1, V/STOL tilt-rotor passenger transports optimized for a short-haul mission fall into the 488 Kg/m^2 (100 lb/sq ft) class, while in Reference 8, fixed-wing aircraft designed for field lengths of 610m (2,000 feet) and 914m (3,000 feet) have wing loadings of 215 Kg/m^2 (44 lb/sq ft) and 287 Kg/m^2 (58 lb/sq ft) respectively.

While the sensitivity of the tilt rotor expressed as the ratio of normal acceleration to gust intensity may be similar to that of conventional fixed-wing transports, the frequency of occurrence is likely to be higher because the tilt rotor cruises at lower altitudes. This will necessitate gust alleviation for passenger acceptance. The current study shows that a simple flap-elevator system can produce alleviation factors up to 70% with no apparent adverse effect on blade loads or hub moments. The amplitudes and rates of control required suggest that little modification to existing actuators would be required, however, their operation will impose additional random fatigue loadings in local structure.

The inclusion of rotor controls was not found to be necessary for alleviation of vertical turbulence, and the rotor response was not significantly different with the flap-elevator system working. Difficulties were expressed incorporating these controls with flap and elevator to reduce hub moments concurrently with normal and pitching acceleration. Additional work is needed to understand these difficulties.

It is recommended that this be accomplished as part of future response studies which will require the rotor controls as primary inputs; for example alleviation in transition flight and in the presence of assymetric longitudinal or lateral turbulence.

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APPENDIX A

DIRECT SOLUTION FOR CHARACTERISTICS OF MULTI-CHANNEL CONTROL SYSTEM

Appendix A - Direct Solution for Characteristics of Multi-Channel Control System

In a tilt-rotor aircraft four controls are typically available for use in rejecting the effects of certical turbulence. These are flap/spoiler, elevator A_1 and B_1 cyclic. These may be applied in combination to produce desired levels of alleviation in up to four chose variables if the frequency response of the variables to each control and to the turbulence is known. The compatibility of level of alleviation demanded with stability requirements (gain and phase margins) may be obtained as an extension of the same analysis and the practical approximation to ideal system characteristic may be evaluated in the same way.

Technical Approach

The equations of motion describing the behavior of an aircraft, rotor and control system combination may be written in the form:

$$A\ddot{q} + B\dot{q} + Cq = F_o u + S_o v$$

where A, B and C are constant coefficient matrices describing the dynamics of the free system at a specific flight condition, and F_o, S_o are also constant coefficient matrices which convert the gust components u, and control inputs v into generalized forces of the system.

If the frequency spectrum of the gust is known this may be expressed in analytical form and in principle, frequency spectra may then be derived for control application which will produce an acceptable net level of response. This procedure is attractive when one output variable is to be controlled by a single channel system. (Reference A1). With several output variables and a similar number of controls, this process loses some of its attraction and a semi-empirical discrete frequency approach becomes more practical. The method developed in the present study is given in the following paragraph. This permits the definition of multi-channel feedback control system which meets specific alleviation requirements. The stability margins may also be computed along with the performance and stability of the practical approximation to the ideal system.

Analysis

If the amplitude and phase responses of an output variable (e.g., cabin normal acceleration) to unit gust and control inputs are known over a range of discrete frequencies, the control applications required to achieve a specific degree of alleviation may be derived as follows.

The response of a selected set of n variables at a given frequency will be given by

$$\underset{(n \times 5)}{\begin{bmatrix} R_{ij} \end{bmatrix}} \begin{Bmatrix} u \\ v \end{Bmatrix}_{5 \times 1} = \begin{Bmatrix} X_1 \\ X_n \end{Bmatrix}$$

where $[R_{ij}]$ is the array of responses to unit gust and unit control inputs to the system at the specified frequency ω and u and v are gust and control values respectively. More specifically, for the system we are considering where we have flap, elevator and A_1, B_1 cyclic controls we may write:

$$\left[R_{iG},\ R_{iF},\ R_{iE},\ R_{iA},\ R_{iB} \right] \begin{Bmatrix} G \\ F \\ E \\ A \\ B \end{Bmatrix} = \begin{Bmatrix} X_1 \\ X_i \\ X_n \end{Bmatrix}$$

$$i = 1 \ldots\ldots\ldots n$$

where $R_{i,G}$, $R_{i,F}$, etc. are response of variable i to unit gust, flap, etc. respectively, and X_i is the net response of variable i.

The response to gust alone is given by

$$\{X_i^1\} = \{R_{i,G}\}\ G$$

Subject to reasonable restriction, alleviation factors p_K may be achieved in a specified set of variables which are responsive to the available controls. The number of independent variables which may be controlled in this way is less than or equal to the number of controls. The control input vector required satisfies the equation

$$\left[R_{KG} \middle| R_{KF},\ R_{KE},\ R_{KA},\ R_{KB} \right] \begin{Bmatrix} 1.0 \\ F \\ E \\ A \\ B \end{Bmatrix} = \left[I - p_K \right] \left\{ X_K^1 \right\}$$

or

$$\begin{bmatrix} R_{K,F} & R_{K,E}, & R_{KA}, & R_{KB} \end{bmatrix} \begin{Bmatrix} F \\ E \\ A \\ B \end{Bmatrix} = - \begin{Bmatrix} p_K & X_K^1 \end{Bmatrix}$$

or

$$\begin{Bmatrix} F \\ E \\ A \\ B \end{Bmatrix} = - \begin{bmatrix} R_{KF}, & R_{KE}, & R_{KA}, & R_{KB} \end{bmatrix}^{-1} \begin{Bmatrix} p_K & R_{KG} \end{Bmatrix}$$

These controls may be applied as feedback signals from a suitable variable of the system. This variable is not necessarily one of the alleviated variables; for example angle of attack which is not a primary object of reduction, but is strongly related to the forcing function may be sensed and with suitable gains and phase shifts will provide the alleviation control values required. If an alleviated variable X_j is sensed the gains and phases required in each channel of control becomes:

$$\text{Gain} = 20 \operatorname{Log}_{10} (F, E, A, B) - 20 \operatorname{Log}_{10} (1-p_j) R_{jG}$$

$$\text{Phase} = \text{Phase } (F, E, A, B) - \text{Phase } (1-p_j) R_{jG}.$$

If the sensed variable X_j is not the subject of attenuation we must calculate its value before the gain and phase requirements can be determined. For example, the angle of attack α after alleviation is given by:

$$\alpha = \begin{bmatrix} R_{\alpha G} & R_{\alpha F} & R_{\alpha E} & R_{\alpha A} & R_{\alpha B} \end{bmatrix} \begin{Bmatrix} 1.0 \\ F \\ E \\ A \\ B \end{Bmatrix}$$

The loop gain and phase may be determined and stability margins evaluated by multiplying and summing the forward loop and feedback gains and phases. If we are alleviating variables X_K and sensing X_j we have

$$\left\{\begin{matrix} F \\ E \\ A_1 \\ B_1 \end{matrix}\right\} = - \left[R_{KF}, R_{KE}, R_{KA}, R_{KB} \right]^{-1} \{P_K R_{KG}\}$$

$$K = 1 \; \ldots\ldots \; n \qquad n \leq 4$$

where subscript K refers to variables being alleviated, and j refers to sensed variables. If signal X_j of unit amplitude is amplified and phased to produce {F} this in time produces

$$X_j^* = [R_{jF}, R_{jE}, R_{jA}, R_{jB}] \{F\}.$$

So that loop gain X_j^*/X_j is equal to

$$[R_{jF} \; R_{jE} \; R_{jA} \; R_{jB}] \; [R_{KF} \; R_{KE} \; R_{KA} \; R_{KB}]^{-1} \{P_K \; R_{KG}\}.$$

The amplitude and phase of this can be readily calculated from the individual responses.

Physical Realization of Ideal System

The foregoing analysis will provide at each frequency a gain plus phase for each channel control. This must be approximated by hardware and compromises must be made. The resulting system can usually be represented by some combination of transfer function representing actuator dynamic, steady-state washout, and response shaping networks. The net performance and stability margins associated with the selected system may be evaluated by calculating the amplitude and phase response of the individual control circuits and combining these with the aircraft response behavior.

Program Coding

To facilitate use of the preceding analyses two simple computer programs were written. The first evaluates gains and phases for flap elevator and cyclic controls to accomplish specified levels of alleviation at discrete frequencies. This also evaluates the system open loop response so that stability margins may be inspected. The second program computes the amplitudes and phase characteristics of the control counts selected to represent the ideal requirements and provides the overall open loop characteristics. The coding for each of these programs is given in the following sheets.

NOPT	Indicator, if = 1 only flap and elevator activated if = 0 flap, elevator, A_1 & B_1 are activated
KASE NO	Indicator used to run multiple cases
ALT	Altitude in Feet } Case Identification Only
VKT	Velocity in Knots } Case Identification Only
XCG	CG Coordinate Longitudinal } Case Identification Only
ZCG	CG Coordinate Vertical } Case Identification Only
GSTAMP	Gust Amplitude in Ft/Sec
FLPAMP	Flap Amplitude in Degrees
ELVAMP	Elevator Amplitude in Degrees
AAMP	A_1 Cyclic Amplitude in Degrees
BAMP	B_1 Cyclic Amplitude in Degrees
OMEGA	Frequency Range in Hertz
PCR	Real Component of Cabin Alleviation Factor
PCI	Imaginary Component of Cabin Alleviation Factor
PTR	Real Component of Pitching Acceleration Alleviation Factor
PTI	Imaginary Component of Pitching Acceleration Alleviation Factor
PZR	Real Component of Yawing Moment Factor
PZI	Imaginary Component of Yawing Moment Factor
PYR	Real Component of Pitching Moment Factor
PYI	Imaginary Component of Yawing Moment Factor
AG	Cabin Acceleration Response to Gust
EPSG	Cabin Acceleration Phase to Gust
BG	Pitch Acceleration Response to Gust Amplitude
PH1G	Pitch Acceleration Phase to Gust

MZG	Yawing Moment Response to Gust
EPZG	Yawing Moment Phase to Gust
MYG	Pitching Moment Response to Gust
EPYG	Pitching Moment Phase to Gust
AF	Cabin Acceleration Response to Flap
EPSF	Cabin Acceleration Phase to Flap
BF	Pitch Acceleration Response to Flap
PH1F	Pitch Acceleration Phase to Flap
MZF	Yawing Moment Response to Flap
EPZF	Yawing Moment Phase to Flap
MYF	Pitching Moment Response to Flap
EPYF	Pitching Moment Phase to Flap
AE	Cabin Acceleration Response to Elevatcr
EPSE	Cabin Acceleration Phase to Elevator
BE	Pitch Acceleration Response to Elevator
PH1E	Pitch Acceleration Phase to Elevator
MZE	Yawing Moment Response to Elevator
EPZE	Yawing Moment Phase to Elevator
MYE	Pitching Moment Response to Elevator
EPYE	Pitching Moment Phase to Elevator
AA	Cabin Acceleration Response to A_1 Cyclic
EPSA	Cabin Acceleration Phase to A_1 Cyclic
BA	Pitch Acceleration Response to A_1 Cyclic
PA1A	Cabin Acceleration Phase A_1 Cyclic
MZA	Yawing Moment Response to A_1 Cyclic

EPZA	Yawing Moment Phase to A_1 Cyclic
MYA	Pitching Moment Response to A_1 Cyclic
EPYA	Pitching Moment Phase to A_1 Cyclic
AB	Cabin Acceleration Response to B_1 Cyclic
EPSB	Cabin Acceleration Phase to B_1 Cyclic
BB	Pitching Acceleration Response to B_1 Cyclic
PHIB	Pitching Acceleration Phase to B_1 Cyclic
MZB	Yawing Moment Response to B_1 Cyclic
EPZB	Yawing Moment Phase to B_1 Cyclic
MYB	Pitching Moment Response to B_1 Cyclic
EPYB	Pitching Moment Phase to B_1 Cyclic
CGG	CG Acceleration Response to Gust
EPSCGG	CG Acceleration Phase to Gust
CGF	CG Acceleration Response to Flap
GEPSF	CG Acceleration Phase to Flap
CGE	CG Acceleration Response to Elevator
GEPSE	CG Acceleration Phase to Elevator
CGA	CG Acceleration Response to A_1 Cyclic
GEPSA	CG Acceleration Phase to A_1 Cyclic
CGB	CG Acceleration Response to B_1 Cyclic
GEPSB	CG Acceleration Phase to B_1 Cyclic
ALFG	Angle of Attack Response to Gust
EPSAL	Angle of Attack Phase to Gust
ALFF	Angle of Attack Response to Flap
ALEPF	Angle of Attack Phase to Flap
ALFE	Angle of Attack Response to Elevator

ALEPE	Angle of Attack Phase to Elevator
ALFA	Angle of Attack Response to A_1 Cyclic
ALEPA	Angle of Attack Phase to A_1 Cyclic
ALFB	Angle of Attack Response to B_1 Cyclic
ALEPB	Angle of Attack Phase to B_1 Cyclic
FZG	Rotor Normal Force Response to Gust
FZEPG	Rotor Normal Force Phase to Gust
FZF	Rotor Normal Force Response to Flap
FZEPF	Rotor Normal Force Phase to Flap
FZE	Rotor Normal Force Response to Elevator
FZEPE	Rotor Normal Force Phase to Elevator
FZA	Rotor Normal Force Response to A_1 Cyclic
FZEPA	Rotor Normal Force Phase to A_1 Cyclic
FZB	Rotor Normal Force Response to B_1 Cyclic
FZEPB	Rotor Normal Force Phase to B_1 Cyclic
FYG	Rotor Side Force Response to Gust
FYEPG	Rotor Side Force Phase to Gust
FYF	Rotor Side Force Response to Flap
FYEPF	Rotor Side Force Phase to Flap
FYE	Rotor Side Force Response to Elevator
FYEPE	Rotor Side Force Phase to Elevator
FYA	Rotor Side Force Response to A_1 Cyclic
FYEPA	Rotor Side Force Phase to A_1 Cyclic
FYB	Rotor Side Force Response to B_1 Cyclic
FYEPB	Rotor Side Force Phase to B_1 Cyclic

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*JOB          MCVEIGH,KP=29,PAGES=35,LINES=60,RUN=CHECK,LIST=SUBS
            DIMENSION A(64),X(8),B(8),LL(8),MM(8),C(16),Y(4),D(4),LLL(4),
          1 MMM(4)
            REAL MZG,MYG,MZF,MYF,MZE,MYE,MZA,MYA,MZB,MYB
          1,LPGNC,LPPHC,LPGNG,LPPHG,LPGAL,LPHAL
            DTR=3.14159/180.
            READ, NOPT
      2001  READ, KASENO
            IF (KASENO. EQ.99) CALL EXIT
            READ,ALT,VKT,XCG,ZCG,GSTAMP,FLPAMP,ELVAMP,AAMP,BAMP
            PRINT 99,ALT,VKT,XCG,ZCG
      99    FORMAT(/,8X,*ALTITUDE=*,F8.2,8X,*VKT=*,F6.2,8X,*XCG=*,
          1 F6.2,8X,*ZCG=*,F6.2)
            PRINT 1000
      1000  FORMAT(/,130(1H*))
      2002  READ,OMEGA
            IF (OMEGA. EQ. 0.0) GO TO 2001
            READ,PCR,PCI,PTR,PTI,PZR,PZI,PYR,PYI
            READ,AG,EPSG,BG,PHIG,MZG,EPZG,MYG,EPYG
            READ,AF,EPSF,BF,PHIF,MZF,EPZF,MYF,EPYF
            READ,AE,EPSE,BE,PHIE,MZE,EPZE,MYE,EPYE
            READ,AA,EPSA,BA,PHIA,MZA,EPZA,MYA,EPYA
            READ,AB,EPSB,BB,PHIB,MZB,EPZB,MYB,EPYB
            READ,CGG,EPSCGG,CGF,GEPSF,CGE,GEPSE,CGA,GEPSA,CGB,GEPSB
            READ,ALFG,EPSAL,ALFF,ALEPF,ALFE,ALFPE,ALFA,ALEPA,ALFB,ALEPB
            READ,FZG,FZEPG,FZF,FZEPF,FZE,FZEPE,FZA,FZEPA,FZB,FZEPB
            READ,FYG,FYEPG,FYF,FYEPF,FYE,FYEPE,FYA,FYEPA,FYB,FYEPB
      101   FORMAT(/,3X,F6.3,2X,F6.3,2X,F6.3,2X,F6.3,3X,F6.3,3X,F6.3)
            PRINT 100
      100   FORMAT(//,4X,*GUST*,4X,*GUST*,4X,*FLAP*,4X,*ELEV*,5X,*A1*,5X,*B1*,
          1 /,4X,*FREQ*,4X,*AMPL*,4X,*AMPL*,4X,*AMPL*,4X,*AMPL*,4X,*AMPL*)
            PRINT 101,OMEGA,GSTAMP,FLPAMP,ELVAMP,AAMP,BAMP
            PRINT 102
      102   FORMAT(/,4X,*PCR*,6X,*PCI*,6X,*PTR*,6X,*PTI*,6X,*PZR*,6X,*PZI*,
          1 6X,*PYR*,6X,*PYI*)
            PRINT 103,PCR,PCI,PTR,PTI,PZR,PZI,PYR,PYI
      103   FORMAT(/,3X,F6.3,3X,F6.3,3X,F6.3,3X,F6.3,3X,F6.3,3X,F6.3,3X,
          1 F6.3,3X,F6.3)
            PRINT 104
      104   FORMAT(/,5X,*CAB RESP TO GUST*,5X,*PITCH RESP TO GUST*,5X,*Y.M. RESP
          1  TO GUST*,5X,*P.M. RESP TO GUST*/,4X,*AMPL     PHASE*,4X,*AMPL*,
          2 10X,*PHASE*4X,*AMPL*,10X,*PHASE*,4X,*AMPL*,10X,*PHASE*)
            PRINT 105,AG,EPSG,BG,PHIG,MZG,EPZG,MYG,EPYG
      105   FORMAT(/,3X,F6.3,2X,F8.3,4X,F6.3,5X,F8.3,6X,F6.1,2X,F8.3,6X,F6.1,
          1 2X,F8.3)
            PRINT 106
      106   FORMAT(/,4X,*CAB RESP TO FLAP*,5X,*PITCH RESP TO FLAP*,5X,*Y.M. DUE
          1 TO FLAP*,5X,*P.M. DUE TO FLAP*/,4X,*AMPL*,5X,*PHASE*,5X,*AMPL*,
          2 9X,*PHASE*,5X,*AMPL*,7X,*PHASE*,5X,*AMPL*,7X,*PHASE*)
            PRINT 107,AF,EPSF,BF,PHIF,MZF,EPZF,MYF,EPYF
      107   FORMAT(/,3X,F6.3,2X,F8.3,3X,F6.3,5X,F8.3,4X,F6.1,3X,F8.3,4X,F6.1,
          1 3X,F8.3)
            PRINT 108
      108   FORMAT(/,4X,*CAB RESP TO ELEV*,5X,*PITCH RESP TO ELEV*,5X,*Y.M. DUE
          1  TO ELEV*,5X,*P.M. DUE TO ELEV*/,4X,*AMPL*,5X,*PHASE*,5X,*AMPL*,
          2 9X,*PHASE*,5X,*AMPL*,7X,*PHASE*,5X,*AMPL*,7X,*PHASE*)
            PRINT 109,AE,EPSE,BE,PHIE,MZE,EPZE,MYE,EPYE
      109   FORMAT(/,3X,F6.3,2X,F8.3,3X,F6.3,5X,F8.3,3X,F6.1,3X,F8.3,4X,
          1 F6.1,3X,F8.3)
            PRINT 110
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 110  FORMAT(/,4X,'CAB RESP TO A1',6X,'PITCH RESP TO A1',8X,'Y.M. RESP
     1 TO A1',7X,'P.M. RESP TO A1'/,4X,'AMPL   PHASE',6X,'AMPL',7X,
     2 'PHASE',8X,'AMPL',5X,'PHASE',7X,'AMPL',5X,'PHASE')
      PRINT 111,AA,EPSA,BA,PHIA,MZA,EPZA,MYA,EPYA
 111  FORMAT(/,3X,F6.3,2X,F8.3,2X,F6.3,3X,F8.3,7X,F6.1,2X,F8.3,5X,
     1 F6.1,2X,F8.3)
      PRINT 112
 112  FORMAT(/,4X,'CAB RESP TO B1',6X,'PITCH RESP TO B1',8X,'Y.M. DUE TO
     1 B1',7X,'P.M. DUE TO B1'/,4X,'AMPL   PHASE',6X,'AMPL',7X,'PHASE'
     2 ,8X,'AMPL',5X,'PHASE',7X,'AMPL',5X,'PHASE')
      PRINT 113,AB,EPSB,BB,PHIB,MZB,EPZB,MYB,EPYB
 113  FORMAT(/,3X,F6.3,2X,F8.3,2X,F6.3,3X,F6.3,7X,F6.1,2X,F8.3,5X,
     1 F6.1,2X,F8.3)
      PRINT 114
 114  FORMAT(/,4X,'CG RESP TO G',3X,'CG RESP TO FLAP',3X,'CG RESP TO
     1  ELEV',3X,'CG RESP TO A1',3X,'CG RESP TO B1'/,4X,'AMPL    PHASE'
     2 ,2X,'AMPL',6X,'PHASE',3X,'AMPL',6X,'PHASE',3X,'AMPL    PHASE',
     3 3X,'AMPL   PHASE')
      PRINT 115,CGG,EPSCGG,CGF,GEPSF,CGE,GEPSE,CGA,GEPSA,CGB,GEPSB
 115  FORMAT(/,3X,F6.3,1X,F8.3,2X,F6.3,2X,F8.3,3X,F6.3,1X,F8.3,3X,
     1 F6.3,1X,F8.3,2X,F6.3,1X,F8.3)
      PRINT 116
 116  FORMAT(/,4X,'ALF RESP TO G',5X,'ALF RESP TO FLAP',5X,
     1 'ALF RESP TO ELEV',5X,'ALF RESP TO A1',5X,'ALF RESP TO B1'
     2 /,4X,'AMPL',4X,'PHASE',4X,'AMPL',7X,'PHASE',5X,'AMPL',7X,
     3 'PHASE',5X,'AMPL',5X,'PHASE',5X,'AMPL',5X,'PHASE')
      PRINT 117,ALFG,EPSAL,ALFF,ALEPF,ALFE,ALEPE,ALFA,ALEPA,ALFB,ALFPB
 117  FORMAT(/,3X,F6.3,1X,F8.3,3X,F6.3,2X,F8.3,5X,F6.3,2X,F8.3,5X,
     1 F6.3,1X,F8.3,4X,F6.3,1X,F8.3)
      PRINT 118
 118  FORMAT(/,4X,'FZ RESP TO G',5X,'FZ RESP TO FLAP',5X,'FZ RESP TO
     1 ELEV',5X,'FZ RESP TO A1',5X,'FZ RESP TO B1'/,4X,'AMPL   PHASE'
     2 ,5X,'AMPL',6X,'PHASE',5X,'AMPL',6X,'PHASE',5X,'AMPL',4X,
     3 'PHASE',5X,'AMPL',4X,'PHASE')
      PRINT 119,FZG,FZEPG,FZF,FZEPF,FZE,FZEPE,FZA,FZEPA,FZB,FZEPB
 119  FORMAT(/,3X,F6.3,1X,F8.3,3X,F6.3,1X,F8.3,5X,F6.3,1X,F8.3,5X,
     1 F6.3,1X,F8.3,3X,F6.3,1X,F8.3)
      PRINT 120
 120  FORMAT(/,4X,'FY RESP TO G',5X,'FY RESP TO FLAP',5X,
     1 'FY RESP TO ELEV',5X,'FY RESP TO A1',5X,'FY RESP TO B1'/,4X,
     2 'AMPL   PHASE',5X,'AMPL',6X,'PHASE',5X,'AMPL',6X,'PHASE',5X,
     3 'AMPL',4X,'PHASE',5X,'AMPL',4X,'PHASE')
       PRINT 121,FYG,FYEPG,FYF,FYEPF,FYE,FYEPE,FYA,FYEPA,FYB,FYEPB
       FORMAT(/,3X,F6.3,1X,F8.3,3X,F6.3,1X,F8.3,5X,F6.3,1X,F8.3,5X,
 121 1 F6.3,1X,F8.3,3X,F6.3,1X,F8.3)
      PRINT 1000
  63  FORMAT(/1X,'FLAP AMP',F8.3,7X,'FLAP PHASE',F8.3,7X,
     1 'ELEV AMP',F8.3,7X,'ELEV PHASE',F8.3/,1X,'A1 AMP',F8.3,
     2 7X,'A1 PHASE',F8.3,7X,'B1 AMP',F8.3,7X,'B1 PHASE',F8.3)
  64  FORMAT(/,1X,'ALLEVIATED CAB NORM ACCN',F8.3,7X,'PHASE OF ACCN',
     1 F8.3/,1X,'FLAP GAIN',F8.3,7X,'FLAP PHASE',F8.3,20X,
     2 'ELEVATOR GAIN',F8.3,7X,'ELEVATOR PHASE',F8.3/,1X,'A1 CYCLIC
     3 GAIN',F8.3,7X,'A1 CYCLIC PHASE',F8.3,15X,'B1 CYCLIC GAIN',
     4 F8.3,7X,'B1 CYCLIC PHASE',F8.3/
     5,1X,'OPEN LOOP GAIN',F8.3,7X,'OPEN LOOP PHASE',F8.3)
      PRINT 1000
  65  FORMAT(/,1X,'ALLEVIATED CG ACCN',F8.3,7X,'PHASE OF ACCN',F8.3/,
     1 1X,'FLAP GAIN',F8.3,7X,'FLAP PHASE',F8.3,7X,'ELEVATOR GAIN',
     2 F8.3,7X,'ELEVATOR PHASE',F8.3/,1X,'A1 CYCLIC GAIN',F8.3,7X,
     3 'A1 CYCLIC PHASE',F8.3,15X,'B1 CYCLIC GAIN',F8.3,7X,
```

```
     4 'HI CYCLIC PHASE',F8.3/
     5,1X,'OPEN LOOP GAIN',F8.3,7X,'OPEN LOOP PHASE',F8.3)
      PRINT 1000
C     NONDIMENSIONALIZE RESPONSE AMPLITUDES BY FORCING AMPLITUDES
      AG=AG/GSTAMP
      BG=BG/GSTAMP
      MZG=MZG/GSTAMP
      MYG=MYG/GSTAMP
      ALFG=ALFG/GSTAMP
      FZG=FZG/GSTAMP
      FYG=FYG/GSTAMP
      CGG=CGG/GSTAMP
      AF=AF/FLPAMP
      BF=BF/FLPAMP
      MZF=MZF/FLPAMP
      MYF=MYF/FLPAMP
      ALFF=ALFF/FLPAMP
      FZF=FZF/FLPAMP
      FYF=FYF/FLPAMP
      CGF=CGF/FLPAMP
      AE=AE/ELVAMP
      BE=BE/ELVAMP
      MZE=MZE/ELVAMP
      MYE=MYE/ELVAMP
      ALFE=ALFE/ELVAMP
      FYE=FYE/ELVAMP
      FZE=FZE/ELVAMP
      CGE=CGE/ELVAMP
      AA=AA/AAMP
      BA=BA/AAMP
      MZA=MZA/AAMP
      MYA=MYA/AAMP
      ALFA=ALFA/AAMP
      FZA=FZA/AAMP
      FYA=FYA/AAMP
      CGA=CGA/AAMP
      AB=AB/BAMP
      BB=BB/BAMP
      MZB=MZB/BAMP
      MYB=MYB/BAMP
      ALFB=ALFB/BAMP
      FZB=FZB/BAMP
      FYB=FYB/BAMP
      CGB=CGB/BAMP
C     CONVERT DEGREES TO RADIANS
      EPSG=EPSG*DTR
      PHIG=PHIG*DTR
      EPZG=EPZG*DTR
      EPYG=EPYG*DTR
      EPSAL=EPSAL*DTR
      FZEPG=FZEPG*DTR
      FYEPG=FYEPG*DTR
      EPSCGG=EPSCGG*DTR
      EPSF=EPSF*DTR
      PHIF=PHIF*DTR
      EPZF=EPZF*DTR
      EPYF=EPYF*DTR
      ALEPF=ALEPF*DTR
      FZEPF=FZEPF*DTR
      FYEPF=FYEPF*DTR
```

```
GEPSF=GEPSF*DTR
EPSF=EPSE*DTR
PHIE=PHIE*DTR
EPZE=EPZE*DTR
EPYE=EPYE*DTR
ALEPE=ALEPE*DTR
FZEPE=FZEPE*DTR
FYEPE=FYEPE*DTR
GEPSE=GEPSE*DTR
EPSA=EPSA*DTR
PHIA=PHIA*DTR
ALEPA=ALEPA*DTR
FZEPA=FZEPA*DTR
FYEPA=FYEPA*DTR
GEPSA=GEPSA*DTR
EPZA=EPZA*DTR
EPYA=EPYA*DTR
EPSB=EPSB*DTR
PHIB=PHIB*DTR
EPZB=EPZB*DTR
EPYB=EPYB*DTR
ALEPB=ALEPB*DTR
FZEPB=FZEPB*DTR
FYEPB=FYEPB*DTR
GEPSB=GEPSB*DTR
ACA=AG*COS(EP3G)
BCA=AG*SIN(EP3G)
ATA=BG*COS(PHIG)
BTA=BG*SIN(PHIG)
AMZA=MZG*COS(EPZG)
BMZA=MZG*SIN(EPZG)
AMYA=MYG*COS(EPYG)
BMYA=MYG*SIN(EPYG)
AALA=ALFG*COS(EPSAL)
BALA=ALFG*SIN(EPSAL)
AFZA=FZG*COS(FZEPG)
BFZA=FZG*SIN(FZEPG)
AFYA=FYG*COS(FYEPG)
BFYA=FYG*SIN(FYEPG)
ACGA=CGG*COS(EPSCGG)
BCGA=CGG*SIN(EPSCGG)
ACF=AF*COS(EPSF)
BCF=AF*SIN(EPSF)
ATF=BF*COS(PHIF)
BTF=BF*SIN(PHIF)
AMZF=MZF*COS(EPZF)
BMZF=MZF*SIN(EPZF)
AMYF=MYF*COS(EPYF)
BMYF=MYF*SIN(EPYF)
AALF=ALFF*COS(ALEPF)
BALF=ALFF*SIN(ALEPF)
AFZF=FZF*COS(FZEPF)
BFZF=FZF*SIN(FZEPF)
AFYF=FYF*COS(FYEPF)
BFYF=FYF*SIN(FYEPF)
ACGF=CGF*COS(GEPSF)
BCGF=CGF*SIN(GEPSF)
ACE=AE*COS(EPSE)
BCE=AE*SIN(EPSE)
ATE=BE*COS(PHIE)
```

```
      BTE=HE*SIN(PHIE)
      AMZE=MZE*COS(EPZE)
      BMZE=MZE*SIN(EPZE)
      AMYE=MYE*COS(EPYE)
      BMYE=MYE*SIN(EPYE)
      AALE=ALFE*COS(ALEPE)
      BALE=ALFE*SIN(ALEPE)
      AFZE=FZE*COS(FZEPE)
      BFZE=FZE*SIN(FZEPE)
      AFYE=FYE*COS(FYEPE)
      BFYE=FYE*SIN(FYEPE)
      ACGE=CGE*COS(GEPSE)
      BCGE=CGE*SIN(GEPSE)
      ACA=AA*COS(EPSA)
      BCA=AA*SIN(EPSA)
      ATA=HA*COS(PHIA)
      BTA=HA*SIN(PHIA)
      AMZA=MZA*COS(EPZA)
      BMZA=MZA*SIN(EPZA)
      AMYA=MYA*COS(EPYA)
      BMYA=MYA*SIN(EPYA)
      AALA=ALFA*COS(ALEPA)
      BALA=ALFA*SIN(ALEPA)
      AFZA=FZA*COS(FZEPA)
      BFZA=FZA*SIN(FZEPA)
      AFYA=FYA*COS(FYEPA)
      BFYA=FYA*SIN(FYEPA)
      ACGA=CGA*COS(GEPSA)
      BCGA=CGA*SIN(GEPSA)
      ACB=AB*COS(EPSB)
      BCB=AB*SIN(EPSB)
      ATB=HB*COS(PHIB)
      BTB=HB*SIN(PHIB)
      AMZB=MZB*COS(EPZB)
      BMZB=MZB*SIN(EPZB)
      AMYB=MYB*COS(EPYB)
      BMYB=MYB*SIN(EPYB)
      AALB=ALFB*COS(ALEPB)
      BALB=ALFB*SIN(ALEPB)
      AFZB=FZB*COS(FZEPB)
      BFZB=FZB*SIN(FZEPB)
      AFYB=FYB*COS(FYEPB)
      BFYB=FYB*SIN(FYEPB)
       ACGB=CGB*COS(GEPSB)
      BCGB=CGB*SIN(GEPSB)
      ACZ=ACW*PCR-BCW*PCI
      BCZ=ACW*PCI+BCW*PCR
      ATH=ATW*PTR-BTW*PTI
      BTH=ATW*PTI+BTW*PTR
      AMZ=AMZW*PZR-BMZW*PZI
      BMZ=AMZW*PZI+BMZW*PZR
      AMY=AMYW*PYR-BMYW*PYI
      BMY=AMYW*PYI+BMYW*PYR
      IF(NOPT.EQ.0) GO TO 3001
      C(1)=ACF
      C(2)=BCF
      C(3)=ATF
      C(4)=BTF
      C(5)=-BCF
      C(6)=ACF
```

```
      C(7)=-BTF
      C(8)=ATF
      C(9)=ACE
      C(10)=BCF
      C(11)=ATE
      C(12)=BTE
      C(13)=-BCF
      C(14)=ACE
      C(15)=-BTE
      C(16)=ATE
      GO TO 3002
 3001 A(1)=ACF
      A(2)=BCF
      A(3)=ATF
      A(4)=BTF
      A(5)=AMZF
      A(6)=BMZF
      A(7)=AMYF
      A(8)=BMYF
      A(9)=-BCF
      A(10)=ACF
      A(11)=-BTF
      A(12)=ATF
      A(13)=-BMZF
      A(14)=AMZF
      A(15)=-BMYF
      A(16)=AMYF
      A(17)=ACE
      A(18)=BCE
      A(19)=ATE
      A(20)=BTE
      A(21)=AMZE
      A(22)=BMZE
      A(23)=AMYE
      A(24)=BMYE
      A(25)=-BCE
      A(26)=ACE
      A(27)=-BTE
      A(28)=ATE
      A(29)=-BMZE
      A(30)=AMZE
      A(31)=-BMYF
      A(32)=AMYE
      A(33)=ACA
      A(34)=BCA
      A(35)=ATA
      A(36)=BTA
      A(37)=AMZA
      A(38)=BMZA
      A(39)=AMYA
      A(40)=BMYA
      A(41)=-BCA
      A(42)=ACA
      A(43)=-BTA
      A(44)=ATA
      A(45)=-BMZA
      A(46)=AMZA
      A(47)=-BMYA
      A(48)=AMYA
      A(49)=ACB
```

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```
           A(50)=HCB
           A(51)=ATB
           A(52)=BTB
           A(53)=AMZB
           A(54)=BMZB
           A(55)=AMYB
           A(56)=BMYB
           A(57)=-HCB
           A(58)=ACB
           A(59)=-BTB
           A(60)=ATB
           A(61)=-BMZB
           A(62)=AMZB
           A(63)=-BMYB
           A(64)=AMYB
           GO TO 3005
      3002 D(1)=-ACZ
           D(2)=-BCZ
           D(3)=-ATH
           D(4)=-BTH
           GO TO 3003
      3005 B(1)=-ACZ
           B(2)=-BCZ
           B(3)=-ATH
           B(4)=-BTH
           B(5)=-AMZ
           B(6)=-BMZ
           B(7)=-AMY
           B(8)=-BMY
           GO TO 3006
C          PRINT,AG,HG,MZG,MYG,ALFG,FZG,FYG,CGG
C          PRINT,EPSG,PHIG,EPZG,EPYG,EPSAL,FZEPG,FYEPG,EPSCGG
C          PRINT,ACW,HCW,ATW,BTW,AMZW,BMZW,AMYW,BMYW
C          PRINT,AALW,BALW,AFZW,BFZW,AFYW,BFYW,ACGW,BCGW
C          PRINT,ACZ,HCZ,ATH,BTH,AMZ,BMZ,AMY,BMY
C          PRINT,(B(I),I=1,8)
      3003 CALL MINV(C,4,CK,LLL,MMM)
           CALL MPRD(C,D,Y,4,4,0,0,1)
           AMPF=SQRT(Y(1)*Y(1)+Y(2)*Y(2))
           PHAZF=ATAN2(Y(2),Y(1))/DTR
           AMPE=SQRT(Y(3)*Y(3)+Y(4)*Y(4))
           PHAZE=ATAN2(Y(4),Y(3))/DTR
           AMPA=.000001
           PHAZA=0
           AMPB=.000001
            PHAZB=0
            GO TO 3004
      3006 CALL MINV (A,8,AK,LL,MM)
           CALL MPRD (A,B,X,8,8,0,0,1)
           AMPF=SQRT(X(1)*X(1)+X(2)*X(2))
            PHAZF=ATAN2(X(2),X(1))/DTR
            AMPE=SQRT(X(3)*X(3)+X(4)*X(4))
           PHAZE=ATAN2(X(4),X(3))/DTR
           AMPA=SQRT(X(5)*X(5)+X(6)*X(6))
           PHAZA=ATAN2(X(6),X(5))/DTR
           AMPB=SQRT(X(7)*X(7)+X(8)*X(8))
           PHAZB=ATAN2(X(8),X(7))/DTR
C          PRINT,(X(K),K=1,8)
C          CALCULATE CAB NORMAL ACCELERATION AFTER ALLEVIATION
      3004 YA=ACW*(1-PCR)
```

```
      YB=BCA*(1-PCR)
      CABACC=SQRT(YA*YA+YB*YB)
      PHAZC=ATAN2(YB,YA)/DTR
C     SUBTRACT 20 LOG BASE 10 "G"
      GFC=20*ALOG10(AMPF/CABACC)-30.15
      GEC=20*ALOG10(AMPE/CABACC)-30.15
      GAC=20*ALOG10(AMPA/CABACC)-30.15
      GBC=20*ALOG10(AMPB/CABACC)-30.15
      PHAZFC=PHAZF-PHAZC
      PHAZEC=PHAZE-PHAZC
      PHAZAC=PHAZA-PHAZC
       PHAZBC=PHAZB-PHAZC
      XYA=YA-ACW*1.0+BCW*0.0
      XYB=YB-BCW*1.0-ACW*0.0
      XMOD=SQRT(XYA*XYA+XYB*XYB)
      PHAZX=ATAN2(XYB,XYA)/DTR
C     OPEN LOOP GAIN AND PHASE
      LPGAC=20*ALOG10(XMOD/CABACC)
      LPPHC=PHAZX+PHAZC
     IF (NOPT.EQ.0) GO TO 3008
C     C.G. ACCELERATION AFTER ALLEVIATION
     CGR=ACGW*1.0-BCGW*0.0+ACGF*Y(1)-BCGF*Y(2)
    1+ACGE*Y(3)-BCGE*Y(4)
     CGI=BCGW*1.0+ACGW*0.0+BCGF*Y(1)+ACGF*Y(2)
    1+BCGE*Y(3)+ACGE*Y(4)
     GO TO 3009
3008  CGR=ACGW*1.0-BCGW*0.
    1 +ACGF*X(1)-BCGF*X(2)+ACGE*X(3)-BCGE*X(4)+ACGA*X(5)-BCGA*X(6)
    2 +ACGB*X(7)-BCGB*X(8)
      CGI=BCGW*1.0+ACGW*0.+BCGF*X(1)+ACGF*X(2)+BCGE*X(3)+ACGE*X(4)
    1 +BCGA*X(5)+ACGA*X(6)+BCGB*X(7)+ACGB*X(8)
3009  CGACC=SQRT(CGR*CGR+CGI*CGI)
      PHCGA=ATAN2(CGI,CGR)/DTR
C     SUBTRACT 20 LOG BASE 10 "G"
      GFCG=20*ALOG10(AMPF/CGACC)-30.15
      GECG=20*ALOG10(AMPE/CGACC)-30.15
      GACG=20*ALOG10(AMPA/CGACC)-30.15
       GBCG=20*ALOG10(AMPB/CGACC)-30.15
      PHFCG=PHAZF-PHCGA
      PHECG=PHAZE-PHCGA
      PHACG=PHAZA-PHCGA
      PHBCG=PHAZB-PHCGA
      XCGR=CGR-ACGW*1.0-BCGW*0.0
      XCGI=CGI-BCGW*1.0-ACGW*0.0
C     OPEN LOOP GAIN AND PHASE
      XCGG=SQRT(XCGR*XCGR+XCGI*XCGI)
      PHGG=ATAN2(XCGI,XCGR)/DTR
      LPGNG=20*ALOG10(XCGG/CGACC)
      LPPHG=PHCGA+PHGG
     IF (NOPT.EQ.0) GO TO 3010
C     ALPHA AFTER ALLEVIATION
     ALFR=AALW*1.0-BALW*0.0+AALF*Y(1)-BALF*Y(2)
    1+AALE*Y(3)-BALE*Y(4)
     ALFI=BALW*1.0-AALW*0.0+BALF*Y(1)+AALF*Y(2)
    1+BALE*Y(3)+AALE*Y(4)
     GO TO 3011
3010  ALFR=AALW*1.0-BALW*0.0+AALF*X(1)-BALF*X(2)+AALE*X(3)-BALE*X(4)
    1 +AALA*X(5)-BALA*X(6)+AALB*X(7)-BALB*X(8)
      ALFI=BALW*1.0-AALW*0.0+BALF*X(1)+AALF*X(2)+BALE*X(3)+AALE*X(4)
    1 +BALA*X(5)+AALA*X(6)+BALB*X(7)+AALB*X(8)
```

```
 3011 ALFM=SQRT(ALFR*ALFR+ALFI*ALFI)
      PHALF=ATAN2(ALFI,ALFR)/DTR
      GFA=20*ALOG10(AMPF/ALFM)
      GEE=20*ALOG10(AMPE/ALFM)
      GEA=20*ALOG10(AMPA/ALFM)
      GEB=20*ALOG10(AMPB/ALFM)
      PHFA=PHAZF-PHALF
      PHEA=PHAZE-PHALF
      PHAA=PHAZA-PHALF
      PHAB=PHAZB-PHALF
      XALFR=ALFR-AALW*1.0-BALW*0.0
      XALFI=ALFI-BALW*1.0-AALW*0.0
C     OPEN LOOP GAIN AND PHASE
      XALF=SQRT(XALFR*XALFR+XALFI*XALFI)
      PHALX=ATAN2(XALFI,XALFR)/DTR
      LPGAL=20*ALOG10(XALF/ALFM)
      LPHAL=PHALF+PHALX
      PRINT 63,AMPF,PHAZF,AMPE,PHAZE,AMPA,PHAZA,AMPB,PHAZB
      PRINT 64,CARACC,PHAZC,GFC,PHAZFC,GEC,PHAZEC,GAC,PHAZAC,GBC,PHAZBC
     1,LPGNC,LPPHC
      PRINT 65,CGACC,PHCGA,GFCG,PHFCG,GECG,PHECG,GACG,PHACG,GBCG,PHBCG
     1,LPGNG,LPPHG
      PRINT 66,ALFM,PHALF,GFA,PHFA,GEE,PHEA,GEA,PHAA,GEB,PHAB
     1,LPGAL,LPHAL
   66 FORMAT(/,1X,'ALLEVIATED ALPHA ',F8.3,4X,'PHASE OF ALPHA',
     1 F8.3/,1X,'FLAP GAIN',F8.3,7X,'FLAP PHASE',F8.3,20X,
     2 'ELEVATOR GAIN',F8.3,7X,'ELEVATOR PHASE',F8.3/,1X,
     3 'A1 CYCLIC GAIN',F8.3,7X,'A1 CYCLIC PHASE',F8.3,15X,
     4 'B1 CYCLIC GAIN',F8.3,7X,'B1 CYCLIC PHASE',F8.3/
     5,1X,'OPEN LOOP GAIN',F8.3,7X,'OPEN LOOP PHASE',F8.3)
      PRINT 1000
      GO TO 2002
      END
```

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```
*EXECUTE
      SUBROUTINE MINV(A,N,D,L,M)                                 MINV
      DIMENSION A(1),L(1),M(1)                                   MINV
      D=1.0                                                      MINV
      NK=-N                                                      MINV
      DO 80 K=1,N                                                MINV
      NK=NK+N                                                    MINV
      L(K)=K                                                     MINV
      M(K)=K                                                     MINV
      KK=NK+K                                                    MINV
      BIGA=A(KK)                                                 MINV
      DO 20 J=K,N                                                MINV
      IZ=N*(J-1)                                                 MINV
      DO 20 I=K,N                                                MINV
      IJ=IZ+I                                                    MINV
   10 IF( ABS(BIGA)- ABS(A(IJ))) 15,20,20                        MINV
   15 BIGA=A(IJ)                                                 MINV
      L(K)=I                                                     MINV
      M(K)=J                                                     MINV
   20 CONTINUE                                                   MINV
      J=L(K)                                                     MINV
      IF(J-K) 35,35,25                                           MINV
   25 KI=K-N                                                     MINV
      DO 30 I=1,N                                                MINV
      KI=KI+N                                                    MINV
      HOLD=-A(KI)                                                MINV
      JI=KI-K+J                                                  MINV
      A(KI)=A(JI)                                                MINV
   30 A(JI) =HOLD                                                MINV
   35 I=M(K)                                                     MINV
      IF(I-K) 45,45,38                                           MINV
   38 JP=N*(I-1)                                                 MINV
      DO 40 J=1,N                                                MINV
      JK=NK+J                                                    MINV
      JI=JP+J                                                    MINV
      HOLD=-A(JK)                                                MINV
      A(JK)=A(JI)                                                MINV
   40 A(JI) =HOLD                                                MINV
   45 IF(BIGA) 48,46,48                                          MINV
   46 D=0.0                                                      MINV
      RETURN                                                     MINV
   48 DO 55 I=1,N                                                MINV
      IF(I-K) 50,55,50                                           MINV
   50 IK=NK+I                                                    MINV
      A(IK)=A(IK)/(-BIGA)                                        MINV
   55 CONTINUE                                                   MINV
      DO 65 I=1,N                                                MINV
      IK=NK+I                                                    MINV
      HOLD=A(IK)                                                 MINV
      IJ=I-N                                                     MINV
      DO 65 J=1,N                                                MINV
      IJ=IJ+N                                                    MINV
      IF(I-K) 60,65,60                                           MINV
   60 IF(J-K) 62,65,62                                           MINV
   62 KJ=IJ-I+K                                                  MINV
      A(IJ)=HOLD*A(KJ)+A(IJ)                                     MINV
   65 CONTINUE                                                   MINV
      KJ=K-N                                                     MINV
      DO 75 J=1,N                                                MINV
      KJ=KJ+N                                                    MINV
```

```
      IF(J-K) 70,75,70                                                  MINV
   70 A(KJ)=A(KJ)/BIGA                                                  MINV
   75 CONTINUE                                                          MINV
      D=D*BIGA                                                          MINV
      A(KK)=1.0/BIGA                                                    MINV
   80 CONTINUE                                                          MINV
      K=N                                                               MINV
  100 K=(K-1)                                                           MINV
      IF(K) 150,150,105                                                 MINV
  105 I=L(K)                                                            MINV
      IF(I-K) 120,120,108                                               MINV
  108 JQ=N*(K-1)                                                        MINV
      JR=N*(I-1)                                                        MINV
      DO 110 J=1,N                                                      MINV
      JK=JQ+J                                                           MINV
      HOLD=A(JK)                                                        MINV
      JI=JR+J                                                           MINV
      A(JK)=-A(JI)                                                      MINV
  110 A(JI) =HOLD                                                       MINV
  120 J=M(K)                                                            MINV
      IF(J-K) 100,100,125                                               MINV
  125 KI=K-N                                                            MINV
      DO 130 I=1,N                                                      MINV
      KI=KI+N                                                           MINV
      HOLD=A(KI)                                                        MINV
      JI=KI-K+J                                                         MINV
      A(KI)=-A(JI)                                                      MINV
  130 A(JI) =HOLD                                                       MINV
      GO TO 100                                                         MINV
  150 RETURN                                                            MINV
      END                                                               MINV
```

```
      SUBROUTINE MPRD(A,B,R,N,M,MSA,MSB,L)                          MPRD
      DIMENSION A(1),B(1),R(1)                                      MPRD
      MS=MSA*10+MSB                                                 MPRD
      IF(MS-22) 30,10,30                                            MPRD
   10 DO 20 I=1,N                                                   MPRD
   20 R(I)=A(I)+B(I)                                                MPRD
      RETURN                                                        MPRD
   30 IR=1                                                          MPRD
      DO 90 K=1,L                                                   MPRD
      DO 90 J=1,N                                                   MPRD
      R(IR)=0                                                       MPRD
      DO 80 I=1,M                                                   MPRD
      IF(MS) 40,60,40                                               MPRD
   40 CALL LOC(J,I,IA,N,M,MSA)                                      MPRD
      CALL LOC(I,K,IB,M,L,MSB)                                      MPRD
      IF(IA) 50,80,50                                               MPRD
   50 IF(IB) 70,80,70                                               MPRD
   60 IA=N*(I-1)+J                                                  MPRD
      IB=M*(K-1)+I                                                  MPRD
   70 R(IR)=R(IR)+A(IA)*B(IB)                                       MPRD
   80 CONTINUE                                                      MPRD
   90 IR=IR+1                                                       MPRD
      RETURN                                                        MPRD
      END                                                           MPRD
```

```
      SUBROUTINE LOC(I,J,IR,N,M,MS)                                     LOC
      IX=I                                                              LOC
      JX=J                                                              LOC
      IF(MS-1) 10,20,30                                                 LOC
   10 IRX=N*(JX-1)+IX                                                   LOC
      GO TO 36                                                          LOC
   20 IF(IX-JX) 22,24,24                                                LOC
   22 IRX=IX+(JX*JX-JX)/2                                               LOC
      GO TO 36                                                          LOC
   24 IRX=JX+(IX*IX-IX)/2                                               LOC
      GO TO 36                                                          LOC
   30 IRX=0                                                             LOC
      IF(IX-JX) 36,32,36                                                LOC
   32 IRX=IX                                                            LOC
   36 IR=IRX                                                            LOC
      RETURN                                                            LOC
      END                                                               LOC
```

OUTPUT

```
****************************************************************************************************

GUST    GUST    FLAP    ELEV    A1      B1
FREQ    AMPL    AMPL    AMPL    AMPL    AMPL

0.500   5.000   1.000   0.500   0.250   0.250

PCR     PCI     PTR     PTI     PZR     PZI     PYR     PYI

0.800   0.000   0.800   0.000   0.800   0.000   0.800   0.000

 CAB RESP TO GUST     PITCH RESP TO GUST      Y.M. R  TO GUST      P.M. RESP TO GUST
AMPL       PHASE     AMPL          PHASE     AMPL          PHASE  AMPL          PHASE

0.100   -66.000      0.160       -42.000       180.0  -300.000    2000.0  -120.000

CAB RESP TO FLAP      PITCH RESP TO FLAP      Y.M. D TO FLAP       P.M. DUE TO FLAP
AMPL       PHASE      AMPL         PHASE      AMPL       PHASE      AMPL         PHASE

0.060  -196.000      0.050      -250.000      100.0   -202.000     145.0   -292.000

CAB RESP TO ELEV      PITCH RESP TO ELEV      Y.M. D  TO ELEV      P.M. DUE TO ELEV
AMPL       PHASE      AMPL         PHASE      AMPL       PHASE     AMPL          PHASE

0.180   -20.000      0.150       -56.000     500.0     -24.000   1400.0      -82.000

CAB RESP TO A1        PITCH RESP TO A1          Y.M. RESP  TO A1        P.M. RESP TO A1
AMPL   PHASE          AMPL        PHASE         AMPL      PHASE         AMPL      PHASE

0.110  -184.000      0.100   -220.000           800.0  -340.000        600.0  -272.000

CAB RESP TO B1         PITCH RESP TO B1         Y.M. DUE T B1          P.M. DUE TO B1
AMPL   PHASE           AMPL       PHASE         AMPL      PHASE        AMPL      PHASE

0.120   -28.000      0.090     -70.000          150.0  -248.000       1200.0   -32.000

CG RESP TO G    CG RESP TO FLAP    CG RESP TO      ELEV   CG RESP TO A1    CG RESP TO B1
AMPL     PHASE  AMPL        PHASE  AMPL          PHASE   AMPL     PHASE   AMPL    PHASE

0.130  -58.000    0.060   -196.000    0.200   -20.000    0.130  -190.000   0.130   -32.000

ALF RESP TO G      ALF RESP TO FLAP      ALF RESP TO ELEV      ALF RESP TO A1      ALF RESP TO B1
AMPL     PHASE     AMPL         PHASE    AMPL          PHASE   AMPL        PHASE   AMPL        PHASE

0.600 -256.000     0.100     -48.000       0.600   -212.000     0.500   -24.000     0.400  -232.000

FZ RESP TO G       FZ RESP TO FLAP       FZ RESP TO      ELEV      FZ RESP TO A1      FZ RESP TO B1
AMPL   PHASE       AMPL        PHASE     AMPL          PHASE      AMPL       PHASE    AMPL     PHASE

0.000     0.000    0.000     0.000       0.000     0.000       0.000     0.000      0.000     0.000

FY RESP TO G       FY RESP TO FLAP       FY RESP TO ELEV       FY RESP TO A1      FY RESP TO B1

AMPL   PHASE       AMPL        PHASE     AMPL         PHASE    AMPL       PHASE   AMPL       PHASE

0.000     0.000    0.000     0.000       0.000     0.000       0.000     0.000      0.000     0.000
****************************************************************************************************

****************************************************************************************************

****************************************************************************************************
FLAP AMP    0.048       FLAP PHASE=161.978       ELEV AMP    0.179       ELEV PHASE=171.253
A1 AMP    0.000        A1 PHASE   0.000       B1 AMP    0.000       B1 PHASE   0.000

ALLEVIATED CAB NORM ACCN    0.004         PHASE OF ACCN -66.000
FLAP GAIN  17.348        FLAP PHASE -95.978                        ELEVATOR GAIN    2.889        ELEVATOR PHASE=105.253
A1 CYCLIC       GAIN=102.191        A1 CYCLIC PHASE  66.000                 B1 CYCLIC GAIN=102.191         B1 CYCLIC PHASE  66.000
OPEN LOOP GAIN  12.041          OPEN LOOP PHASE  48.000

ALLEVIATED CG ACCN    0.006         PHASE OF ACCN -87.829
FLAP GAIN  13.775          FLAP PHASE -74.149         ELEVATOR GAIN  -0.684         ELEVATOR PHASE -63.424
A1 CYCLIC GAIN=105.765         A1 CYCLIC PHASE  87.829                  B1 CYCLIC GAIN=105.765         B1 CYCLIC PHASE  87.829
OPEN LOOP GAIN  10.821         OPEN LOOP PHASE  42.399

ALLEVIATED ALPHA     0.161     PHASE OF ALPHA  18.285
FLAP GAIN  15.410          FLAP PHASE=180.263                        ELEVATOR GAIN   0.955        ELEVATOR PHASE=189.538
A1 CYCLIC GAIN=104.125         A1 CYCLIC PHASE -18.285                  B1 CYCLIC GAIN=104.125         B1 CYCLIC PHASE -18.285
OPEN LOOP GAIN   1.000         OPEN LOOP PHASE  -1.674

****************************************************************************************************
```

Program to calculate open loop Bode diagram of gust alleviation system with transfer functions selected to represent ideal system.

$$\frac{\delta_F}{\ddot{Z}} = \frac{S^2}{S^2+2\xi_{1i}\omega_{1i}S+\omega_{1i}^2} \cdot \frac{S^2+2\xi_{2i}\omega_{2i}S+\omega_{2i}^2}{S^2+2\xi_{3i}\omega_{3i}S+\omega_{3i}^2} \cdot \frac{1+\tau_{1i}S}{1+\tau_{2i}S} \cdot \frac{1}{1+\tau_{3i}S}$$

i = F, E, A_1 and B_1 refers to flap elevator and A_1 and B_1 cyclic

Modulus and phase of flap and elevator are evaluated at specified frequencies and response of sensed signal computed using data bank information. The net response constitutes the open loop gain and phase diagram.

KASE NO	Indicator used to run multiple cases	
ALT	Altitude in Feet	Case Identification Only
VKT	Velocity in Knots	
XCG	CG Location Logitudinal	
ZCG	CG Location Vertical	
FLPAMP	Flap Amplitude in Degrees	
ELVAMP	Elevator Amplitude in Degrees	
AAMP	A Cyclic Amplitude in Degrees	
BAMP	B Cyclic Amplitude in Degrees	
W1i	Washout Corner Frequency	
W2i	Shaping Enumerator Corner Frequency	
W3i	Shaping Denominator Corner Frequency	
Z1i	Fraction of Critical Damping in Washout	
Z2i	Fraction of Critical Damping in Shaping Function Enumerator	
Z3i	Fraction of Critical Damping in Shaping Function Denominator	
T1i	Parameter of Lead-Lag Network	
T2i	Parameter of Lead-Lag Network	
T3i	Time Constant Representing Rate Limit of Control Actuator	
	$i = F, E, A_1, B_1$ refers to Flap Elevator and A_1 , B_1 Cyclic	
HERTZ	Frequency Range Covered	
AF	Cabin Acceleration Response to Flap	
EPSF	Cabin Acceleration Phase to Flap	
AE	Cabin Acceleration Response to Elevator	
EPSE	Cabin Acceleration Phase to Elevator	

AA	Cabin Acceleration Response to A_1 Cyclic
EPSA	Cabin Acceleration Response to A_1 Cyclic
AB	Cabin Acceleration Response to B_1 Cyclic
EPSB	Cabin Acceleration Phase to B_1 Cyclic

240 KNOTS, 10,000 FEET, FORWARD CG

```
*JOB            MCVLIGH,KP=29,PAGES=35,LINES=60,RUN=CHECK
              REAL KF,KE,KA,KB,IF,IE,IA,IB
              DTR=3.14159/180.
       2001   READ,KASENO
              IF(KASENO.EQ.99) CALL EXIT
              READ,ALT,VKT,XCG,ZCG,FLPAMP,ELVAMP,AAMP,RAMP
              READ,KF,KE,KA,KB
              READ,W1F,W2F,W3F,Z1F,Z2F,Z3F
              READ,T1F,T2F,T3F
              READ,W1E,W2E,W3E,Z1E,Z2E,Z3E
              READ,T1E,T2E,T3E
              READ,W1A,W2A,W3A,Z1A,Z2A,Z3A
              READ,T1A,T2A,T3A
              READ,W1B,W2B,W3B,Z1B,Z2B,Z3B
              READ,T1B,T2B,T3B
              PRINT 99,ALT,VKT,XCG,ZCG
       99     FORMAT(/,8X,'ALTITUDE=',8X,F8.2,'VKT=',F6.2,8X,'XCG=',
            1 F6.2,8X,'ZCG=',F6.2)
              PRINT 1000
       1000   FORMAT(/,130(1H*))
       2002   READ,HERTZ
              IF (HERTZ.EQ.0.0) GO TO 2001
              READ,AF,EPSF,AE,EPSE,AA,EPSA,AB,EPSB
              OMEGA=HERTZ*6.28
              FAF1=KF*(OMEGA**2)
              FAF2=SQRT(((W2F**2-OMEGA**2)**2)+(4*Z2F**2*W2F**2*OMEGA**2))
              FAF3=SQRT(1+T1F**2*OMEGA**2)
              FAF4=SQRT(((W1F**2-OMEGA**2)**2)+(4*Z1F**2*W1F**2*OMEGA**2))
              FAF5=SQRT(((W3F**2-OMEGA**2)**2)+(4*Z3F**2*W3F**2*OMEGA**2))
              FAF6=SQRT(1+T2F**2*OMEGA**2)
              FAF7=SQRT(1+T3F**2*OMEGA**2)
              PRINT,FAF1,FAF2,FAF3,FAF4,FAF5,FAF6,FAF7
              FAF=(FAF1*FAF2*FAF3)/(FAF4*FAF5*FAF6*FAF7)
              EAE1=KE*(OMEGA**2)
              EAE2=SQRT(((W2E**2-OMEGA**2)**2)+(4*Z2E**2*W2E**2*OMEGA**2))
              EAE3=SQRT(1+T1E**2*OMEGA**2)
              EAE4=SQRT(((W1E**2-OMEGA**2)**2)+(4*Z1E**2*W1E**2*OMEGA**2))
              EAE5=SQRT(((W3E**2-OMEGA**2)**2)+(4*Z3E**2*W3E**2*OMEGA**2))
              EAE6=SQRT(1+T2E**2*OMEGA**2)
              EAE7=SQRT(1+T3E**2*OMEGA**2)
              PRINT,EAE1,FAF2,EAE3,FAE4,EAE5,FAF6,EAE7
              EAF=(FAF1*EAE2*EAF3)/(FAE4*EAF5*EAE6*FAE7)
              AAA=(KA*(OMEGA**2)*SQRT(((W2A**2-OMEGA**2)**2)+(4*Z2A**2*W2A**2
            1 *OMEGA**2))*SQRT(1+T1A**2*OMEGA**2))/(SQRT(((W1A**2-OMEGA**2)**2)
            2 +(4*Z1A**2*W1A**2*OMEGA**2))*SQRT(((W3A**2-OMEGA**2)**2)
            3 +(4*Z3A**2*W3A**2*OMEGA**2))*SQRT(1+T2A**2*OMEGA**2)*SQRT
            4 (1+T3A**2*OMEGA**2))
              PRINT,FAF,EAF
              BAB=(KB*(OMEGA**2)*SQRT(((W2B**2-OMEGA**2)**2)+(4*Z2B**2*W2B**2
            1 *OMEGA**2))*SQRT(1+T2B**2*OMEGA**2))/(SQRT(((W1B**2-OMEGA**2)**2)
            2 +(4*Z1B**2*W1B**2*OMEGA**2))*SQRT(((W3B**2-OMEGA**2)**2)
            3 +(4*Z3B**2*W3B**2*OMEGA**2))*SQRT(1+T2B**2*OMEGA**2)*SQRT
            4 (1+T3B**2*OMEGA**2))
              F1=ATAN2(0.,-W1F**2*OMEGA**2)
              F2=ATAN2(2*T1F*W1F*OMEGA,W1F**2-OMEGA**2)
              F3=ATAN2(2*T2F*W2F*OMEGA,W2F**2-OMEGA**2)
              F4=ATAN2(2*T3F*W3F*OMEGA,W3F**2-OMEGA**2)
              F5=ATAN2(T1F*OMEGA,1.)
              F6=ATAN2(T2F*OMEGA,1.)
              F7=ATAN2(T3F*OMEGA,1.)
```

```
      PRINT,F1,F2,F3,F4,F5,F6,F7
      E1=ATAN2(0.,-W1E**2*OMEGA**2)
      E2=ATAN2(2*T1E*W1E*OMEGA,W1E**2-OMEGA**2)
      E3=ATAN2(2*T2E*W2E*OMEGA,W2E**2-OMEGA**2)
      E4=ATAN2(2*T3E*W3E*OMEGA,W3E**2-OMEGA**2)
      E5=ATAN2(T1E*OMEGA,1.)
      E6=ATAN2(T2E*OMEGA,1.)
      E7=ATAN2(T3E*OMEGA,1.)
      PRINT,E1,E2,E3,E4,E5,E6,E7
      A1=ATAN2(0.,-W1A**2*OMEGA**2)
      A2=ATAN2(2*T1A*W1A*OMEGA,W1A**2-OMEGA**2)
      A3=ATAN2(2*T2A*W2A*OMEGA,W2A**2-OMEGA**2)
      A4=ATAN2(2*T3A*W3A*OMEGA,W3A**2-OMEGA**2)
      A5=ATAN2(T1A*OMEGA,1.)
      A6=ATAN2(T2A*OMEGA,1.)
      A7=ATAN2(T3A*OMEGA,1.)
      B1=ATAN2(0.,-W1B**2*OMEGA**2)
      B2=ATAN2(2*T1B*W1B*OMEGA,W1B**2-OMEGA**2)
      B3=ATAN2(2*T2B*W2B*OMEGA,W2B**2-OMEGA**2)
      B4=ATAN2(2*T3B*W3B*OMEGA,W3B**2-OMEGA**2)
      B5=ATAN2(T1B*OMEGA,1.)
      B6=ATAN2(T2B*OMEGA,1.)
      B7=ATAN2(T3B*OMEGA,1.)
      FEPSF=F1-F2+F3-F4+F5-F6-F7
      FEPSE=E1-E2+E3-E4+E5-E6-E7
      FEPSA=A1-A2+A3-A4+A5-A6-A7
      FEPSB=B1-B2+B3-B4+B5-B6-B7
      AF=AF/FLPAMP*32.2
      AE=AE/FLVAMP*32.2
      PRINT,FEPSF,FEPSE,AF,AE
      AA=AA/AAMP*32.2
      AB=AB/BAMP*32.2
      EPSF=EPSF*DTR
      EPSE=EPSE*DTR
      EPSA=EPSA*DTR
      EPSB=EPSB*DTR
      PAF=AF*EAF
      PAE=AE*EAE
      PAA=AA*AAA
      PAB=AB*BAB
      PEPSF=EPSF+FEPSF
      PEPSE=EPSE+FEPSE
      PRINT,PAF,PAE,PEPSF,PEPSE
      PEPSA=EPSA+FEPSA
      PEPSB=EPSB+FEPSB
      RF=PAF*COS(PEPSF)
      IF=PAF*SIN(PEPSF)
      RE=PAE*COS(PEPSE)
      IE=PAE*SIN(PEPSE)
      PRINT,RF,RE,IF,IE
      RA=PAA*COS(PEPSA)
      IA=PAA*SIN(PEPSA)
      RB=PAB*COS(PEPSB)
      IB=PAB*SIN(PEPSB)
      X1=RF+RE+RA+RB
      X2=IF+IE+IA+IB
      AMP=20*ALOG10(SQRT(X1**2+X2**2))
      PHASE=ATAN2(X2,X1)/DTR
     PRINT,AMP,PHASE,HERTZ
      PRINT 1000
      GO TO 2002
      END
```

PROGRAM OUTPUT

0,9859595E 01	0,1367059E 02	0,1012249E 01	0,8651926E 01	0,8651926E 01	0,1012249E 01	0,1012249E 01
~~0,1470939E 01~~	~~0,1367359E 02~~	~~0,1012249E 01~~	~~0,8651926E 01~~	~~0,8651926E 01~~	~~0,1012249E 01~~	~~0,1027355E 01~~
0,1804951E 01	0,2607445E 00					
0,3141592E 01	0,3049533E 01	0,1118431E 00	0,3049533E 01	0,1557287E 00	0,1557287E 00	0,1557287E 00
~~0,3141592E 01~~	~~0,3049533E 01~~	~~0,1118431E 00~~	~~0,3002505E 01~~	~~0,1557287E 00~~	~~0,1557287E 00~~	~~0,2312056E 00~~
-0,2999359E 01	-0,3028686E 01	0,1931999E 01	0,1159200E 02			
0,3486969E 01	0,3092125E 01	-0,6420200E 01	-0,3377951E 01			
~~0,3454288E 01~~	~~-0,3000145E 01~~	~~-0,4762737E 00~~	~~0,7240824E 00~~			
-0,5813294E 01	0,2893977E 02	0,5000000E 00				

GAIN PHASE FREQUENCY

APPENDIX A - REFERENCES

A.1 DiStefano III, Stubberad and Williams, "Theory and Problems of Feedback and Control Systems". Schaum's Outline Series, McGraw-Hill Book Company, Inc., New York, 1967.

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APPENDIX B

FREQUENCY RESPONSE AND GUST ALLEVIATION SYSTEM DATA FOR FORWARD AND AFT CENTER OF GRAVITY LOCATIONS AT 240 KNOTS, 3049M (10,000 FEET) 5,909 Kg (13,000 LB) GROSS WEIGHT

240 KNOTS, 3049M (10,000 FEET), FORWARD CG

$\omega_g = \pm 5$ FT/SEC

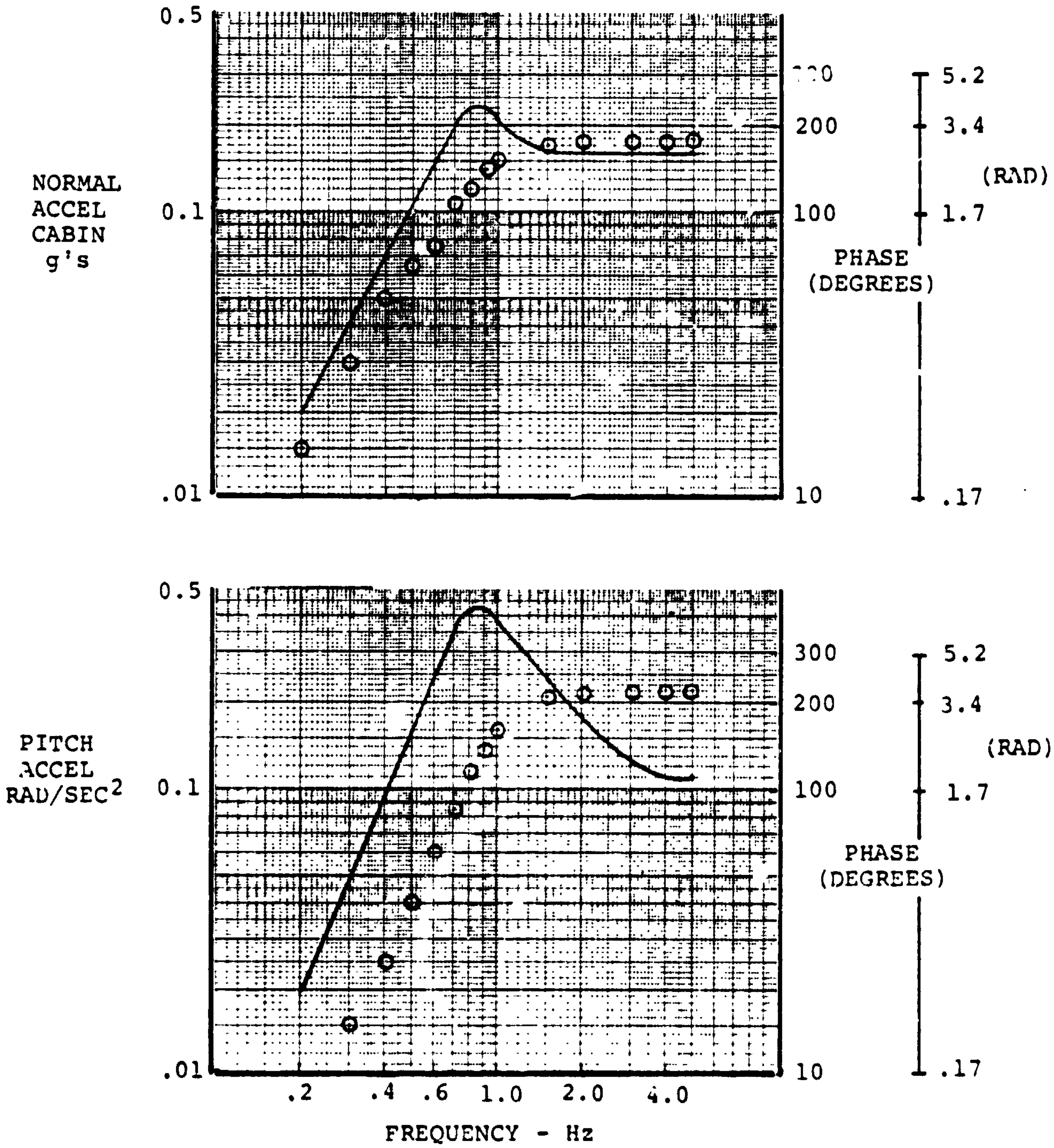

FIGURE B-1. FREQUENCY RESPONSE OF CABIN NORMAL AND PITCH ACCELERATIONS DUE TO VERTICAL GUST (240 KNOTS, 3049 METERS, FORWARD CG)

240 KNOTS, 3049M (10,000 FEET), FORWARD CG

$\omega_g = \pm 5$ FT/SEC

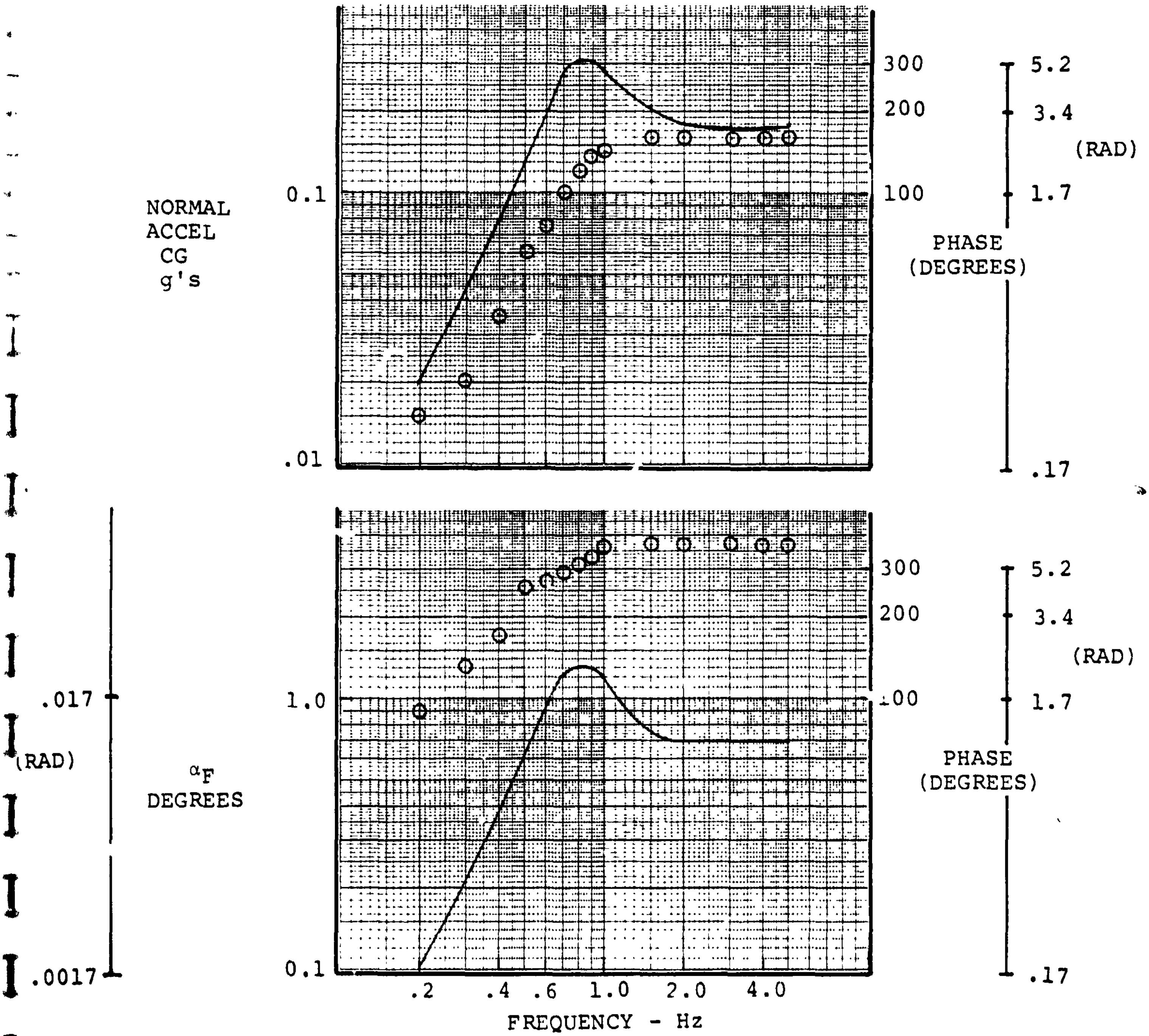

FIGURE B-2. FREQUENCY RESPONSE OF NORMAL ACCELERATION AT CG AND FUSELAGE ANGLE OF ATTACK DUE TO VERTICAL GUSTS (240 KNOTS, 3049 METERS, FORWARD CG)

240 KNOTS, 3049M (10,000 FEET), FORWARD CG
ω_g = 5 FT/SEC

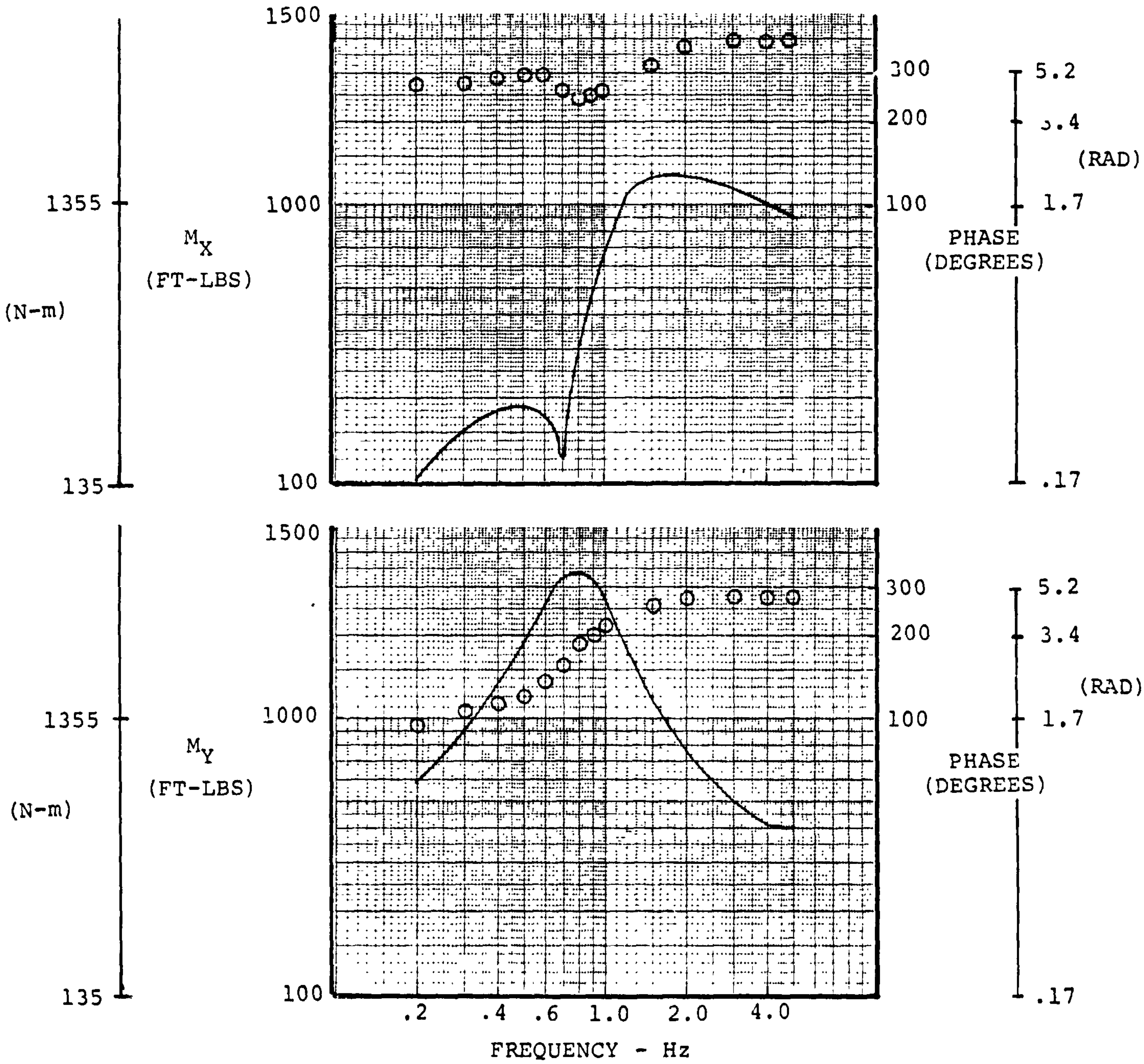

FIGURE B-3. FREQUENCY RESPONSE OF ROTOR HUB MOMENTS DUE TO VERTICAL GUSTS (240 KNOTS, 3049 METERS, FORWARD CG)

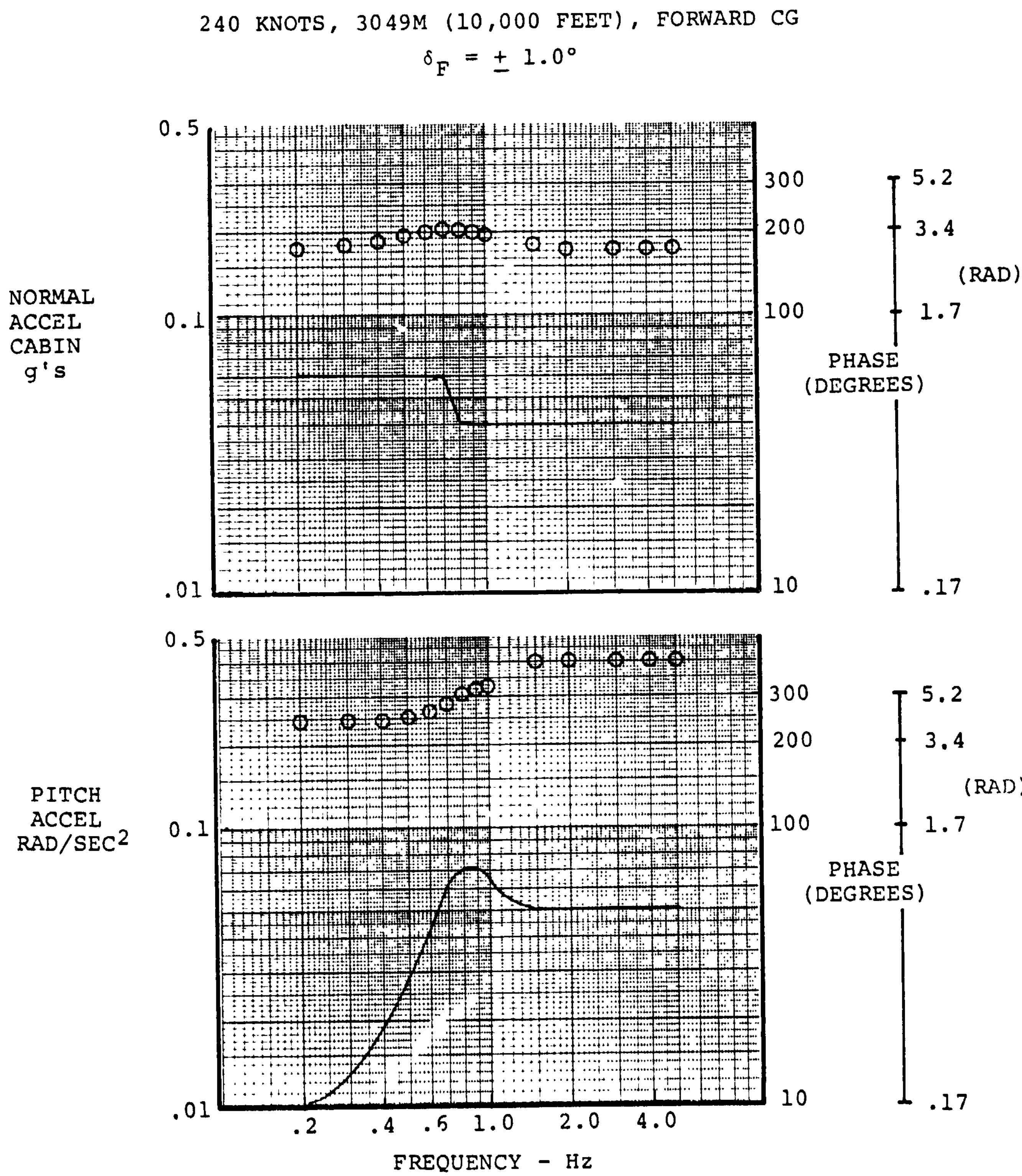

FIGURE B-4. FREQUENCY RESPONSE OF CABIN NORMAL AND PITCH ACCELERATIONS DUE TO δ_F (240 KNOTS, 3049 METERS, FORWARD CG)

240 KNOTS, 3049M (10,000 FEET), FORWARD CG

$\delta_F = \pm 1°$

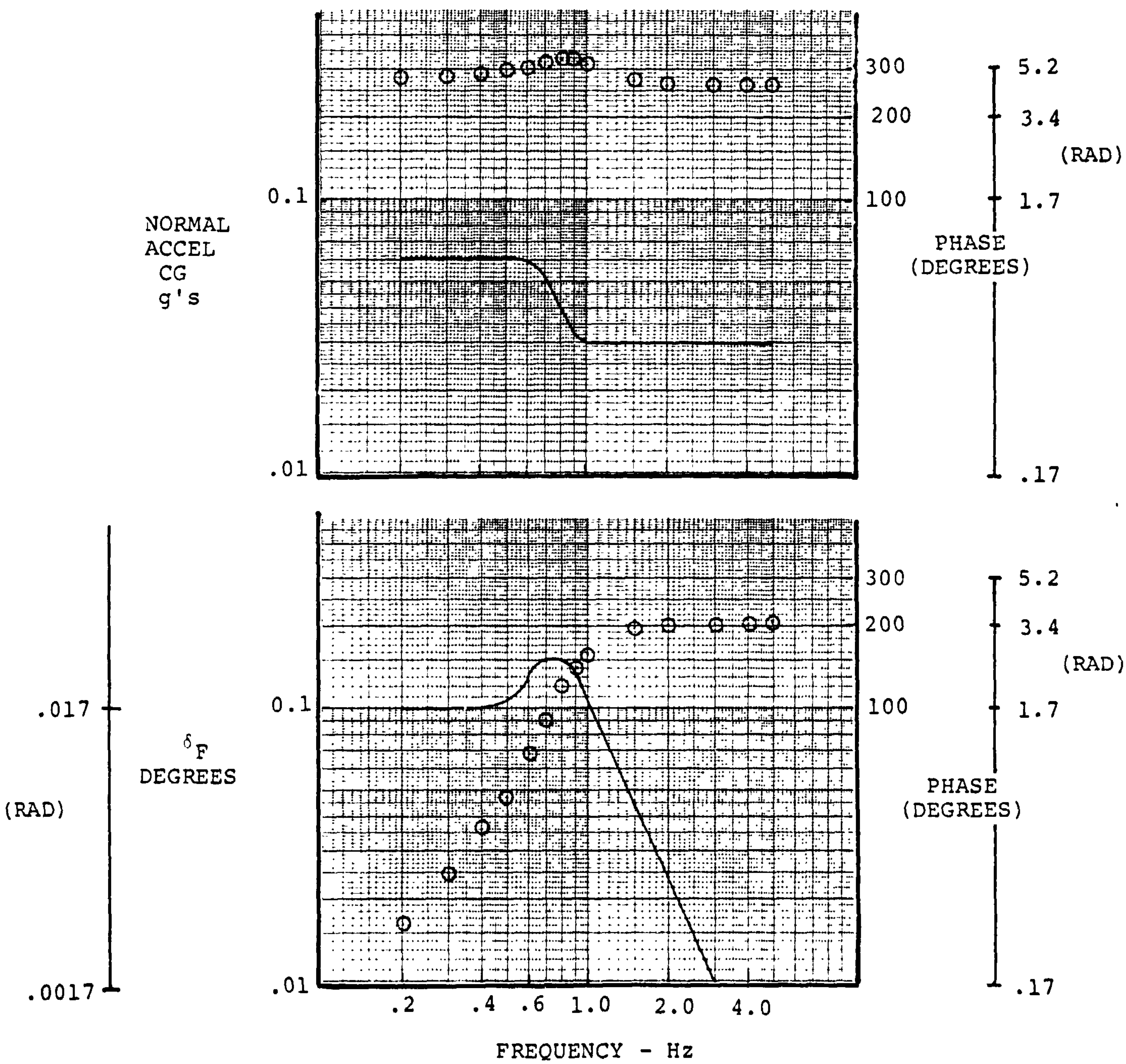

FIGURE B-5. FREQUENCY RESPONSE AT NORMAL ACCELERATION AT CG AND FUSELAGE ANGLE OF ATTACK DUE TO δ_F (240 KNOTS, 3049 METERS, FORWARD CG)

240 KNOTS, 3049M (10,000 FEET), FORWARD CG

$\delta_F = \pm 1.0°$

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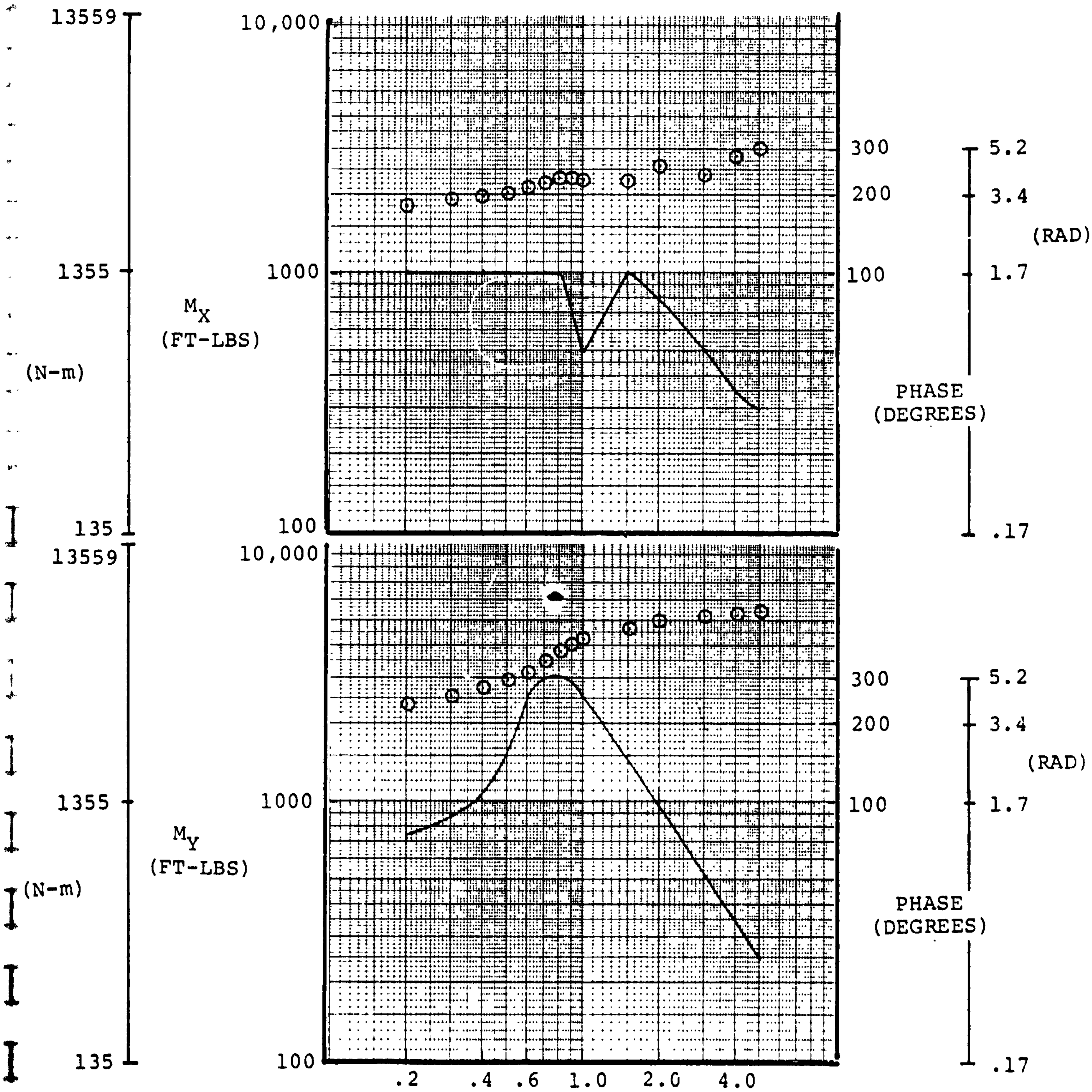

FIGURE B-6. FREQUENCY RESPONSE OF ROTOR HUB MOMENTS DUE TO δ_F (240 KNOTS, 3049 METERS, FORWARD CG)

240 KNOTS, 3049M (10,000 FEET), FORWARD CG

$\delta_e = \pm .5°$

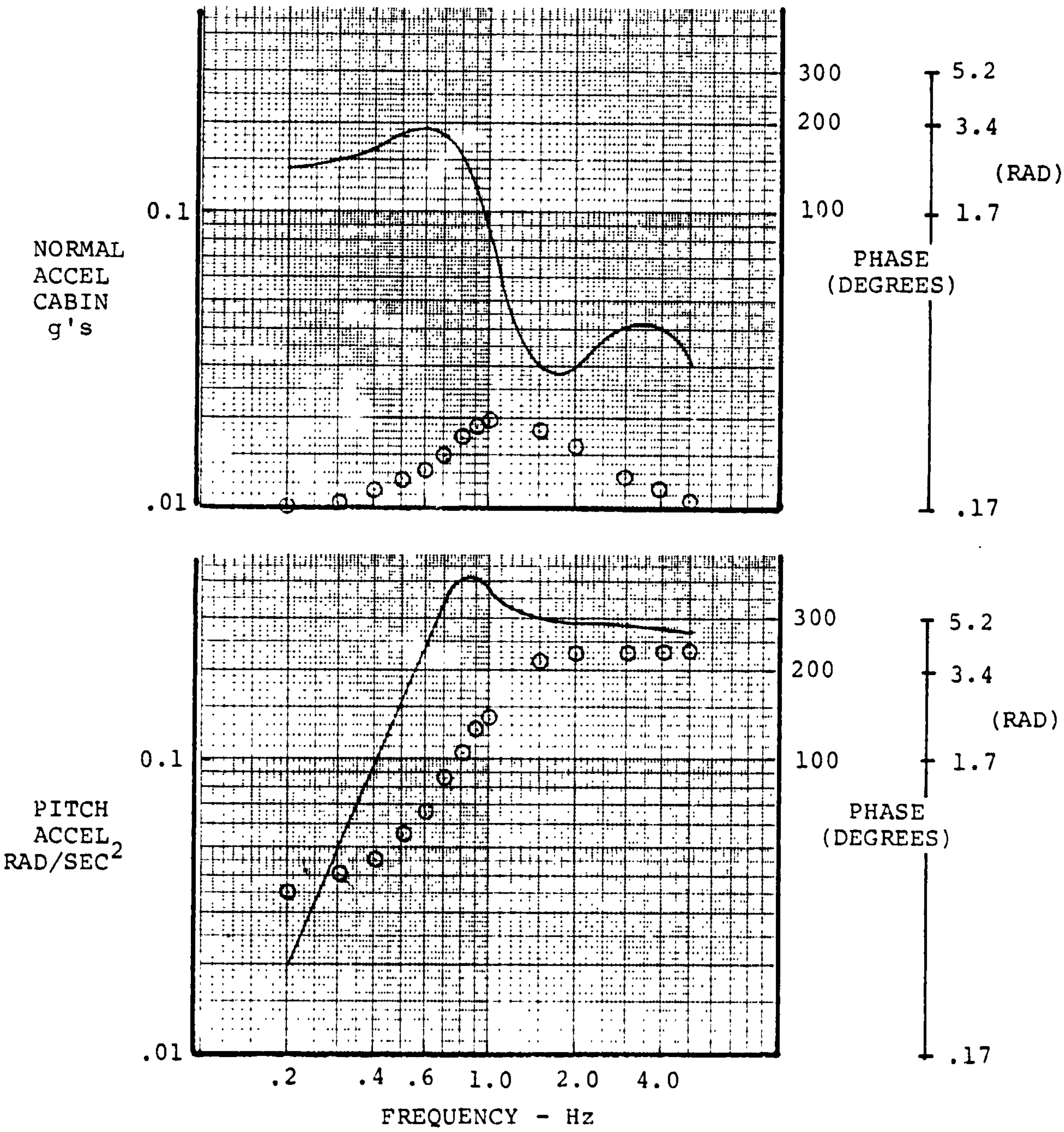

FIGURE B-7. FREQUENCY RESPONSE OF CABIN NORMAL AND PITCH ACCELERATIONS DUE TO δ_e (240 KNOTS, 3049 METERS, FORWARD CG)

240 KNOTS, 3049M (10,000 FEET), FORWARD CG

$\delta_e = \pm .5°$

D210-11231-1

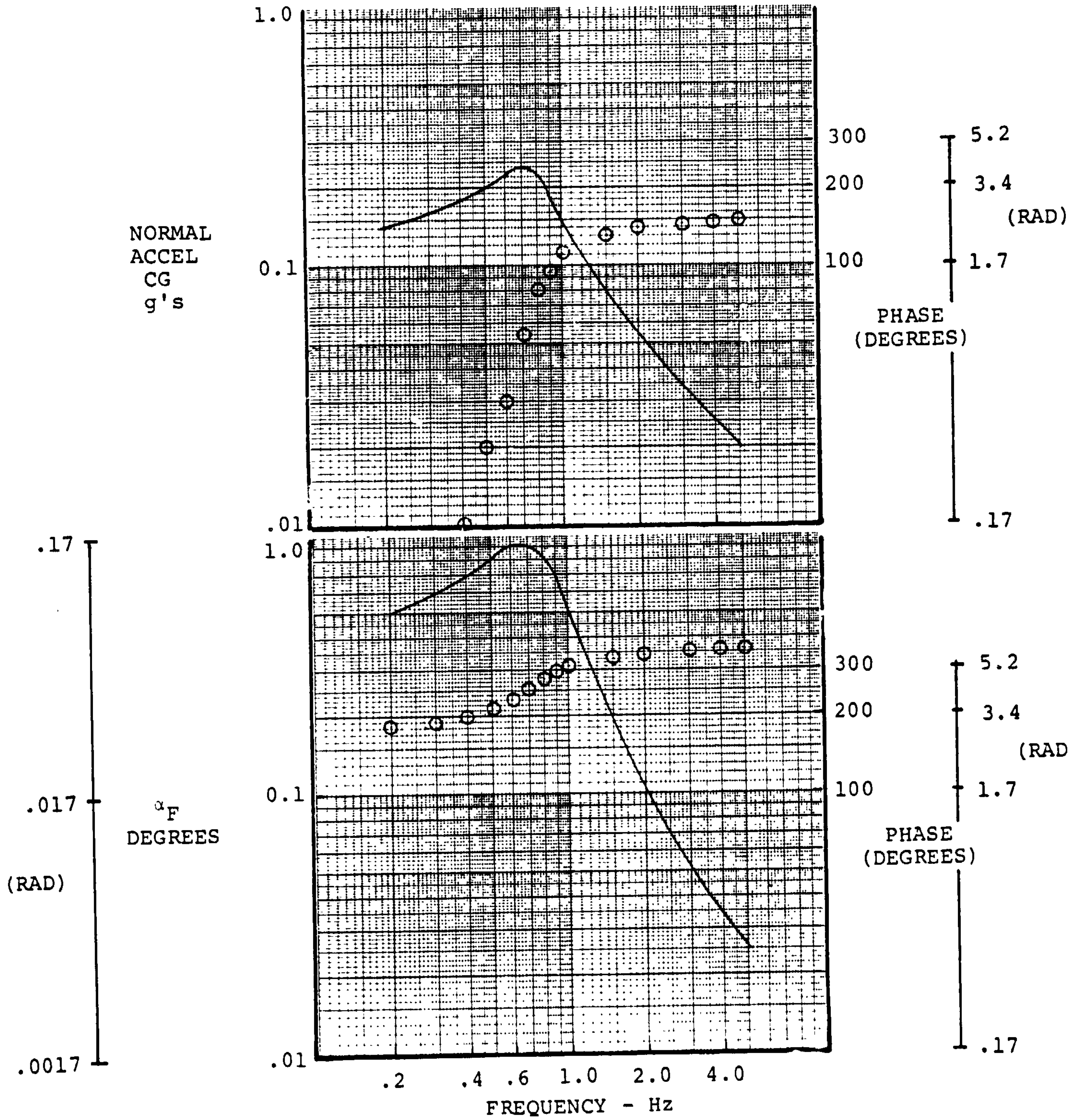

FIGURE B-8. FREQUENCY RESPONSE OF NORMAL ACCELERATION AT CG AND FUSELAGE ANGLE OF ATTACK DUE TO δ_e (240 KNOTS, 3049 METERS, FORWARD CG)

240 KNOTS, 3049M (10,000 FEET), FORWARD CG

$\delta_e = \pm .5°$

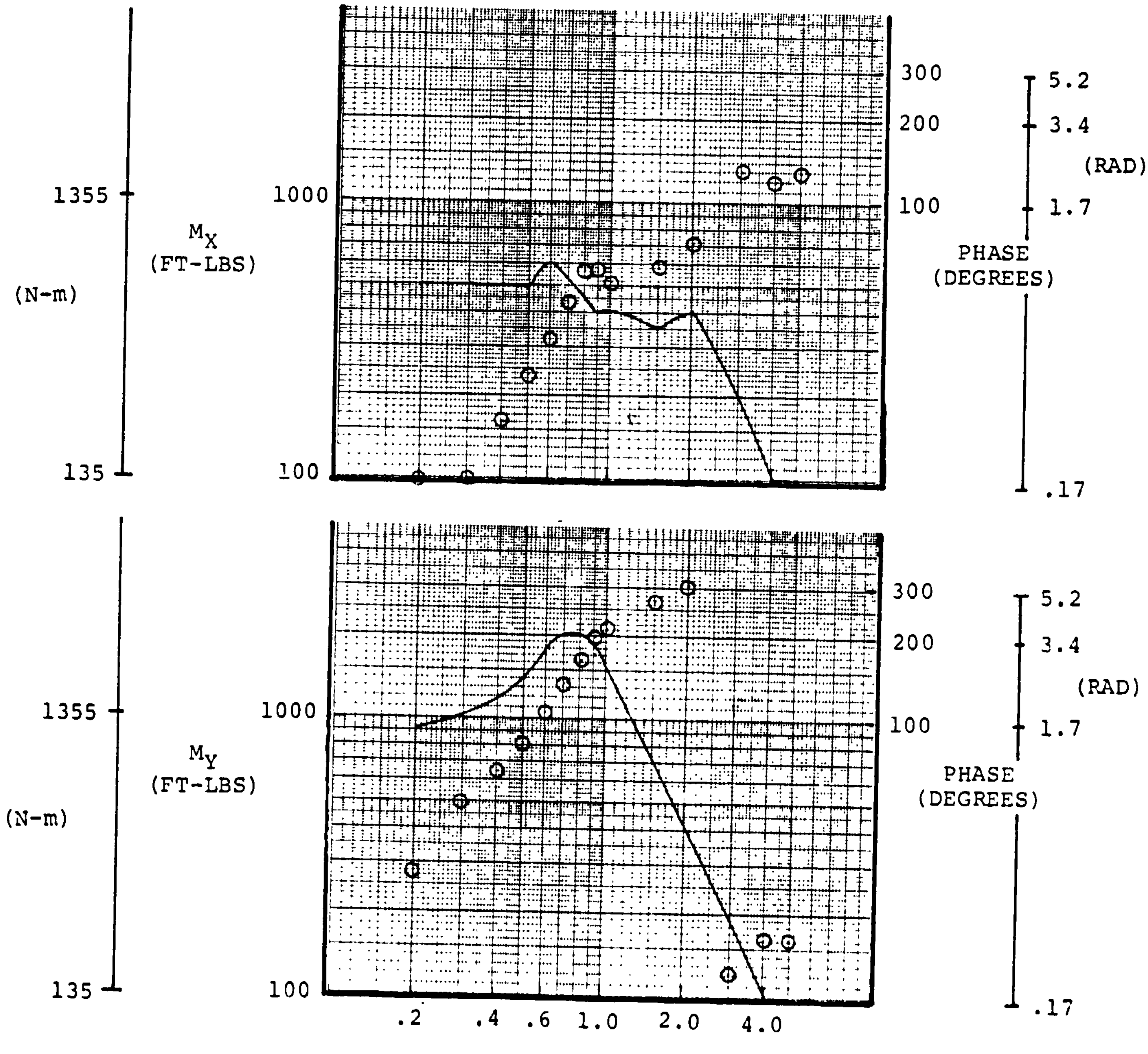

FIGURE B-9. FREQUENCY RESPONSE OF ROTOR HUB MOMENTS DUE TO δ_e (240 KNOTS, 3049 METERS, FORWARD CG)

240 KNOTS, 3049M (10,000 FEET), FORWARD CG
$\delta A_1 = \pm .25°$

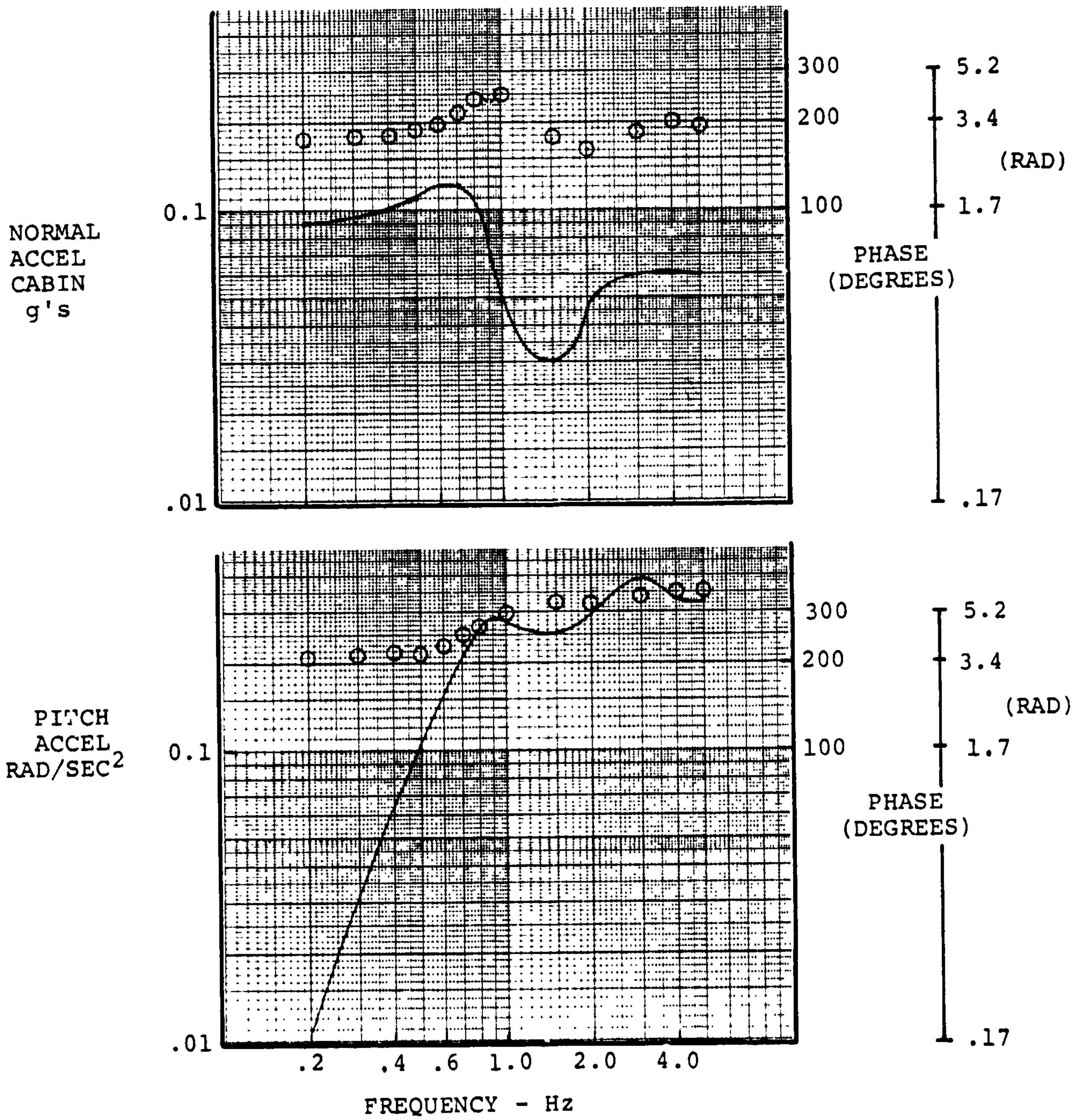

FIGURE B-10. FREQUENCY RESPONSE OF CABIN NORMAL AND PITCH ACCELERATIONS DUE TO A_1 CYCLIC (240 KNOTS, 3049 METERS, FORWARD CG)

240 KNOTS, 3049M (10,000 FEET), FORWARD CG

$\delta A_1 = \pm.25°$

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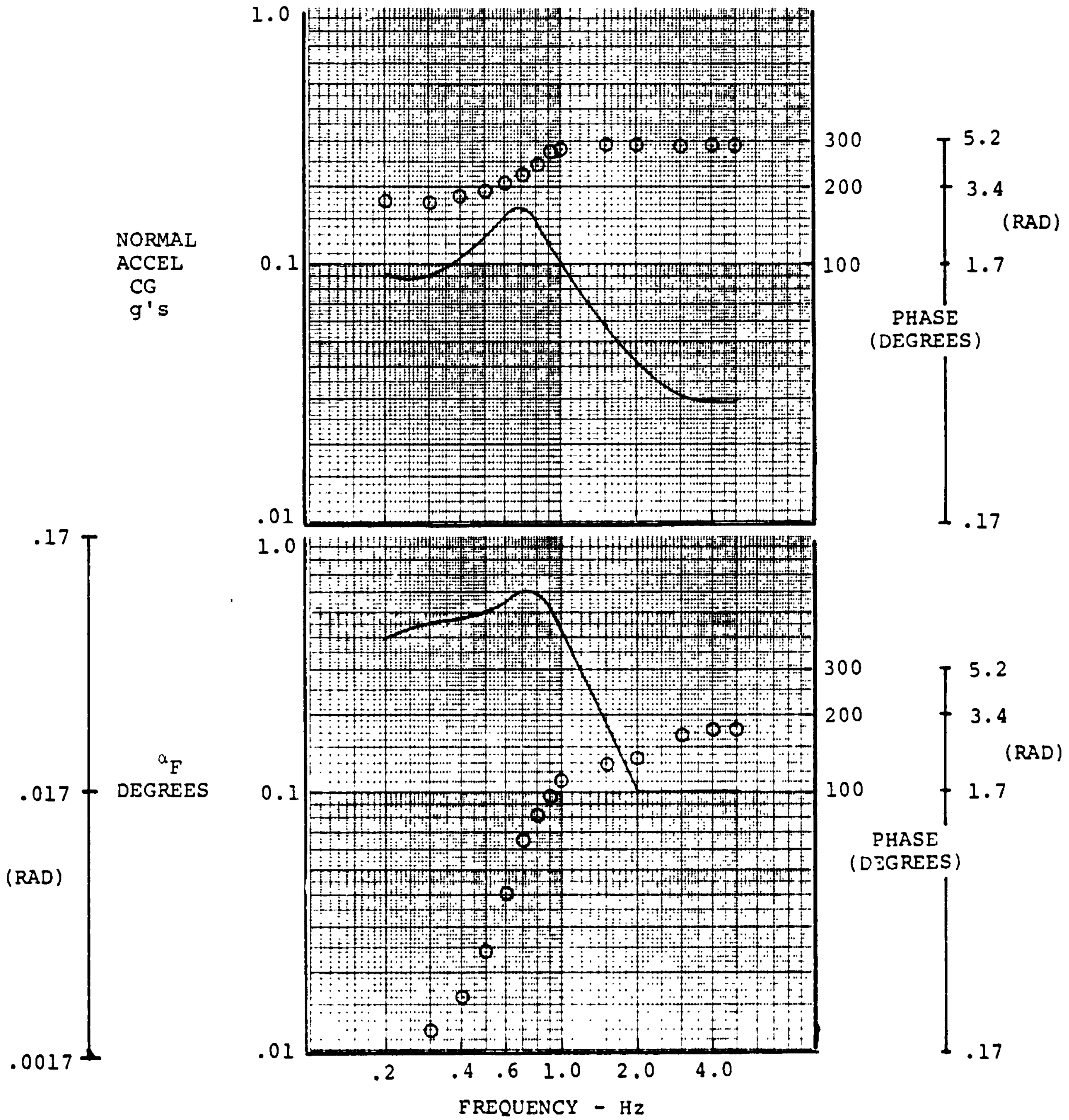


FIGURE B-11. FREQUENCY RESPONSE OF NORMAL ACCELERATION AT CG AND FUSELAGE ANGLE OF ATTACK DUE TO A_1 CYCLIC (240 KNOTS, 3049 METERS, FORWARD CG)

240 KNOTS, 3049M (10,000 FEET), FORWARD CG

$\delta A_1 = \pm .25°$

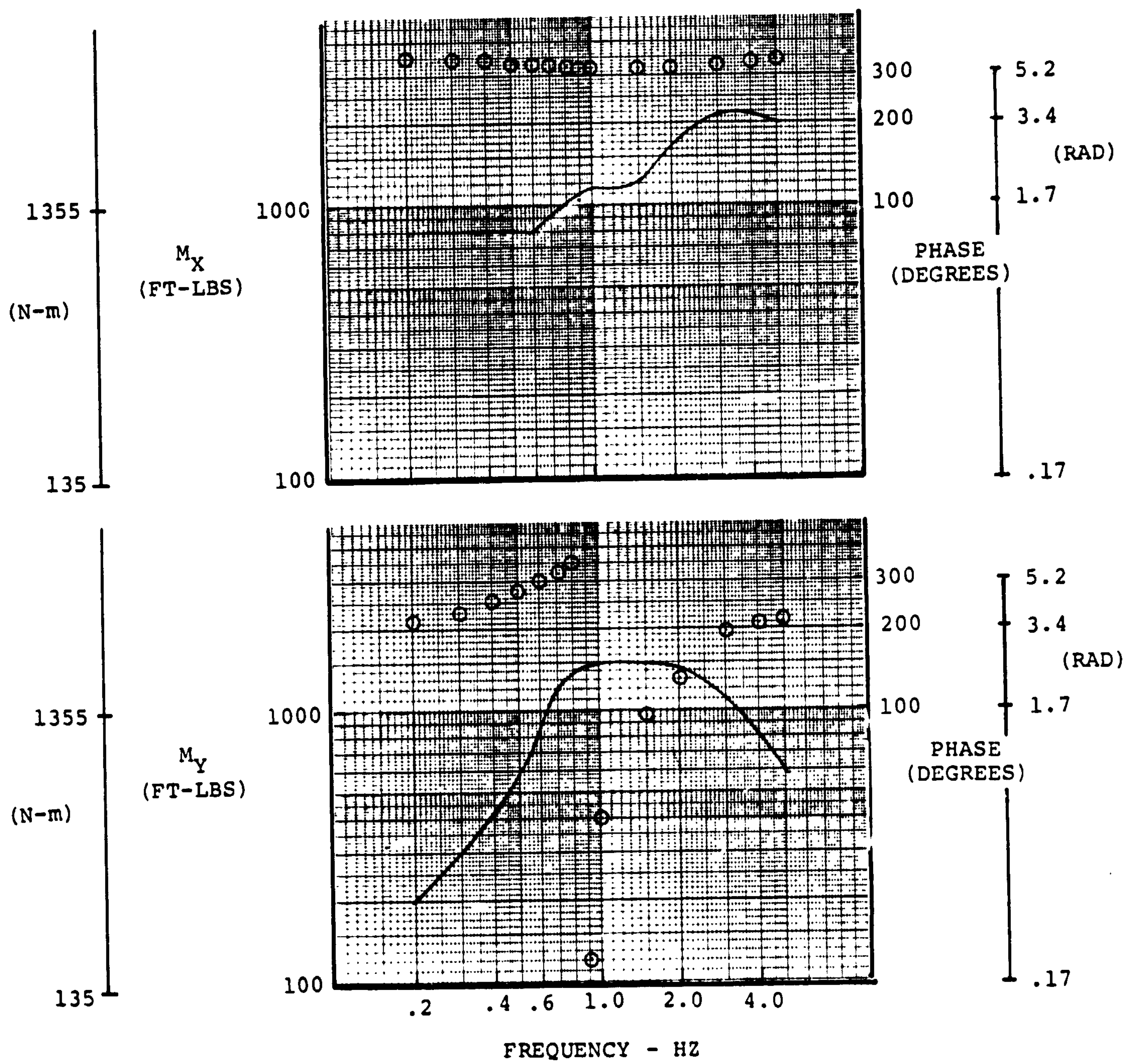


FIGURE B-12. FREQUENCY RESPONSE OF ROTOR HUB MOMENTS DUE TO A_1 CYCLIC (240 KNOTS, 3049 METERS, FORWARD CG)

240 KNOTS, 3049M (10,000 FEET), FORWARD CG
$\delta B_1 = \pm .25°$

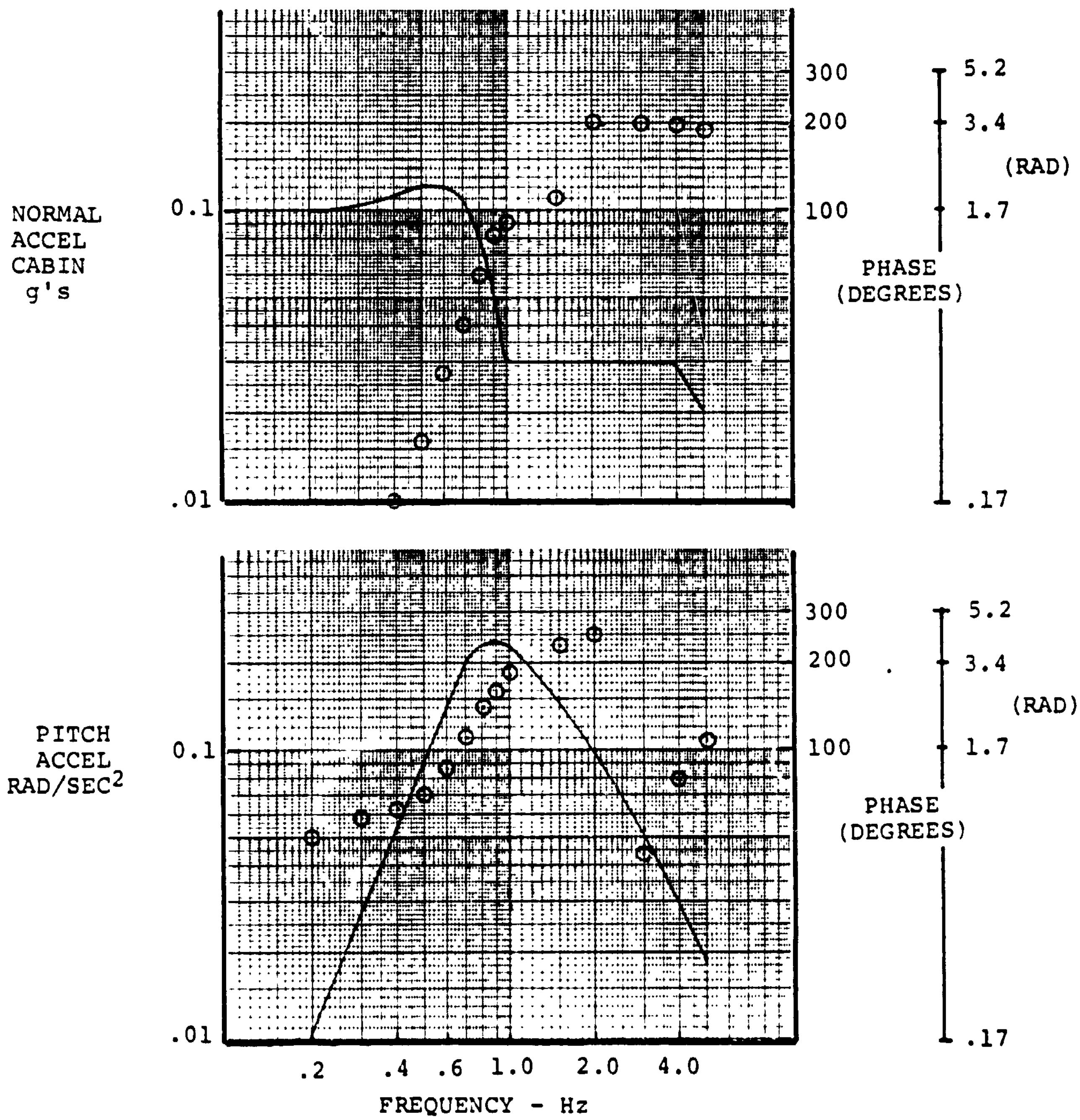


FIGURE B-13. FREQUENCY RESPONSE OF CABIN NORMAL AND PITCH ACCELERATIONS DUE TO B_1 CYCLIC (240 KNOTS, 3049 METERS, FORWARD CG)

240 KNOTS, 3049M (10,000 FEET), FORWARD CG

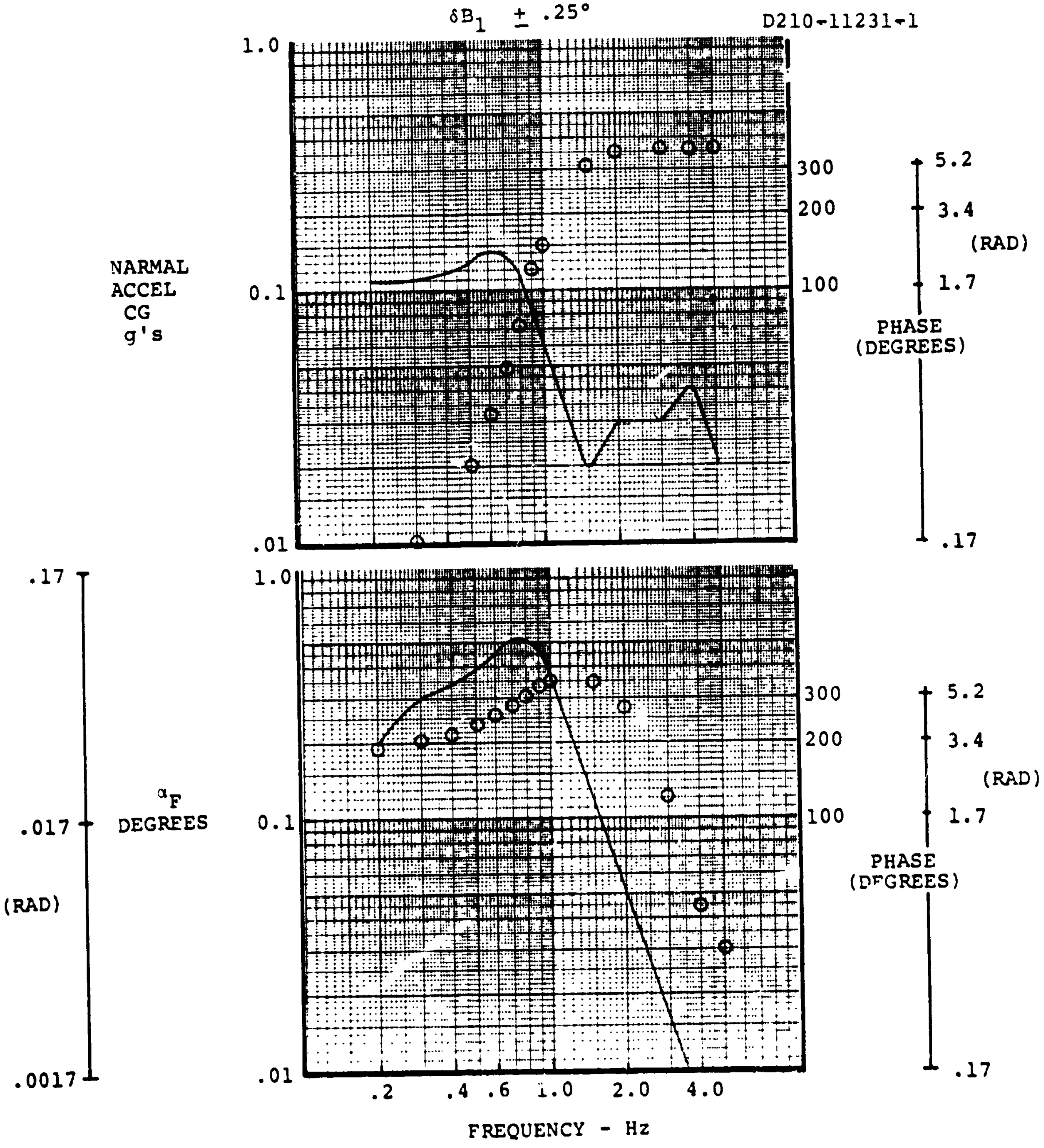


FIGURE B-14. FREQUENCY RESPONSE OF NORMAL ACCELERATION AT CG AND FUSELAGE ANGLE OF ATTACK DUE TO B_1 CYCLIC (240 KNOTS, 3049 METERS, FORWARD CG)

240 KNOTS, 3049M (10,000 FEET), FORWARD CG

$\delta B_1 = \pm .25°$

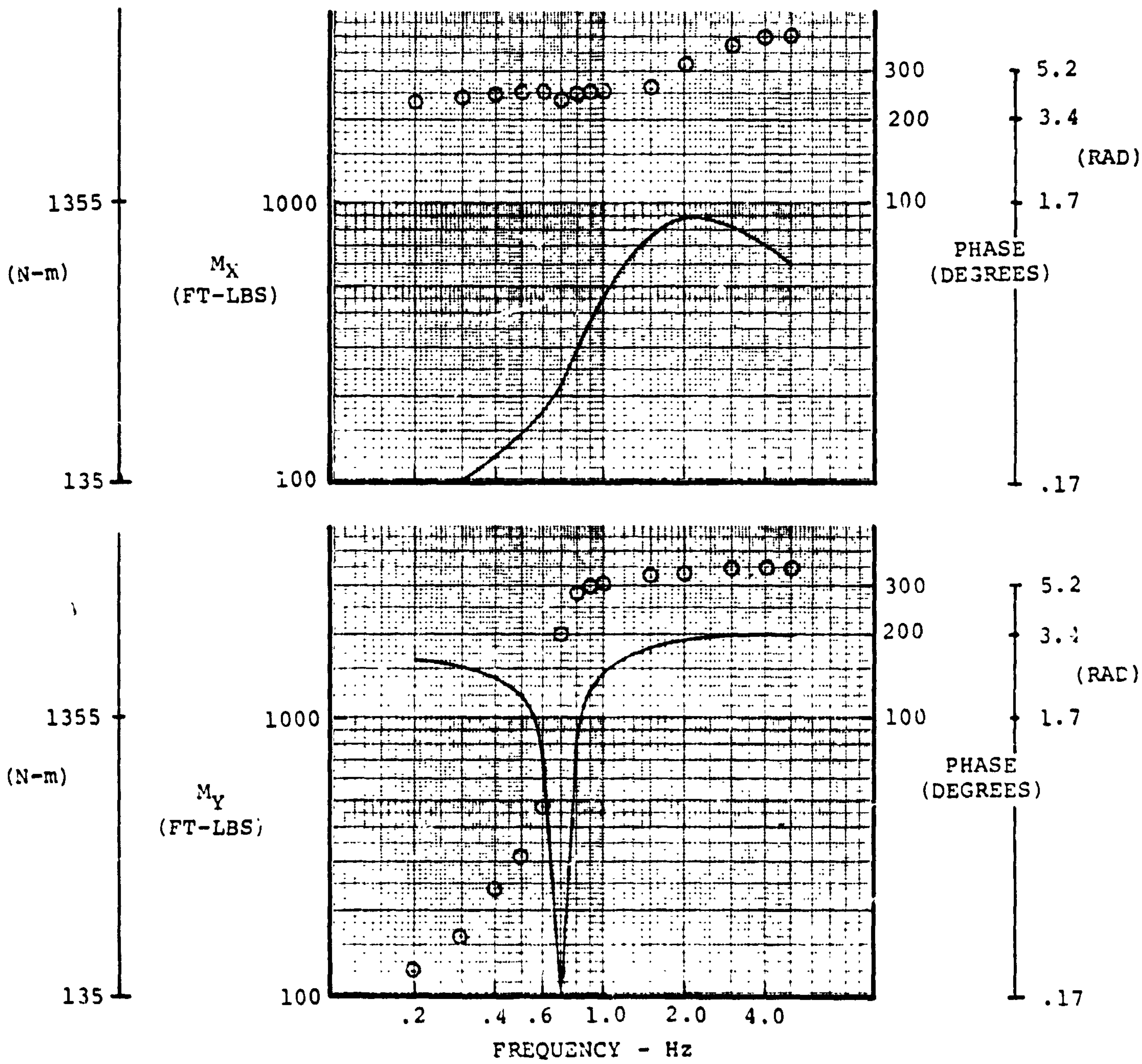
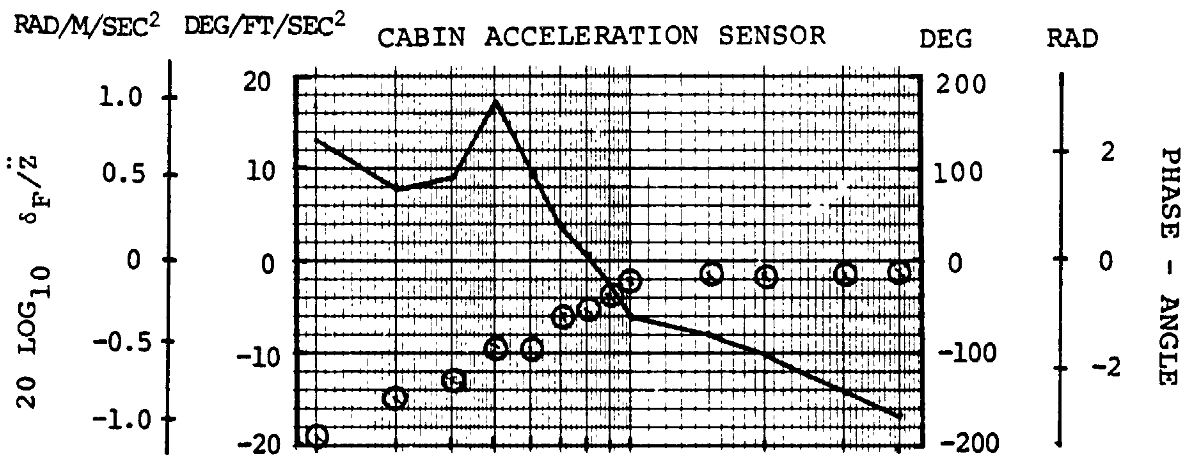


FIGURE B-15. FREQUENCY RESPONSE OF ROTOR HUB MOMENTS DUE TO B_1 CYCLIC (240 KNOTS, 3049 METERS, FORWARD CG)

FEEDBACK REQUIRED FOR SPECIFIED ALLEVIATION IN CABIN

240 KNOTS, 10,000 FEET (3049M), FOREWARD CG



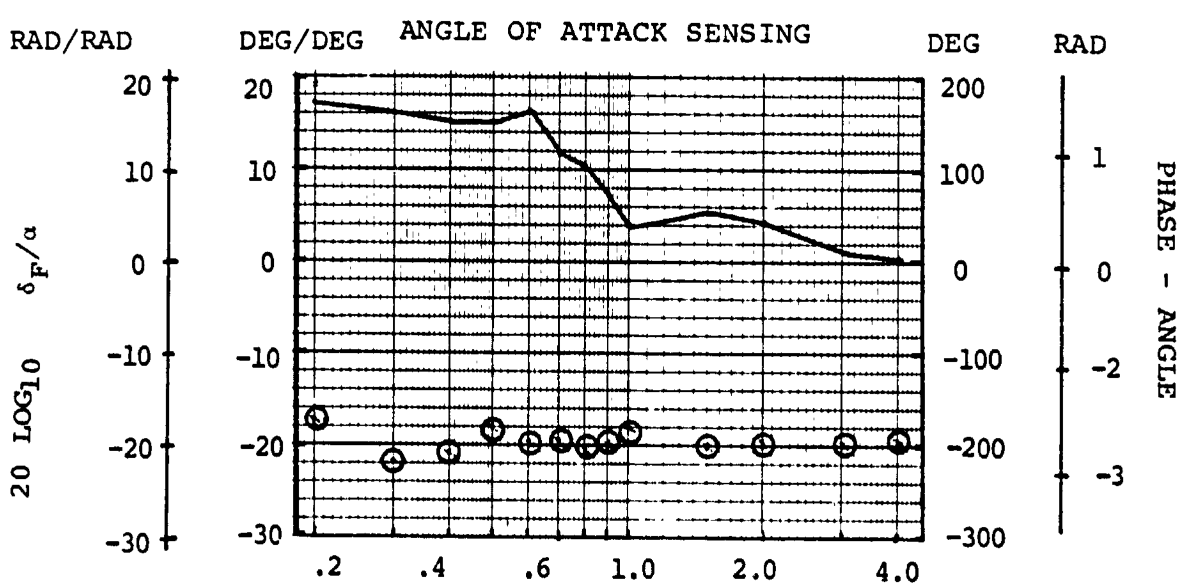


FIGURE B-16. FLAP FEEDBACK REQUIRED WITH ACCELERATION AND α SENSING RESPECTIVELY, 240 KNOTS, 3049 METERS, FORWARD CG, NO A_1, B_1 FEEDBACK

FEEDBACK REQUIRED FOR SPECIFIED ALLEVIATION IN CABIN

240 KNOTS, 10,000 FEET (3049M), FORWARD CG

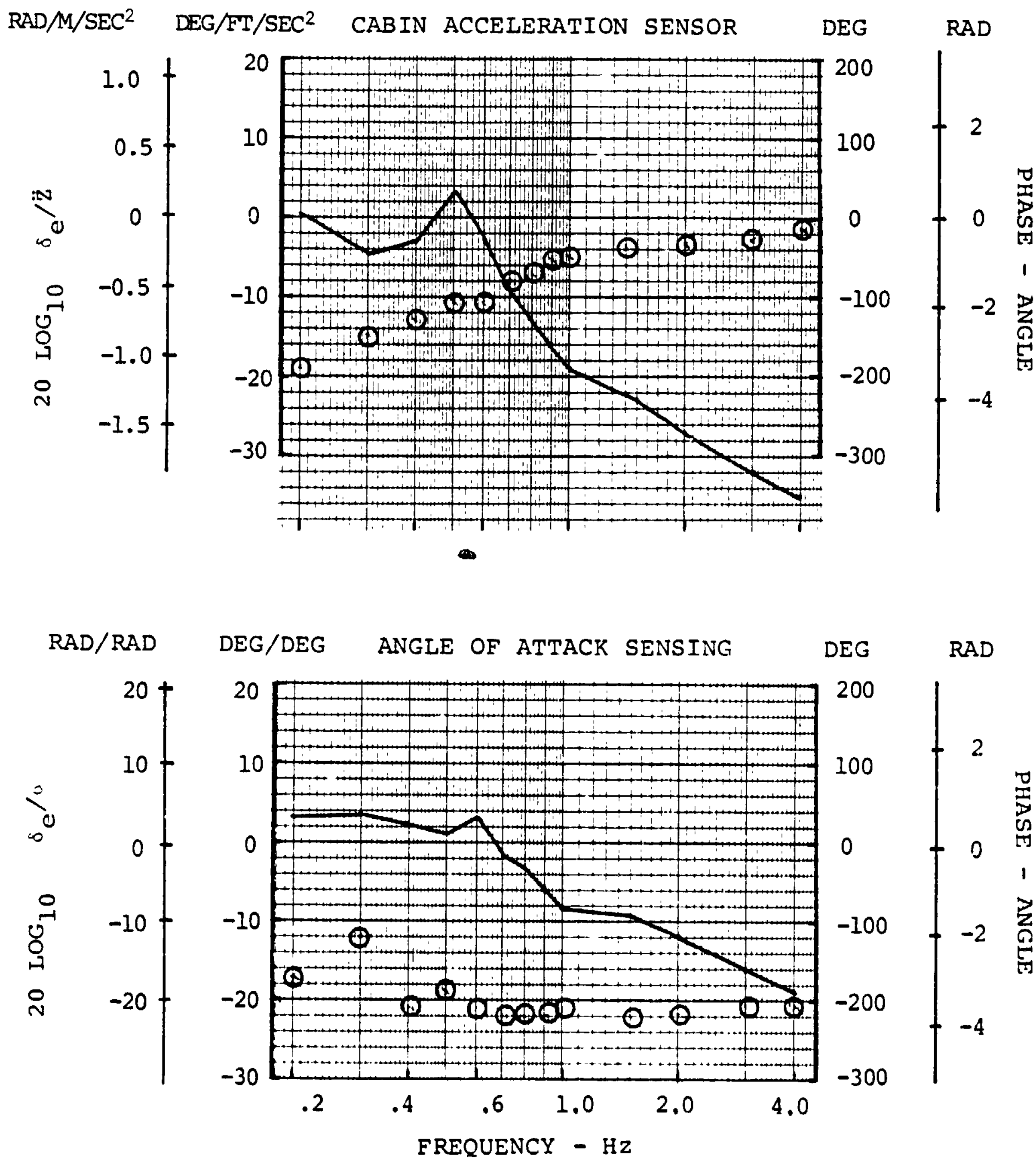
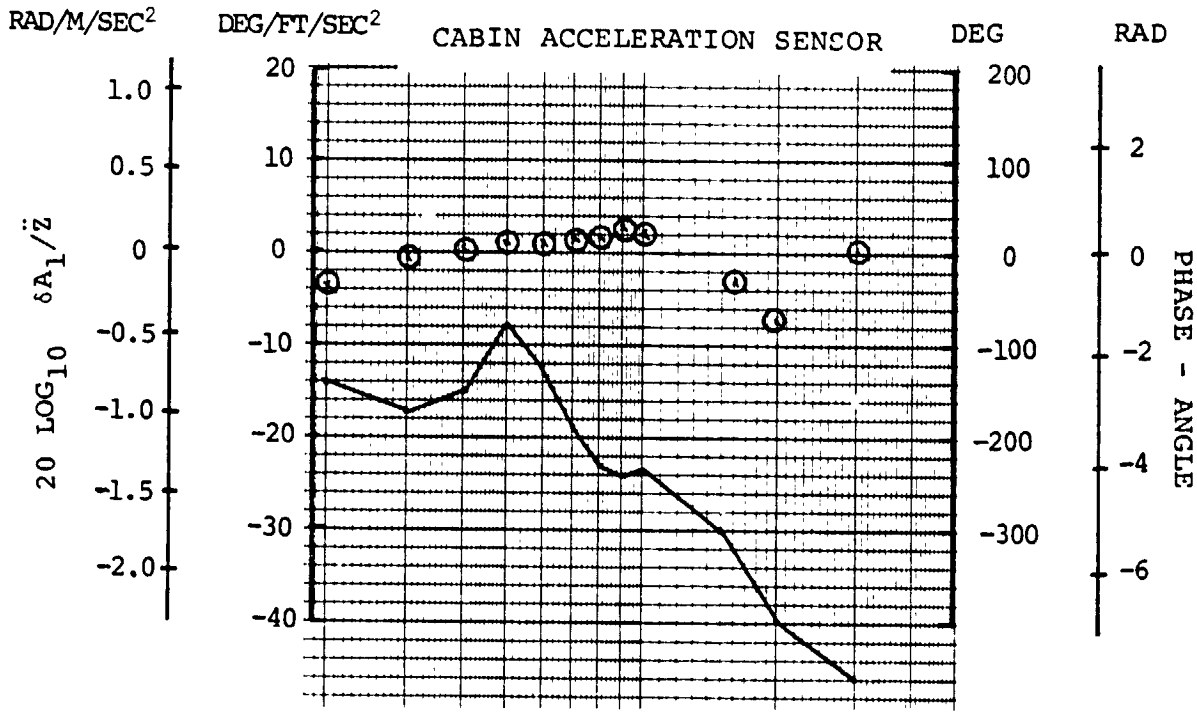


FIGURE B-17. ELEVATOR FEEDBACK REQUIRED WITH ACCELERATION AND α SENSING RESPECTIVELY, 240 KNOTS, 3049 METERS, FORWARD CG, NO A_1, B_1 FEEDBACK

FEEDBACK REQUIRED FOR SPECIFIED ALLEVIATION IN CABIN

240 KNOTS, 10,000 FEET (3049M), FORWARD CG



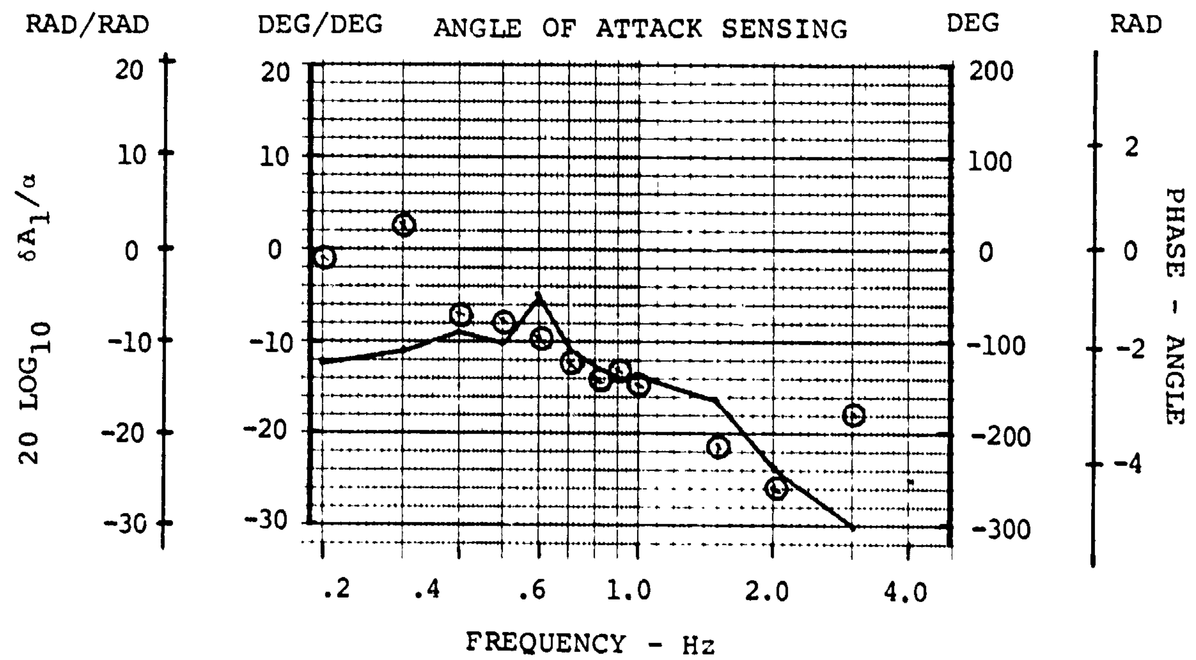


FIGURE B-18. A_1 FEEDBACK REQUIRED WITH ACCELERATION AND α SENSING RESPECTIVELY, 240 KNOTS, 3049 METERS, FORWARD CG

FEEDBACK REQUIRED FOR SPECIFIED ALLEVIATION IN CABIN

240 KNOTS, 10,000 FEET (3049M), FORWARD CG

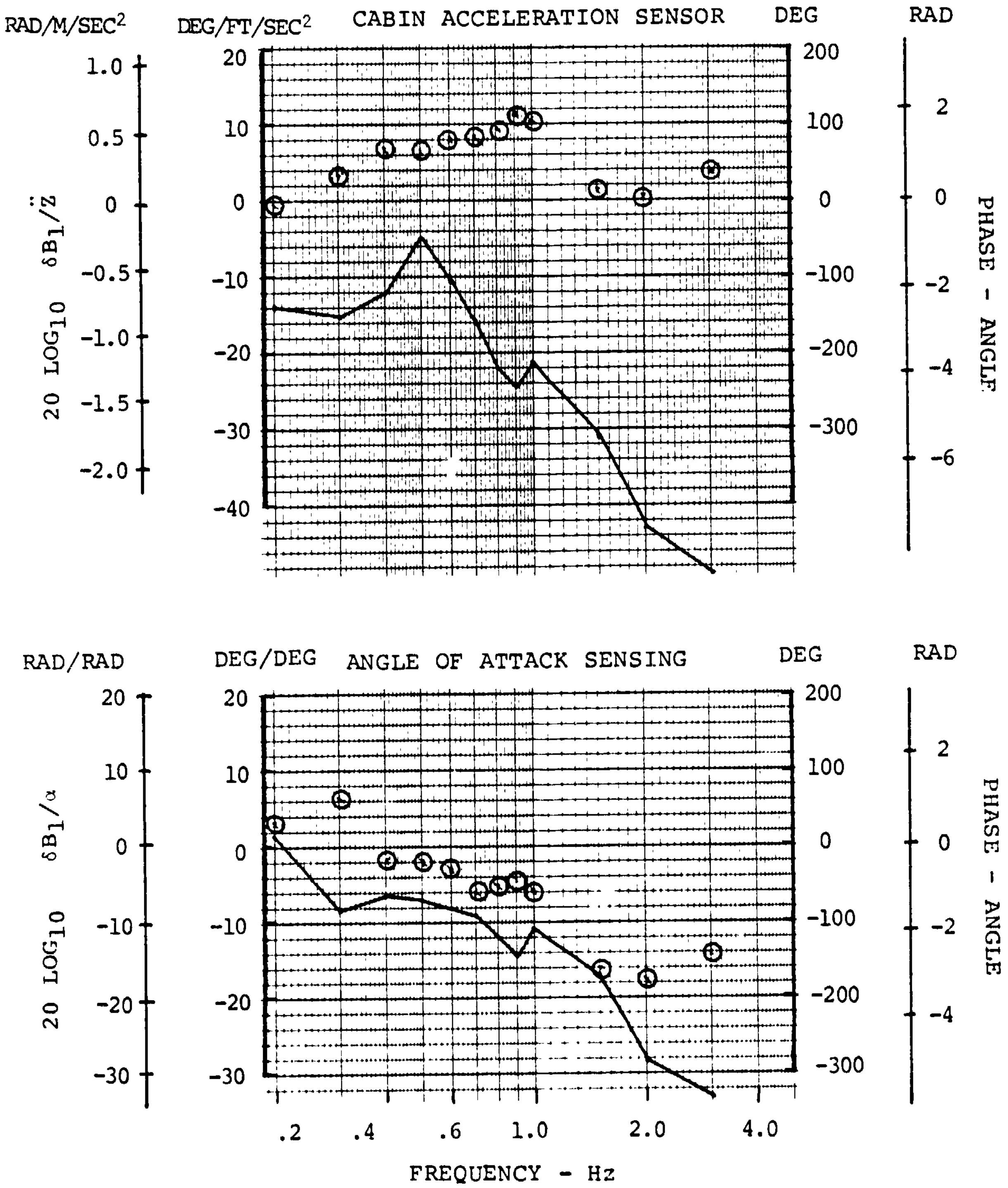


FIGURE B-19. B_1 FEEDBACK REQUIRED WITH ACCELERATION AND α SENSING RESPECTIVELY, 240 KNOTS, 3049 METERS, FORWARD CG

FEEDBACK REQUIRED FOR SPECIFIED ALLEVIATION IN CABIN

240 KNOTS, 10,000 FEET (3049M), FORWARD CG

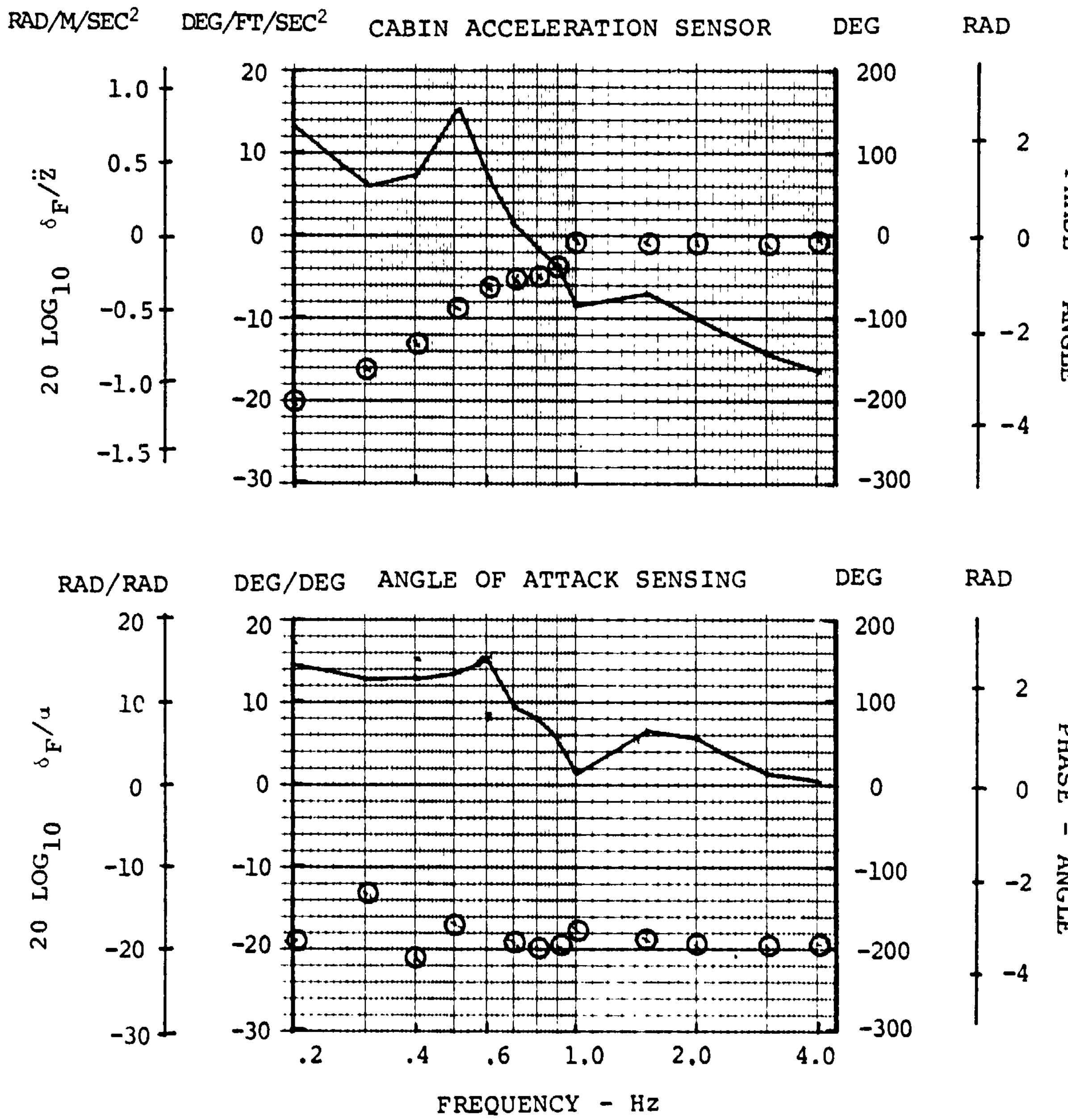


FIGURE B-20. FLAP FEEDBACK REQUIRED WITH ACCELERATION AND α SENSING RESPECTIVELY, 240 KNOTS, 3049 METERS, FORWARD CG, A_1 & B_1 FEEDBACK INCLUDED

FEEDBACK REQUIRED FOR SPECIFIED ALLEVIATION IN CABIN

240 KNOTS, 10,000 FEET (3049M), FORWARD CG

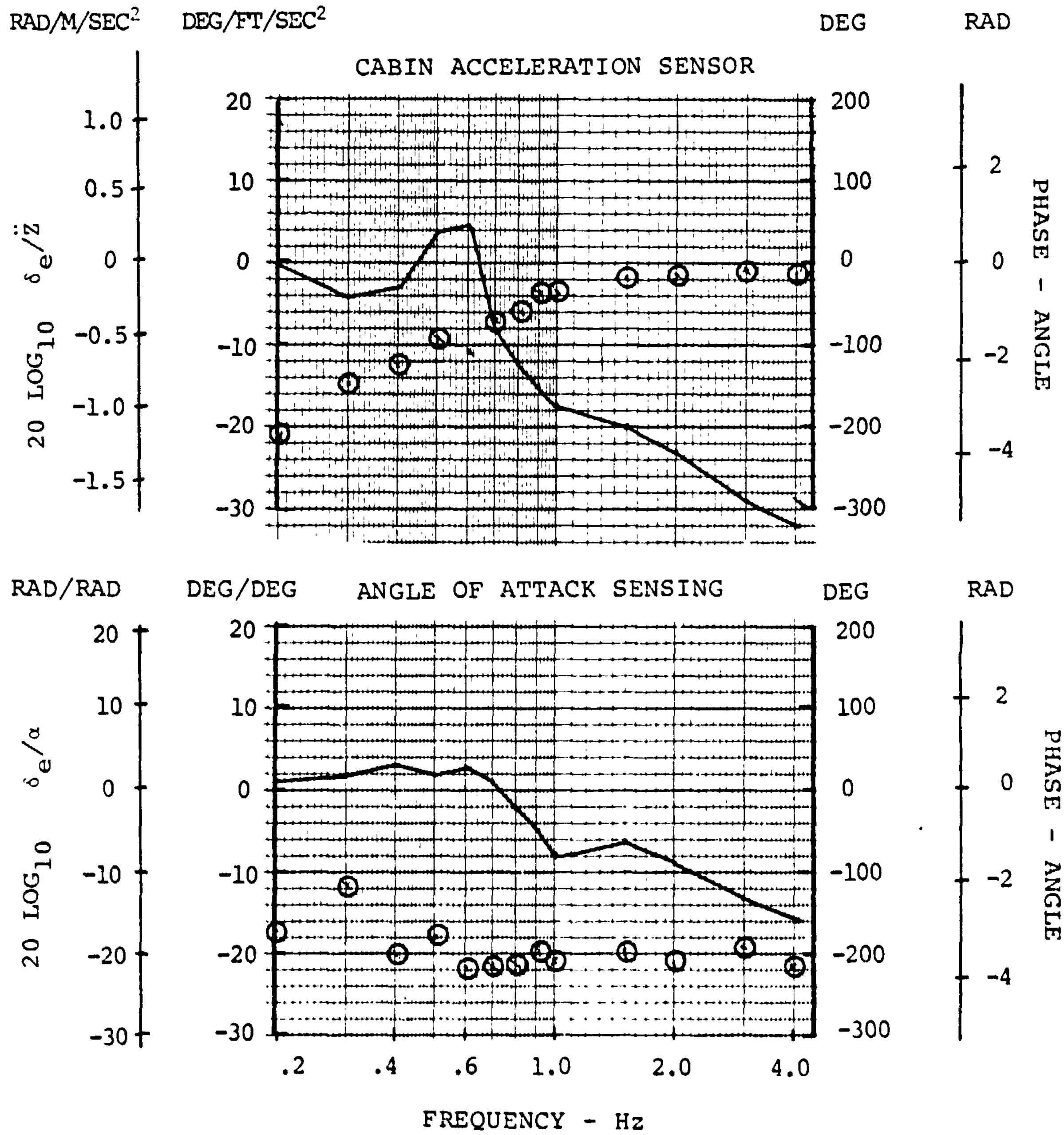


FIGURE B-21. ELEVATOR FEEDBACK REQUIRED WITH ACCELERATION AND α SENSING RESPECTIVELY, 240 KNOTS, 3049 METERS, FORWARD CG, A_1 & B_1 FEEDBACK INCLUDED

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OF POOR QUALITY

FLIGHT CONDITION: 240 KNOTS, 10,000 FEET, (3,049m), FORWARD CG

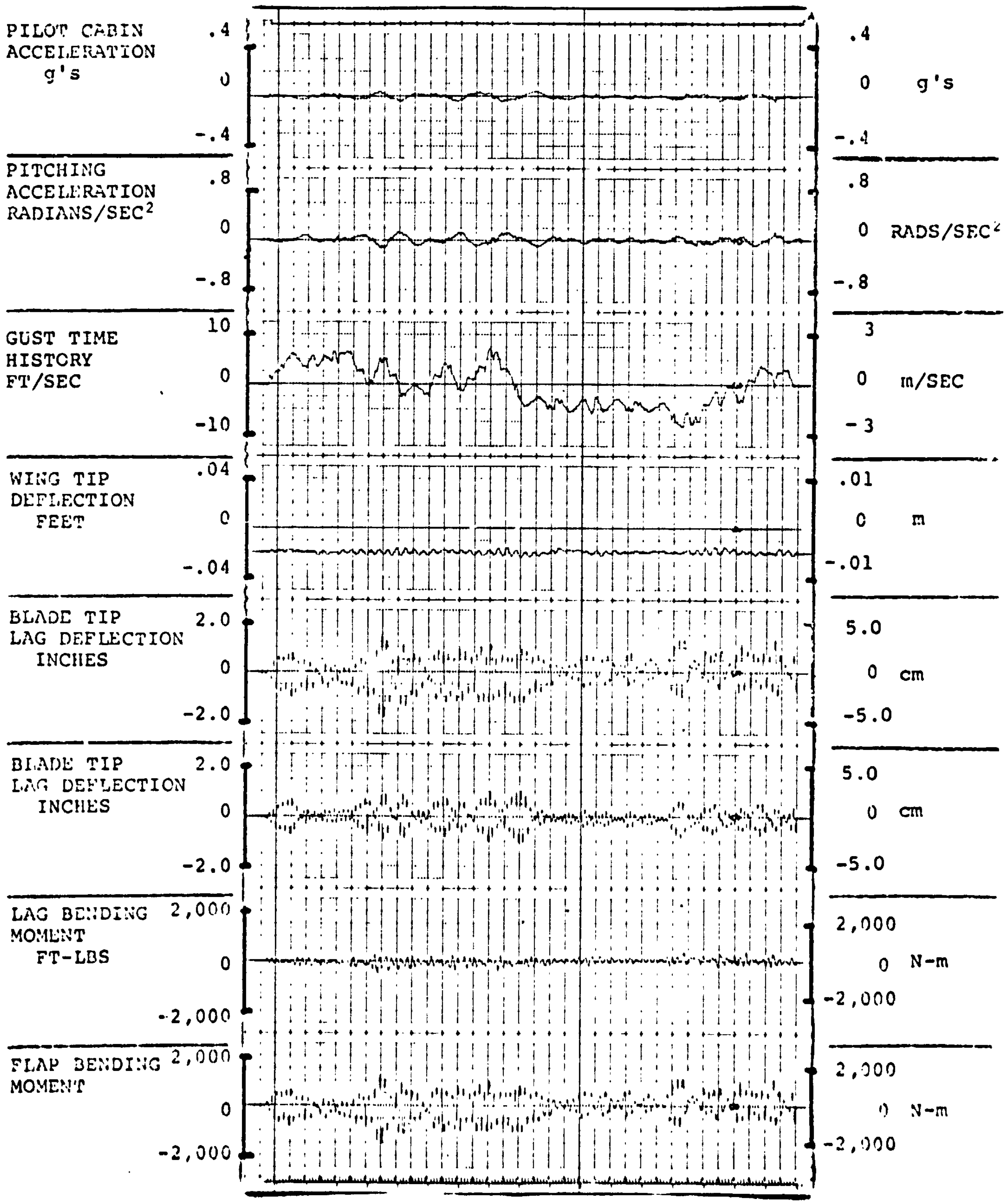

FIGURE B-22. RESPONSES FOR GAIN F = 4.0, GAIN E = .6 1-16

FLIGHT CONDITION: 240 KNOTS, 10,000 FEET, (3,049m), FORWARD CG

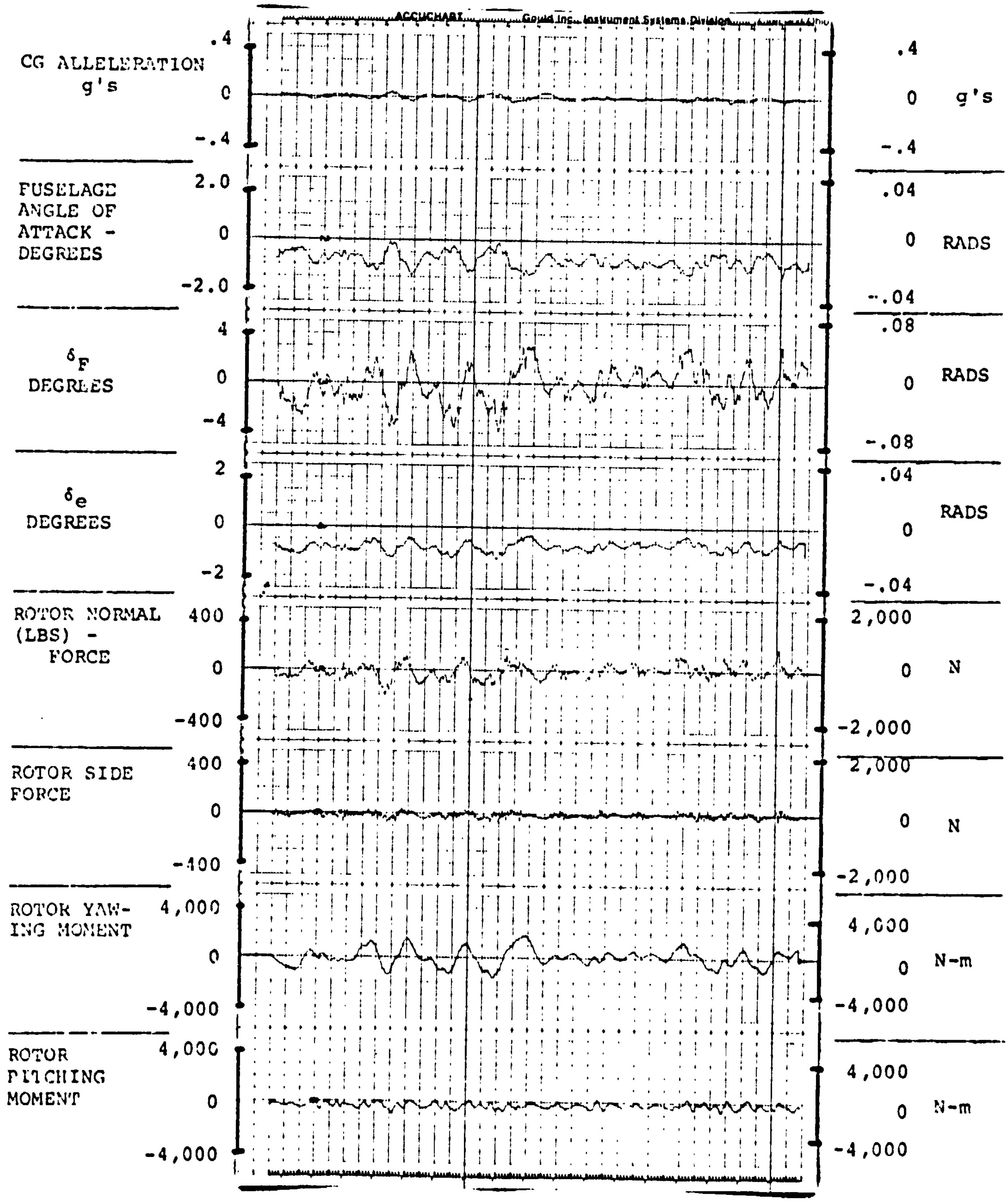

FIGURE B-23. RESPONSES FOR GAIN F = 4.0, GAIN E = .6

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FLIGHT CONDITION: 240 KNOTS, 10,000 FEET, (3,049m), FORWARD CG

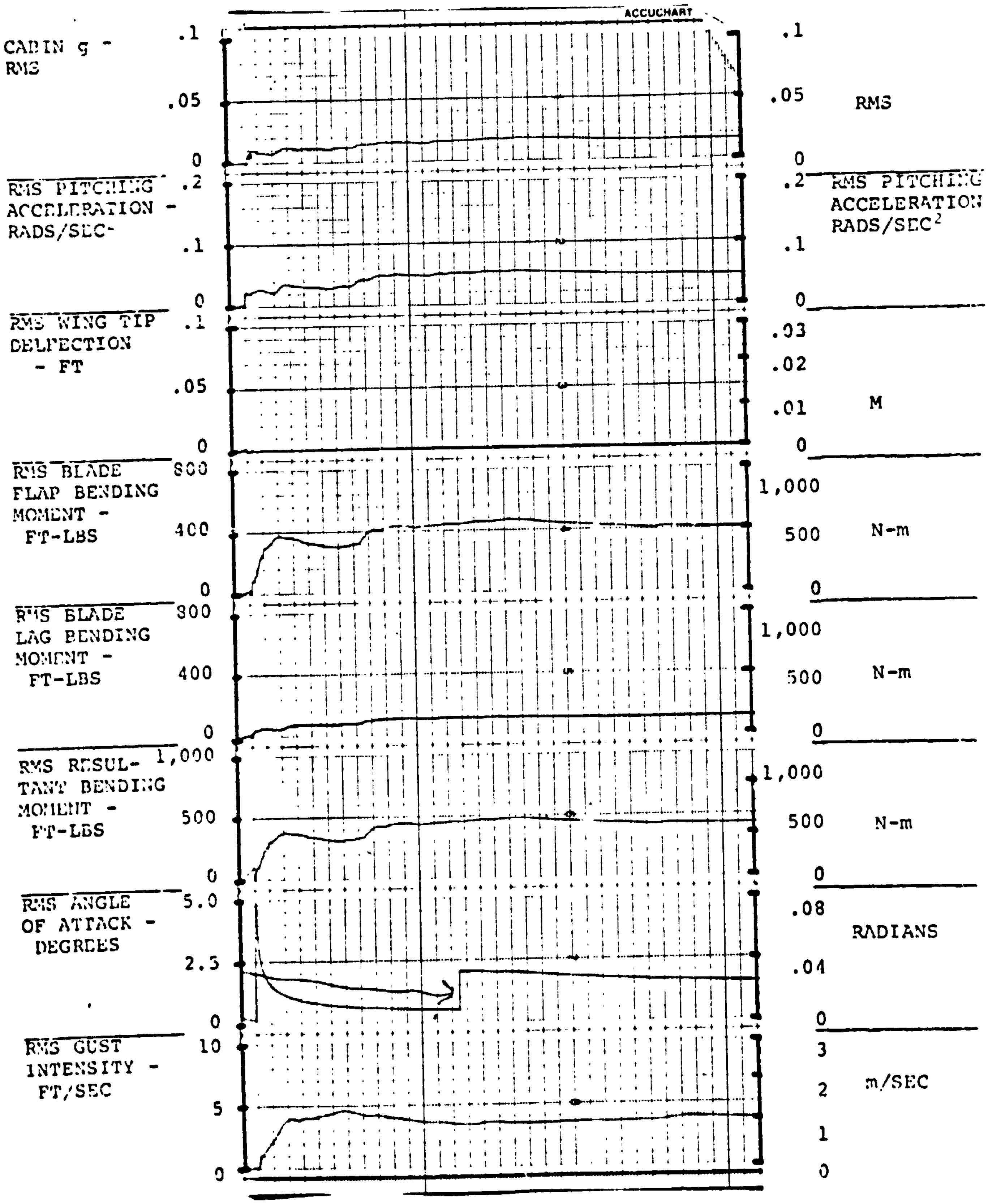

FIGURE B-24. RESPONSES FOR GAIN F = 4.0, GAIN E = .6 1-18

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FLIGHT CONDITION: 240 KNOTS, 10,000 FEET, (3,048m), FORWARD CG
α FEEDBACK

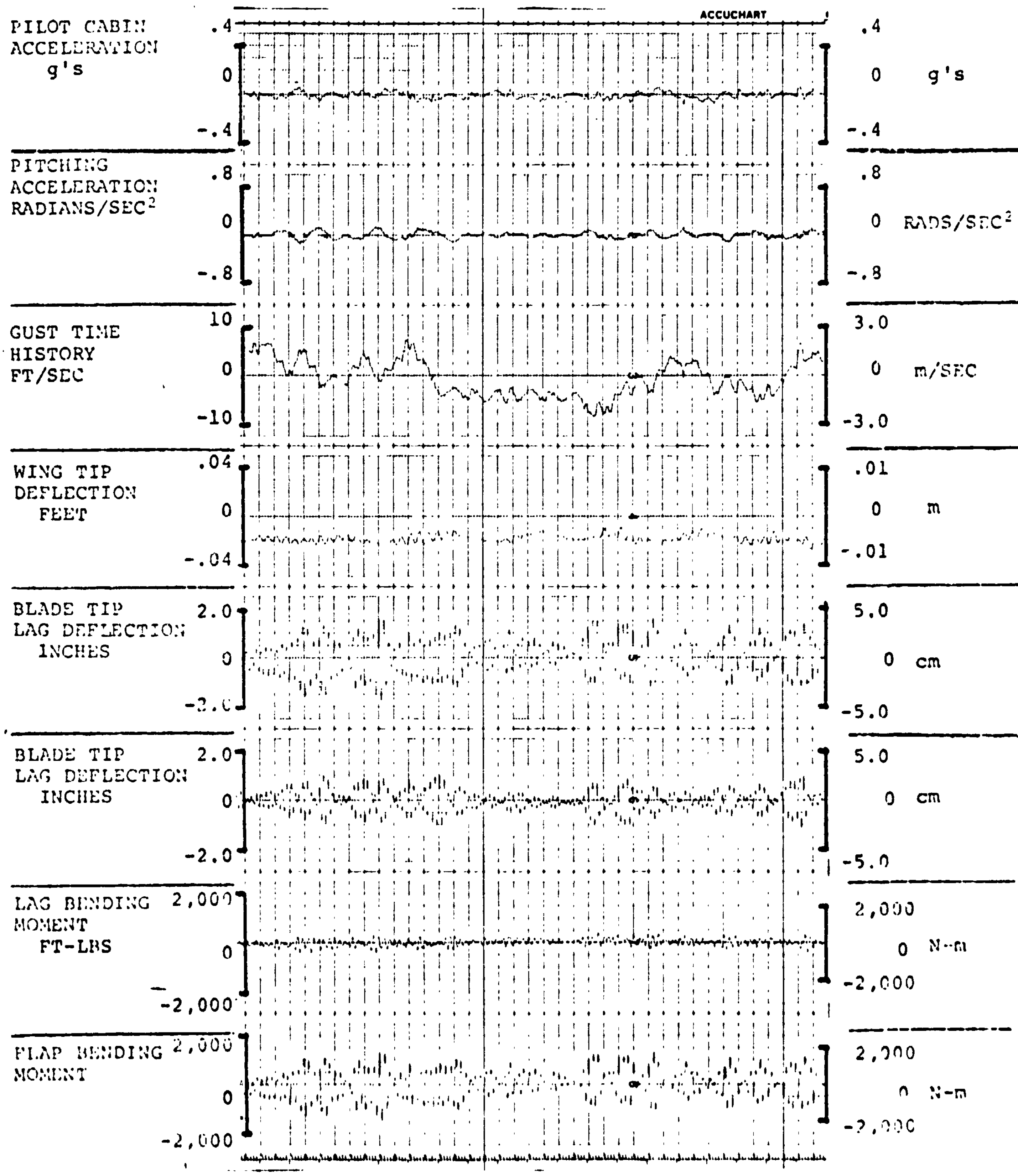

FIGURE B-25. RESPONSES FOR GAIN F = 4.0, GAIN E = .6

FLIGHT CONDITION: 240 KNOTS, 10,000 FEET, (3,049m), FORWARD CG
α FEEDBACK

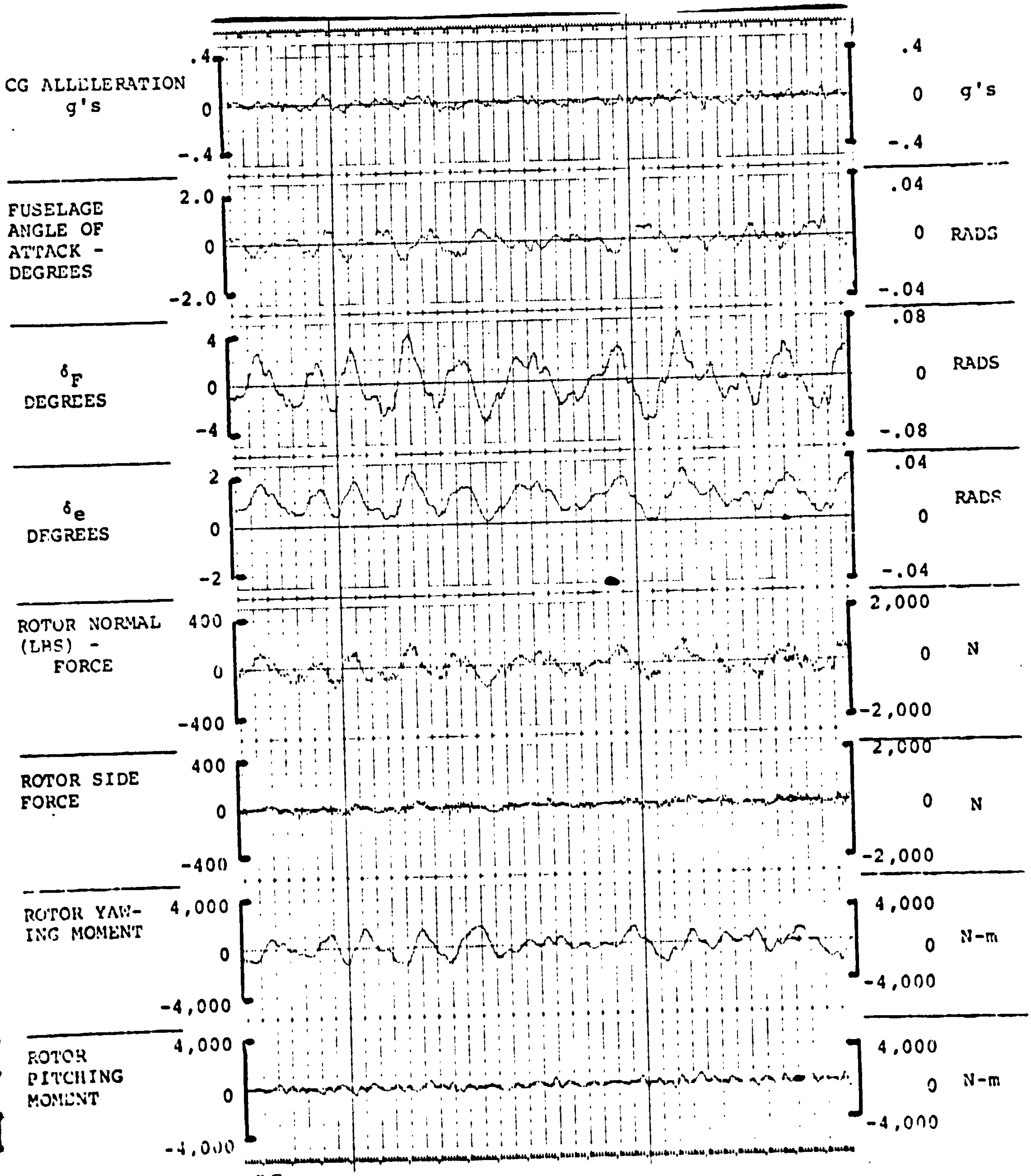

FIGURE B-26. RESPONSES FOR GAIN F = 4.0, GAIN E = .6

FLIGHT CONDITION: 240 KNOTS, 10,000 FEET, (3,049m), FORWARD CG, α FEEDBACK

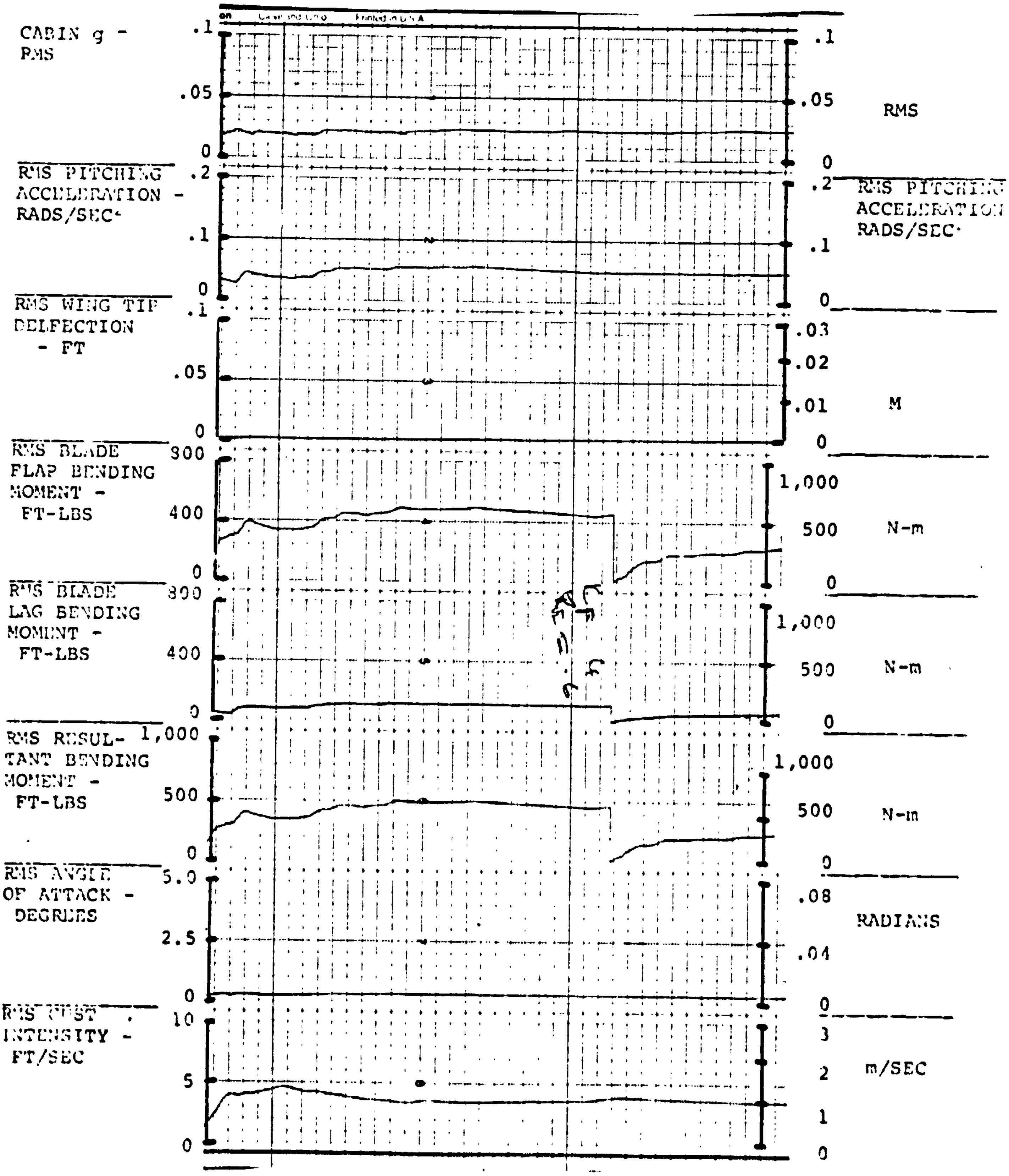

FIGURE B-27. RESPONSES FOR GAIN F = 4.0, GAIN E = .6

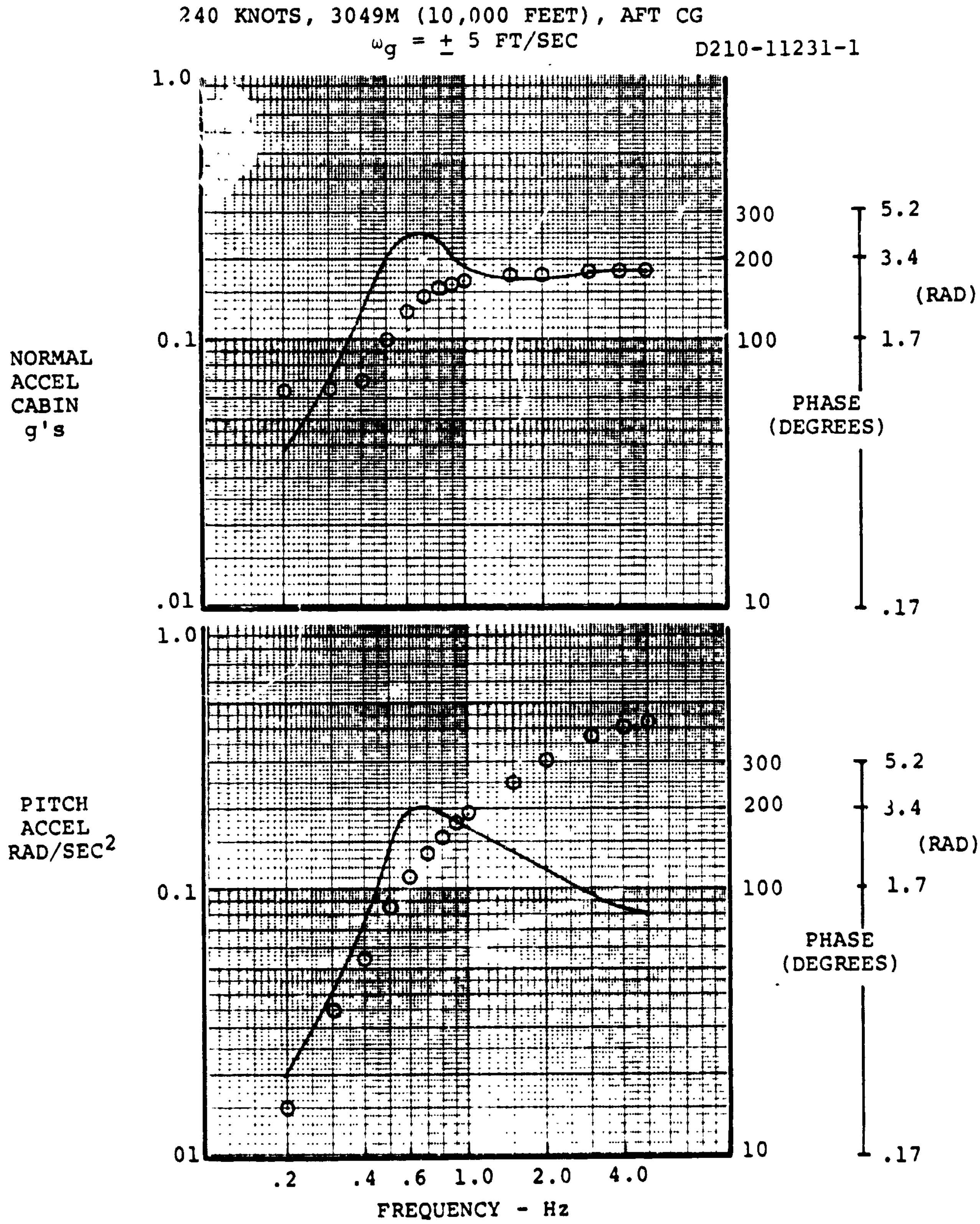

FIGURE B-28. FREQUENCY RESPONSE OF NORMAL AND PITCH ACCELERATION DUE TO VERTICAL GUST (240 KNOTS, 3049 METERS, AFT CG)

240 KNOTS, 3049M (10,000 FEET), AFT CG

$\omega_g = \pm 5$ FT/SEC D210-11231-1

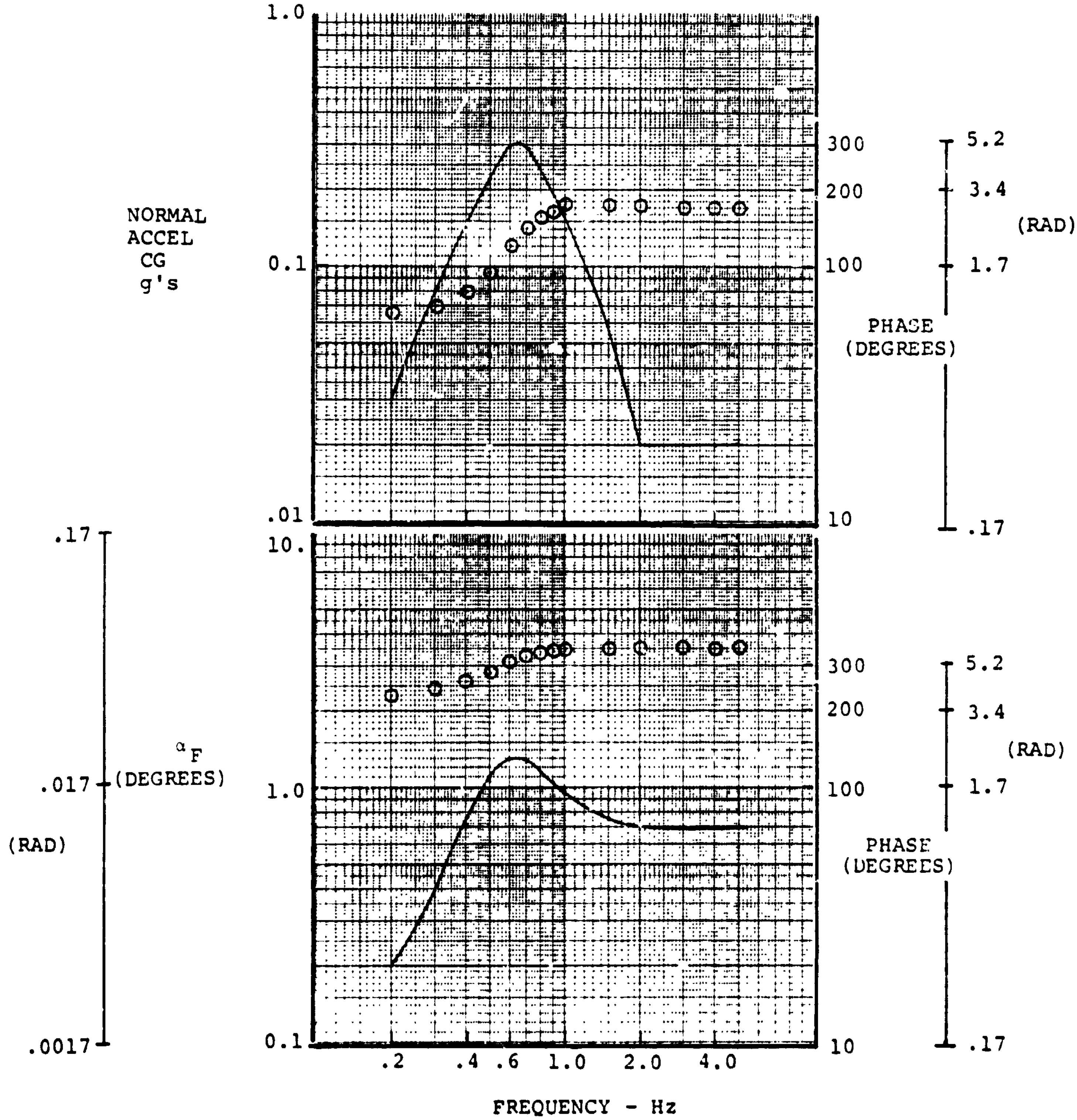

FIGURE B-29. FREQUENCY RESPONSE OF NORMAL ACCELERATION AT CG AND FUSELAGE ANGLE OF ATTACK DUE TO VERTICAL GUSTS (240 KNOTS, 3049 METERS, AFT CG)

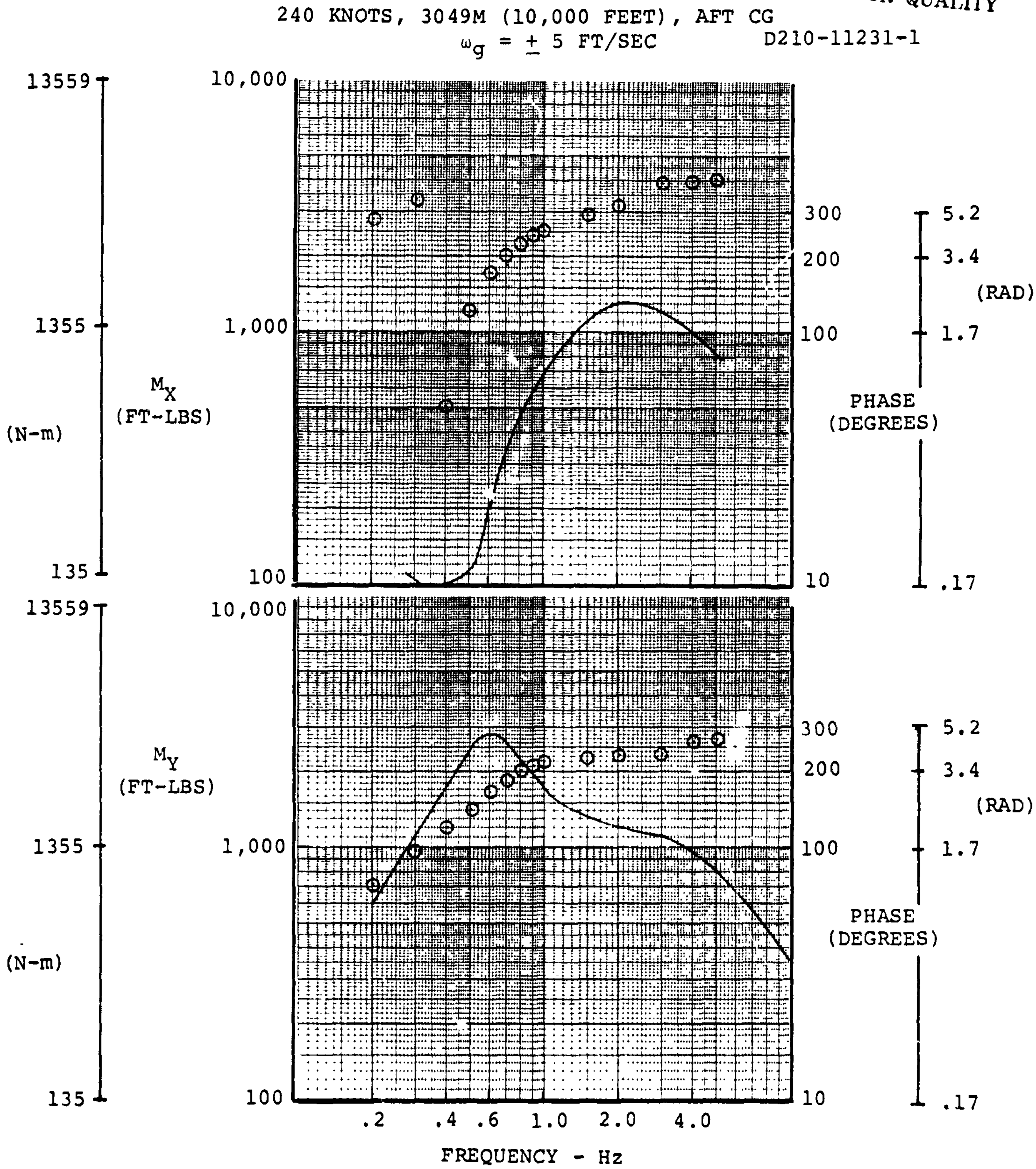

FIGURE B-30. FREQUENCY RESPONSE OF HUB MOMENTS DUE TO VERTICAL GUSTS (240 KNOTS, 3049 METERS, AFT CG)

240 KNOTS, 3049M (10,000 FEET), AFT CG
$\delta_F = \pm 1.0°$ D210-11231-1

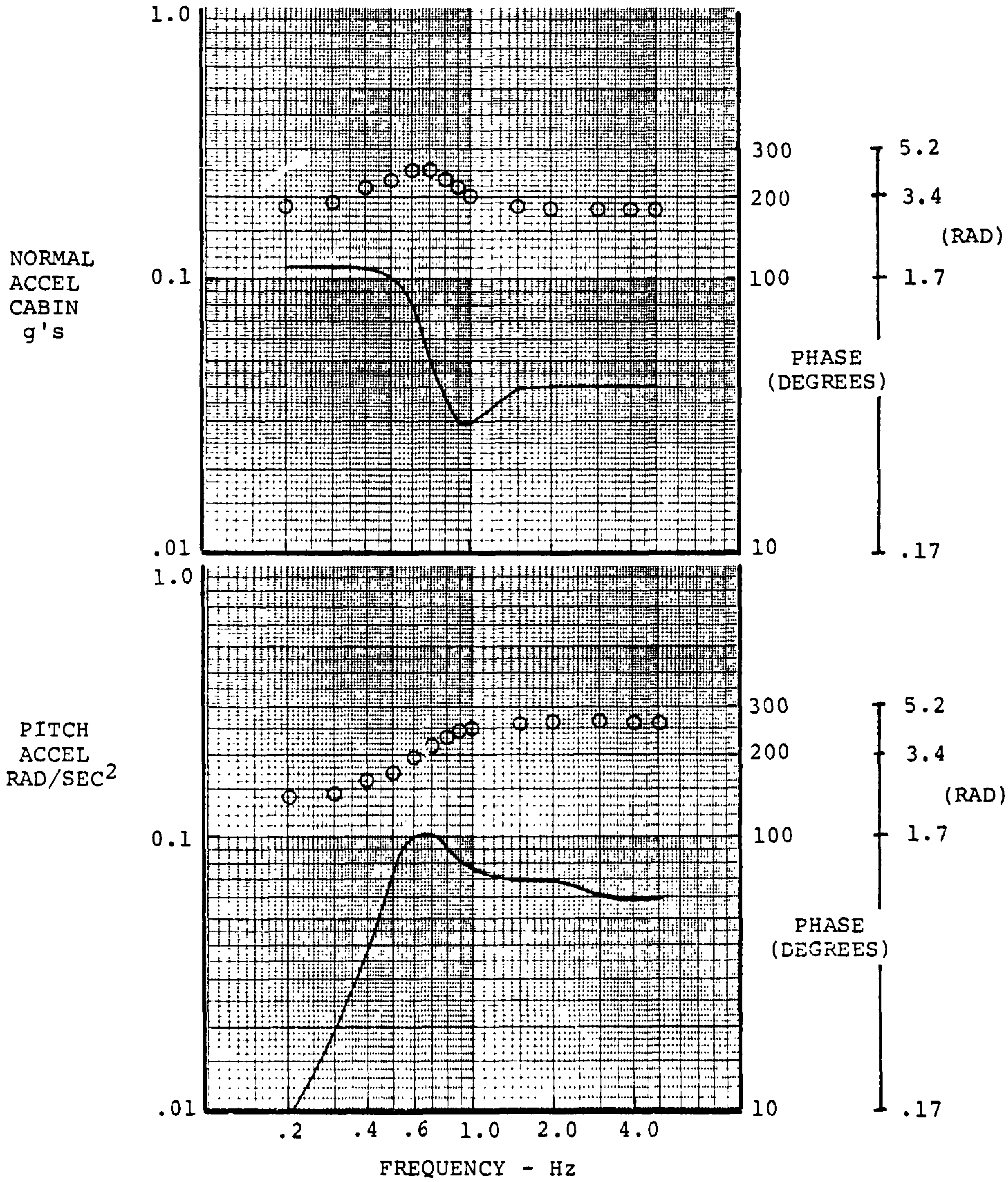

FIGURE B-31. FREQUENCY RESPONSE OF NORMAL AND PITCH ACCELERATION DUE TO δ_F (240 KNOTS, 3049 METERS, AFT CG)

240 KNOTS, 3049M (10,000 FEET), AFT CG

$\delta_F = \pm 1.0°$

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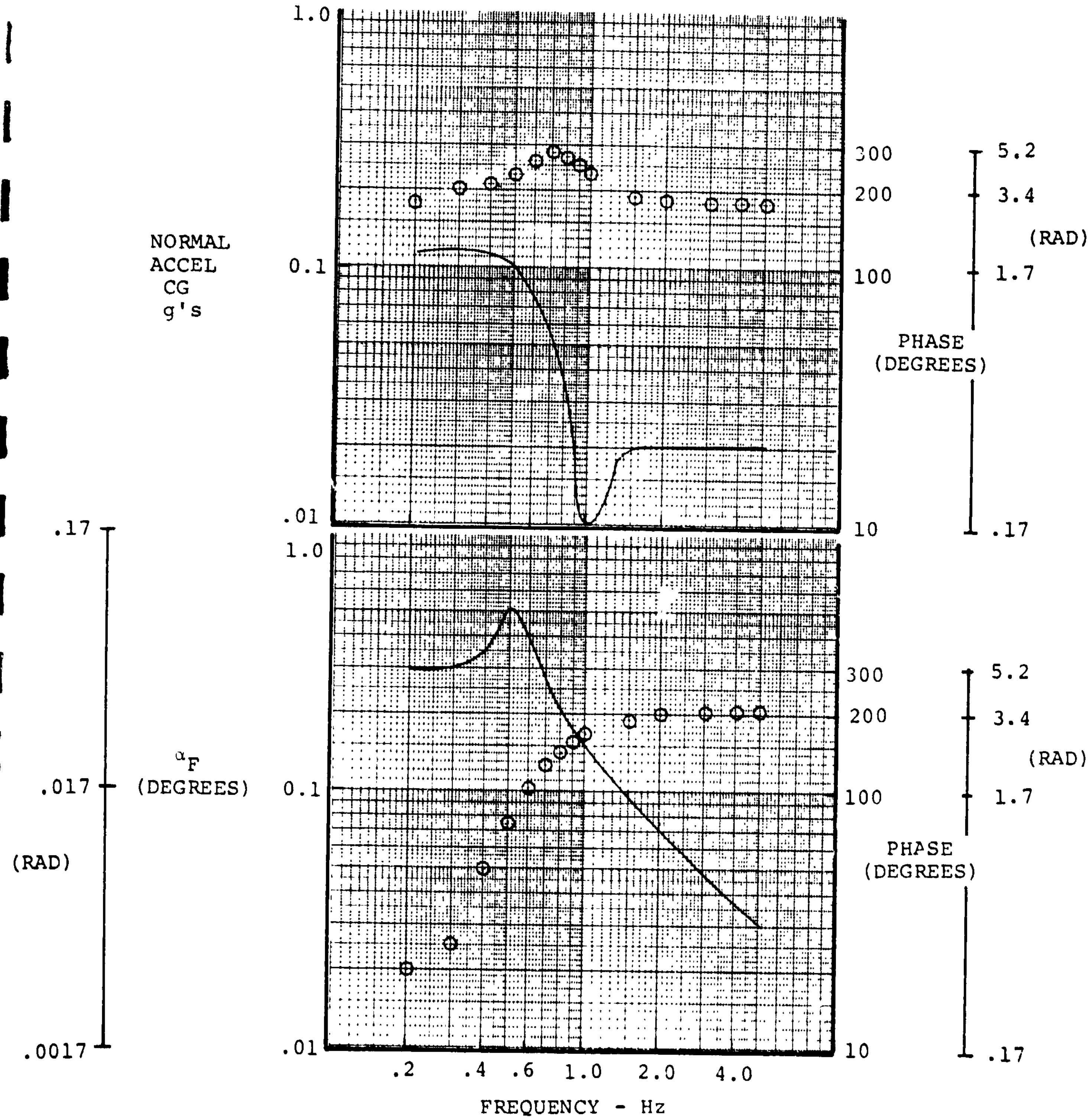

FIGURE B-32. FREQUENCY RESPONSE OF NORMAL ACCELERATION AT CG AND FUSELAGE ANGLE OF ATTACK DUE TO δ_F (240 KNOTS, 3049 METERS, AFT CG)

240 KNOTS, 3049M (10,000 FEET), AFT CG

$\delta_F = \pm 1.0°$

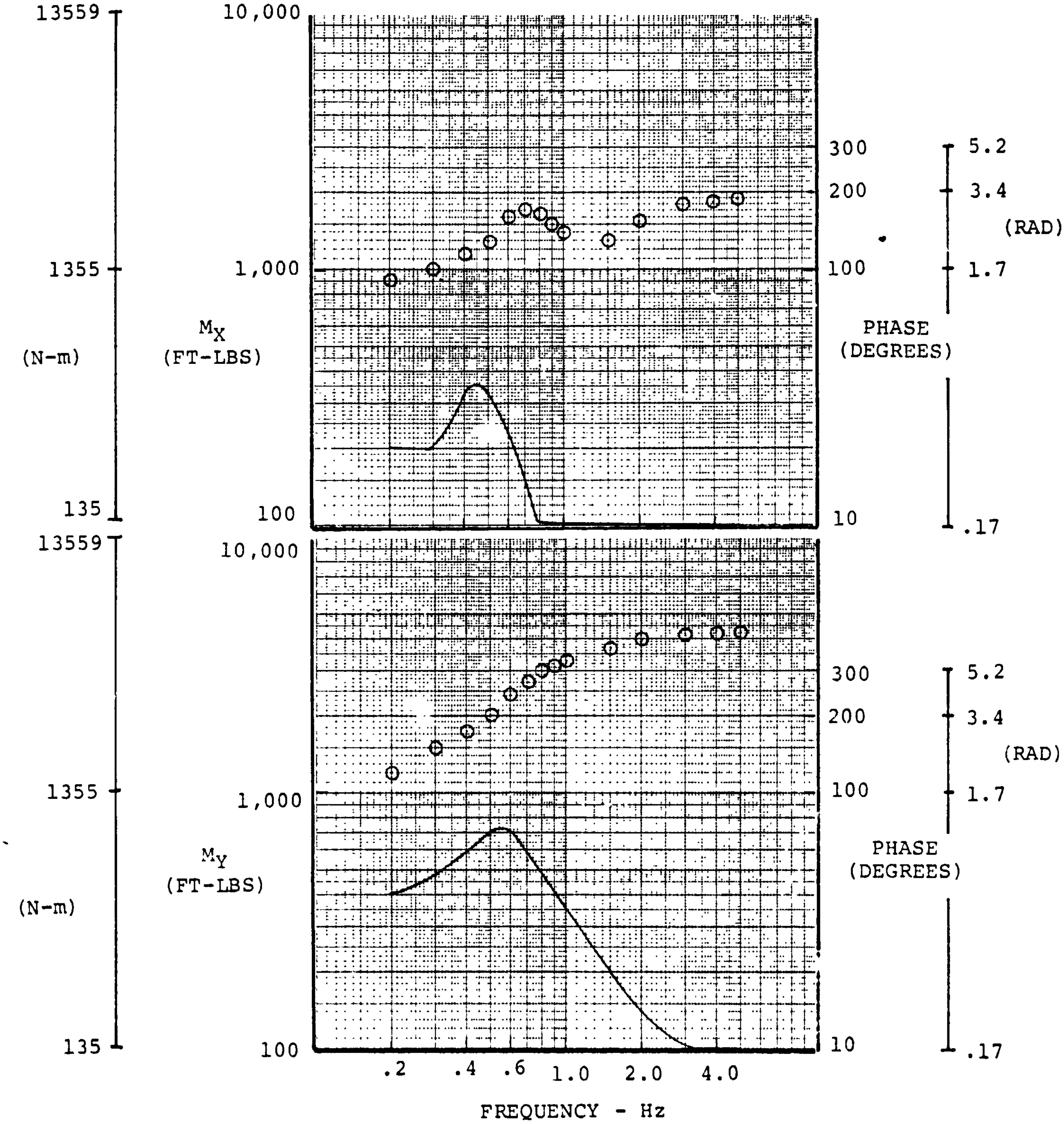

FIGURE B-33. FREQUENCY RESPONSE OF HUB MOMENTS DUE TO δ_F (240 KNOTS, 3049 METERS, AFT CG)

240 KNOTS, 3049M (10,000 FEET), AFT CG

$\delta_e = \pm .5°$ D210-11231-1

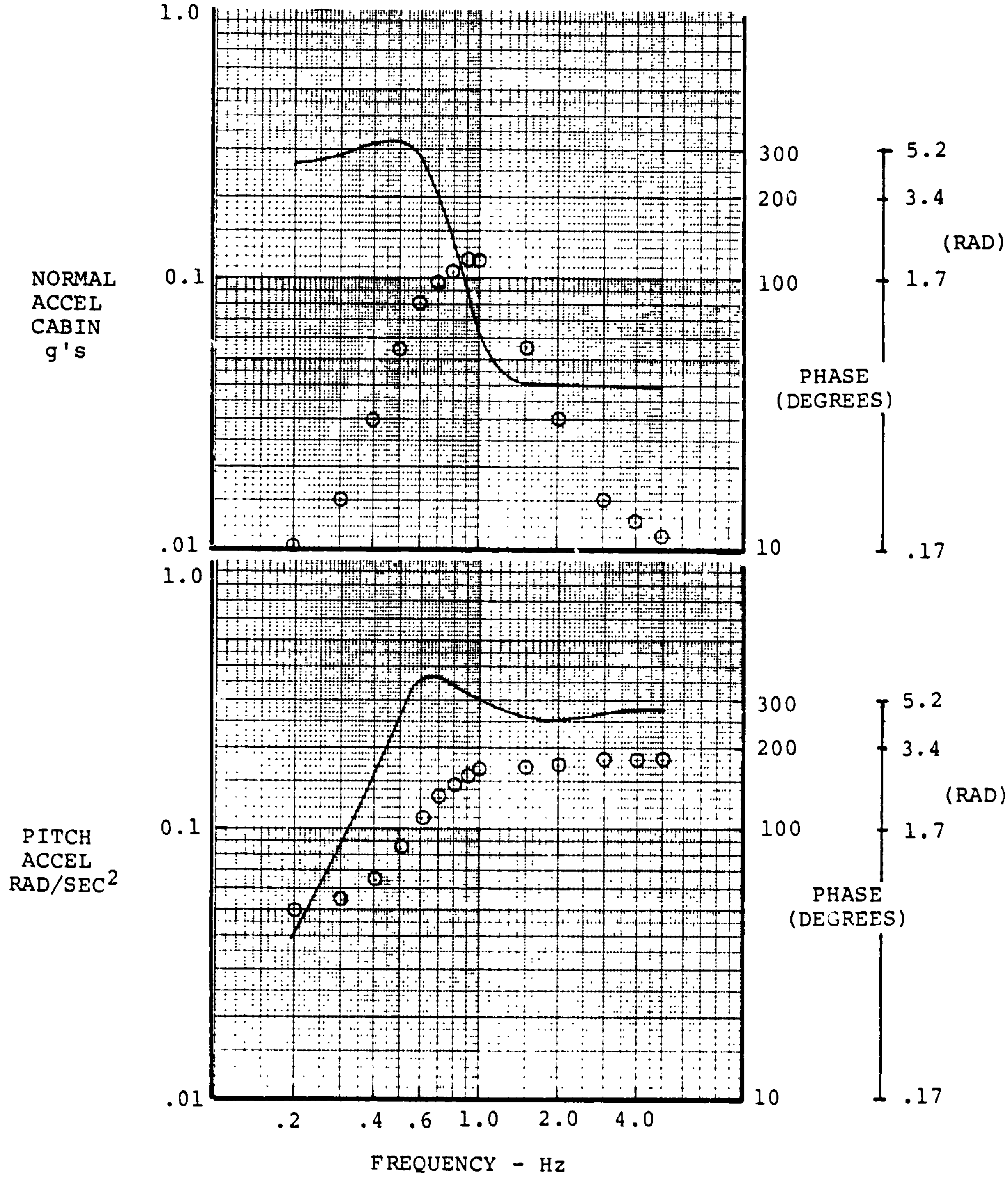

FIGURE B-34. FREQUENCY RESPONSE OF NORMAL AND PITCH ACCELERATION DUE TO δ_e (240 KNOTS, 3049 METERS, AFT CG)

240 KNOTS, 3049M (10,000 FEET), AFT CG

$\delta_e = \pm .5°$ D210-11231-1

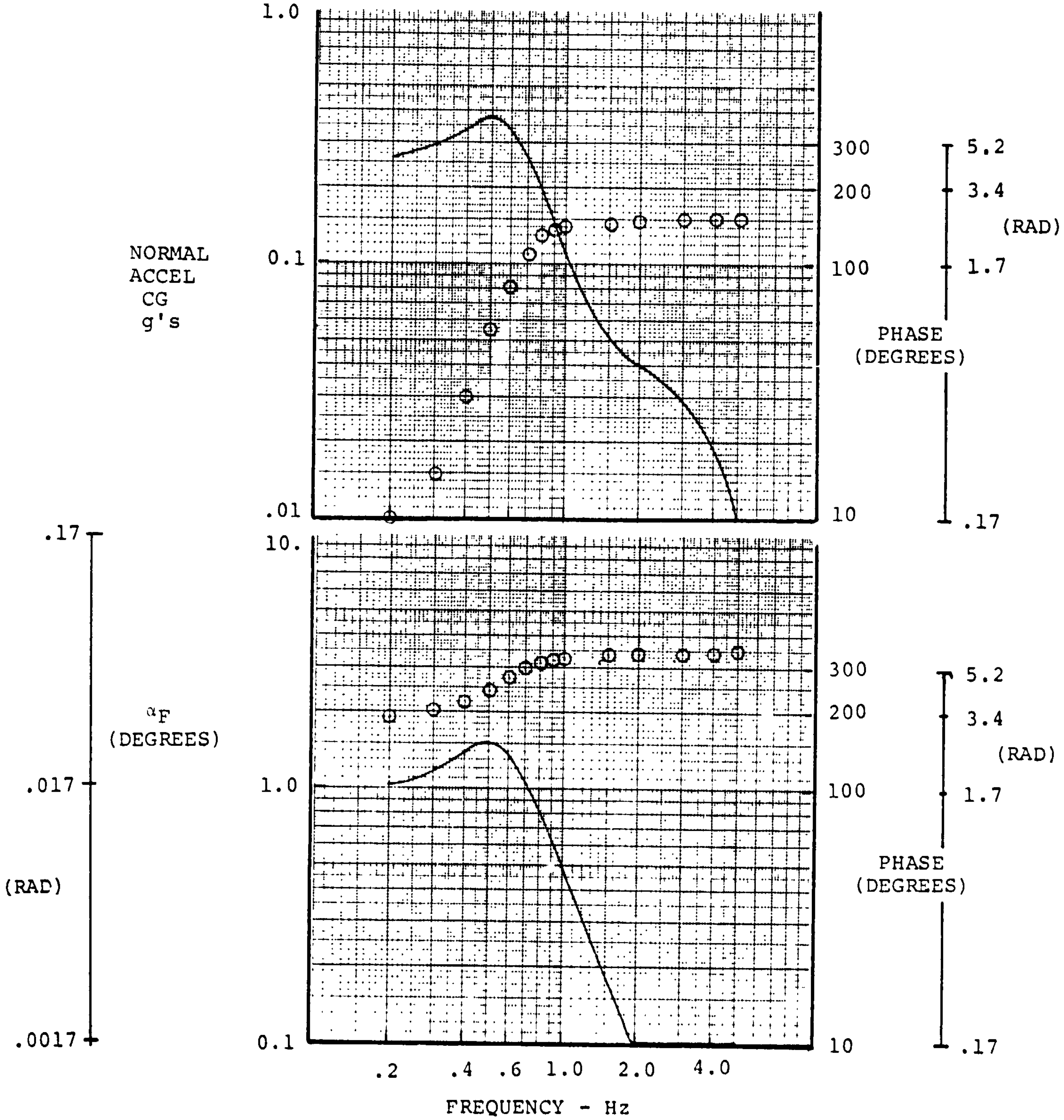

FIGURE B-35. FREQUENCY RESPONSE OF NORMAL ACCELERATION AT CG AND FUSELAGE ANGLE OF ATTACK DUE TO δ_e (240 KNOTS, 3049 METERS, AFT CG)

240 KNOTS, 3049M (10,000 FEET), AFT CG
$\delta_e = \pm .5°$

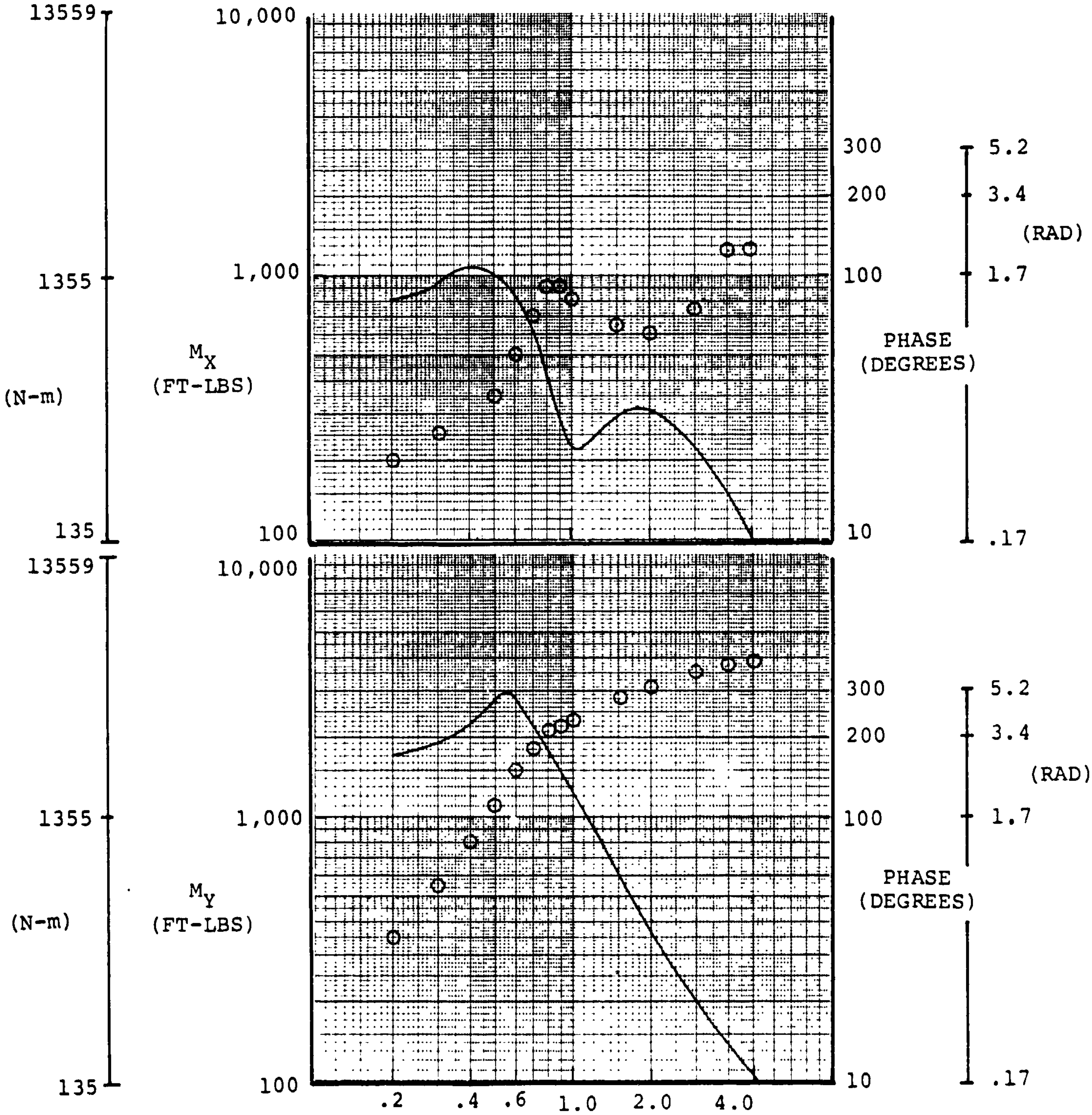

FIGURE B-36. FREQUENCY RESPONSE OF HUB MOMENTS DUE TO δ_e (240 KNOTS, 3049 METERS, AFT CG)

240 KNOTS, 3049M (10,000 FEET), AFT CG
$\delta A_1 = \pm .25°$

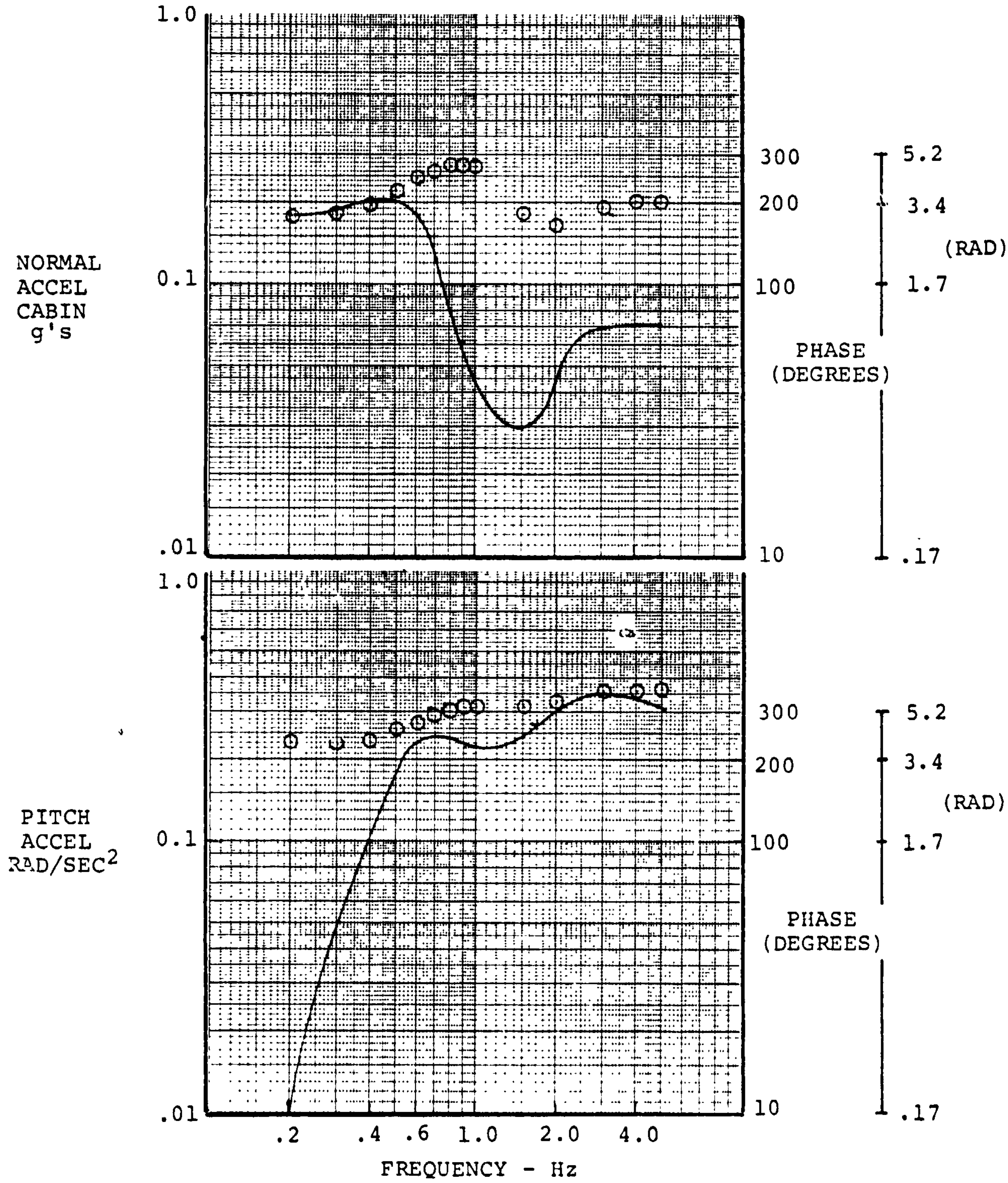

FIGURE B-37. FREQUENCY RESPONSE OF NORMAL AND PITCH ACCELERATION DUE TO A_1 CYCLIC (240 KNOTS, 3049 METERS, AFT CG)

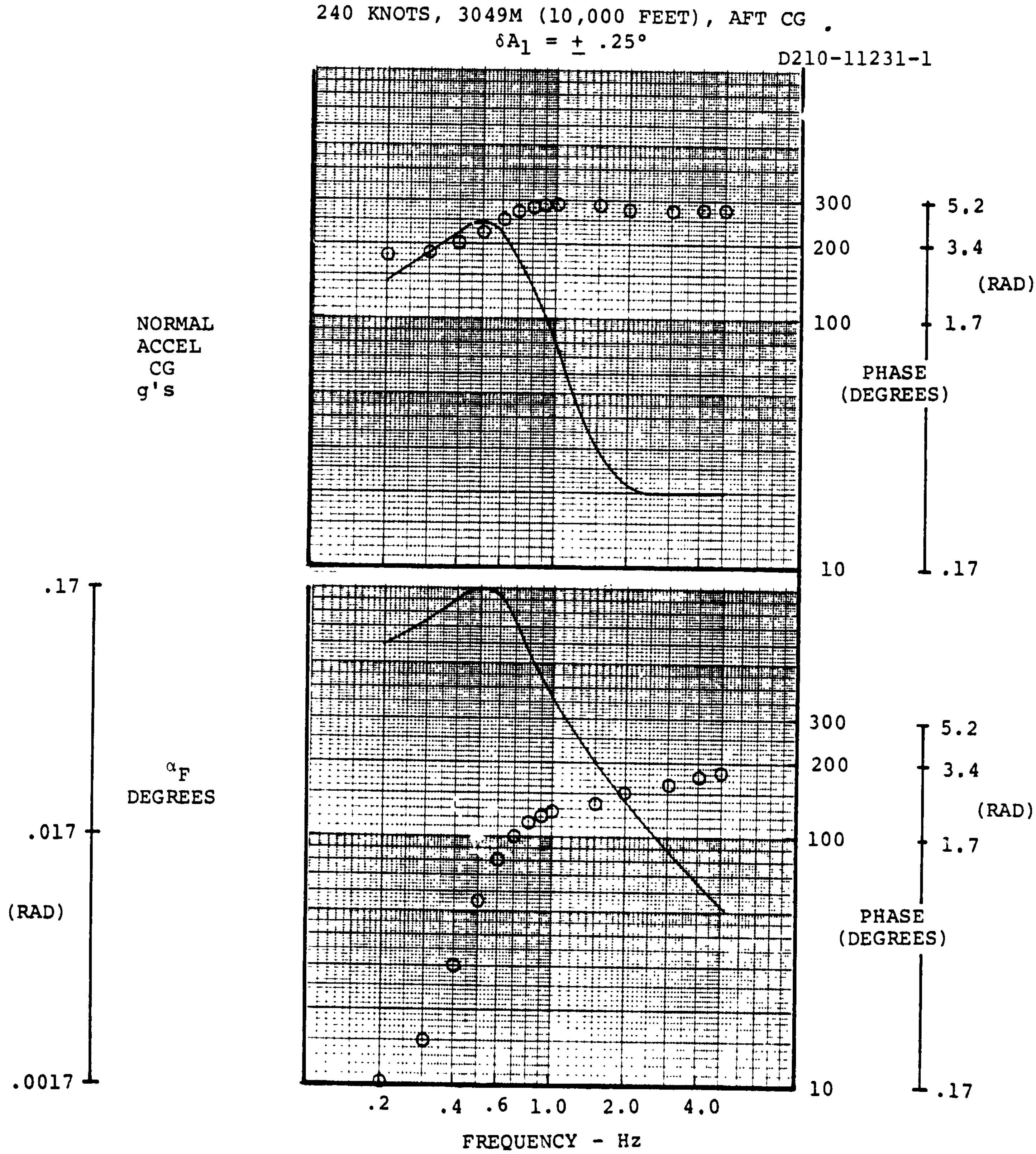

FIGURE B-38. FREQUENCY RESPONSE OF NORMAL ACCELERATION AT CG AND FUSELAGE ANGLE OF ATTACK DUE TO A_1 CYCLIC (240 KNOTS, 3049 METERS, AFT CG)

240 KNOTS, 3049M (10,000 FEET), AFT CG

$\delta A_1 = \pm .25°$

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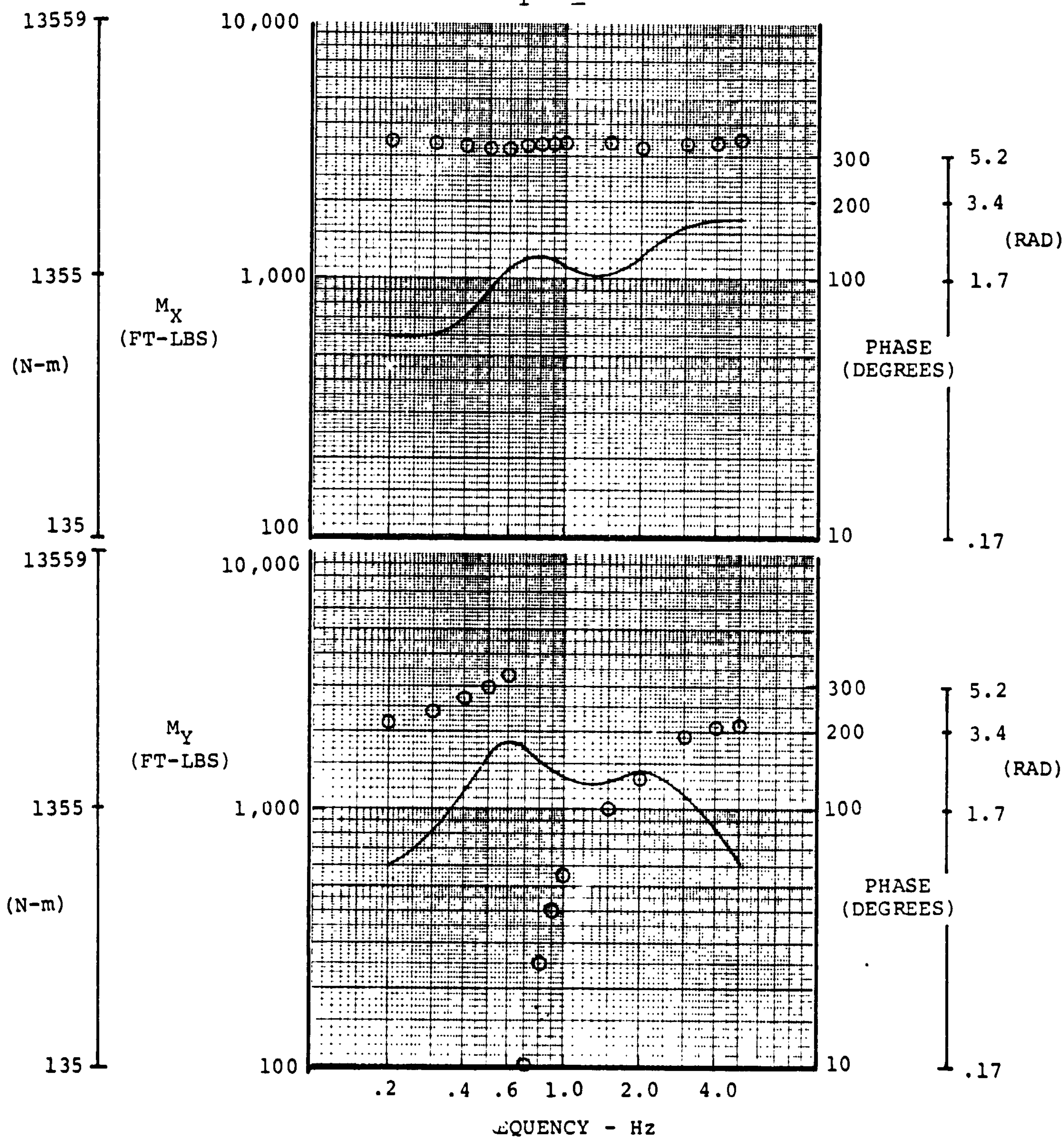

FIGURE B-39. FREQUENCY RESPONSE OF ROTOR HUB MOMENTS DUE TO A_1 CYCLIC (240 KNOTS, 3049 METERS, AFT CG)

240 KNOTS, 3049M (10,000 FEET), AFT CG

$\delta B_1 = \pm .25°$

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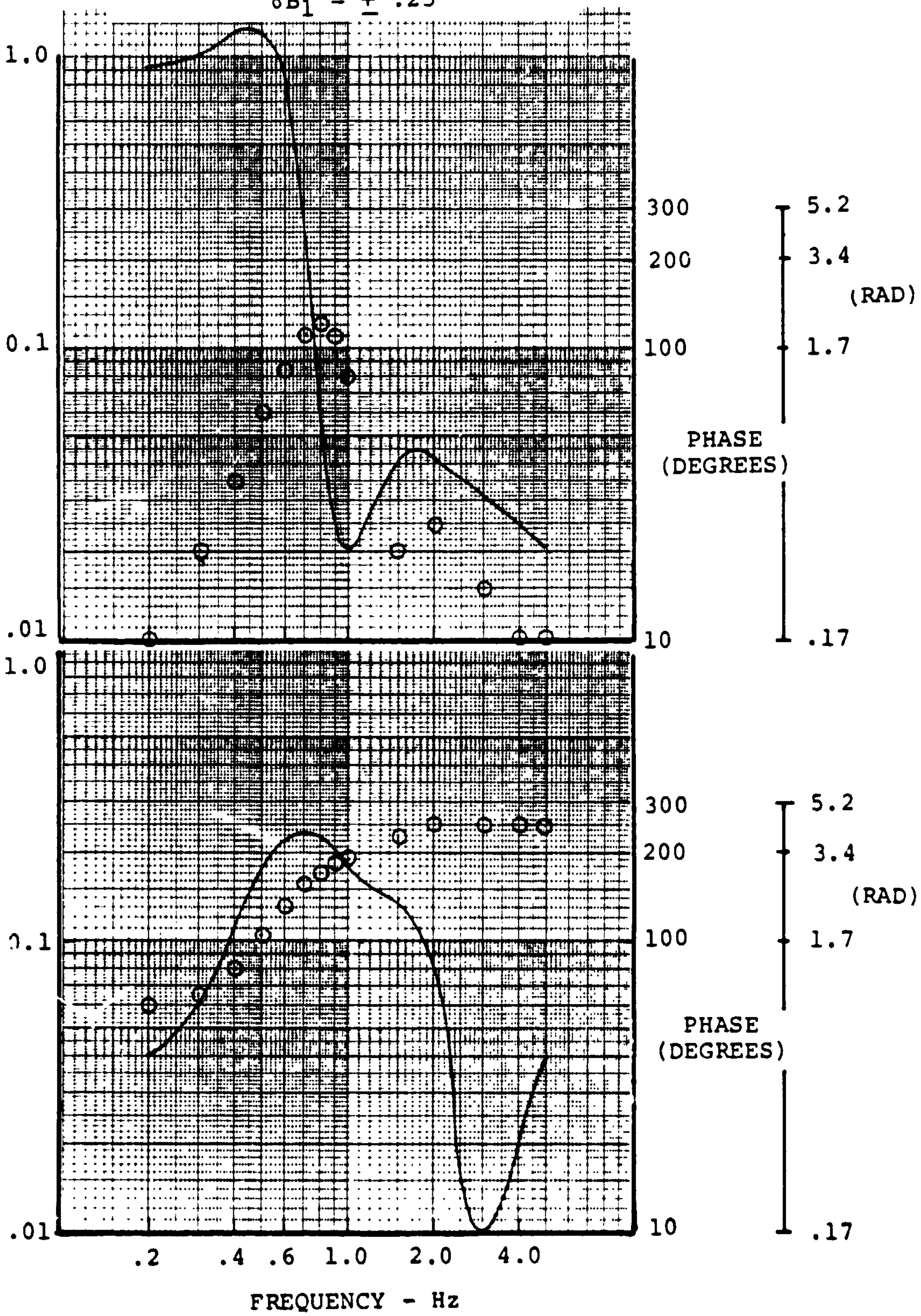

FIGURE B-40. FREQUENCY RESPONSE OF NORMAL AND PITCH ACCELERATION DUE TO B_1 CYCLIC (240 KNOTS, 3049 METERS, AFT CG)

240 KNOTS, 3049M (10,000 FEET), AFT CG
$\delta B_1 = \pm .25°$ D210-11231-1

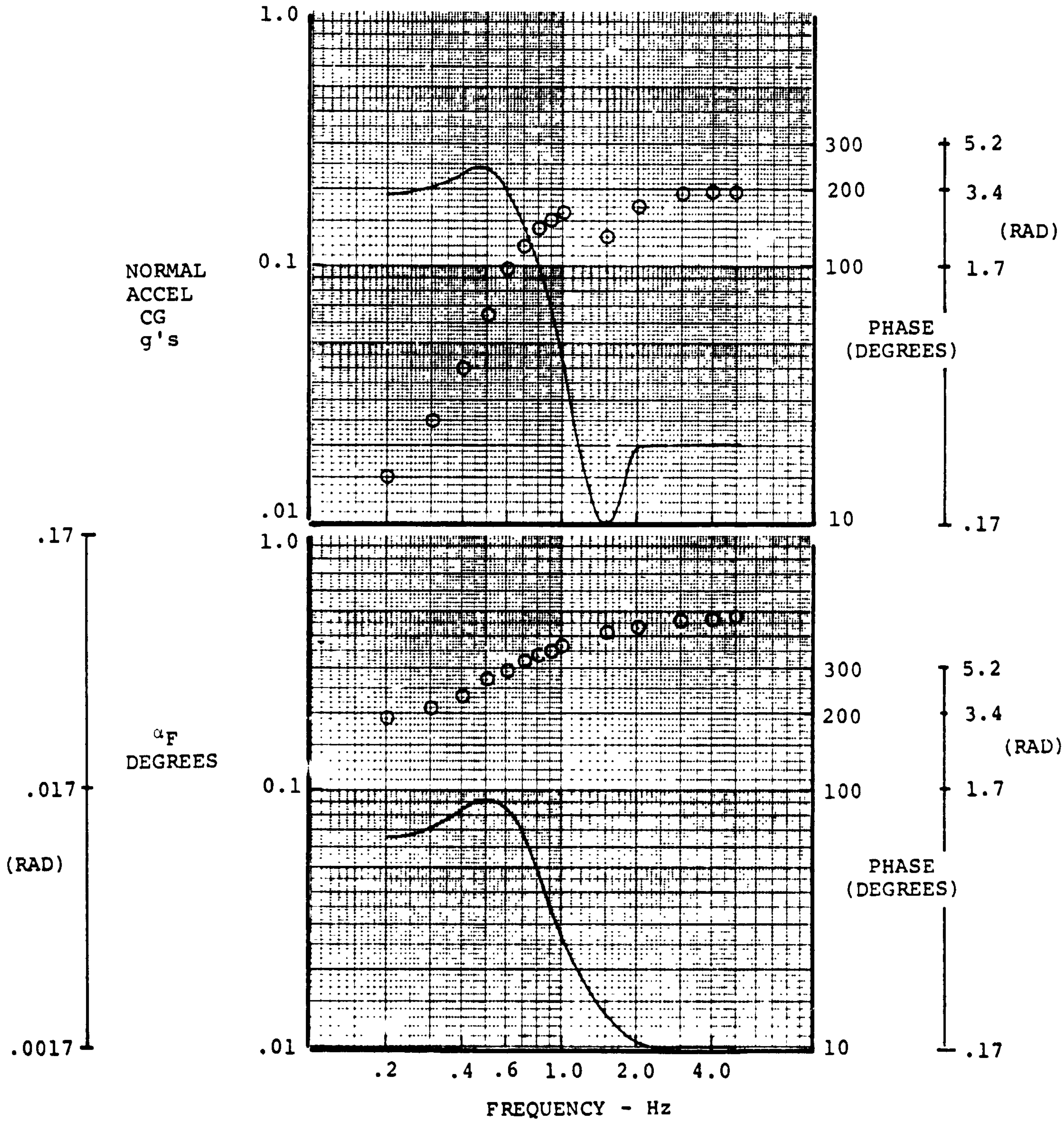

FIGURE B-41. FREQUENCY RESPONSE OF NORMAL ACCELERATION AT CG AND FUSELAGE ANGLE OF ATTACK DUE TO B_1 CYCLIC (240 KNOTS, 3049 METERS, AFT CG)

240 KNOTS, 3049M (10,000 FEET), AFT CG
$\delta B_1 = \pm .25°$

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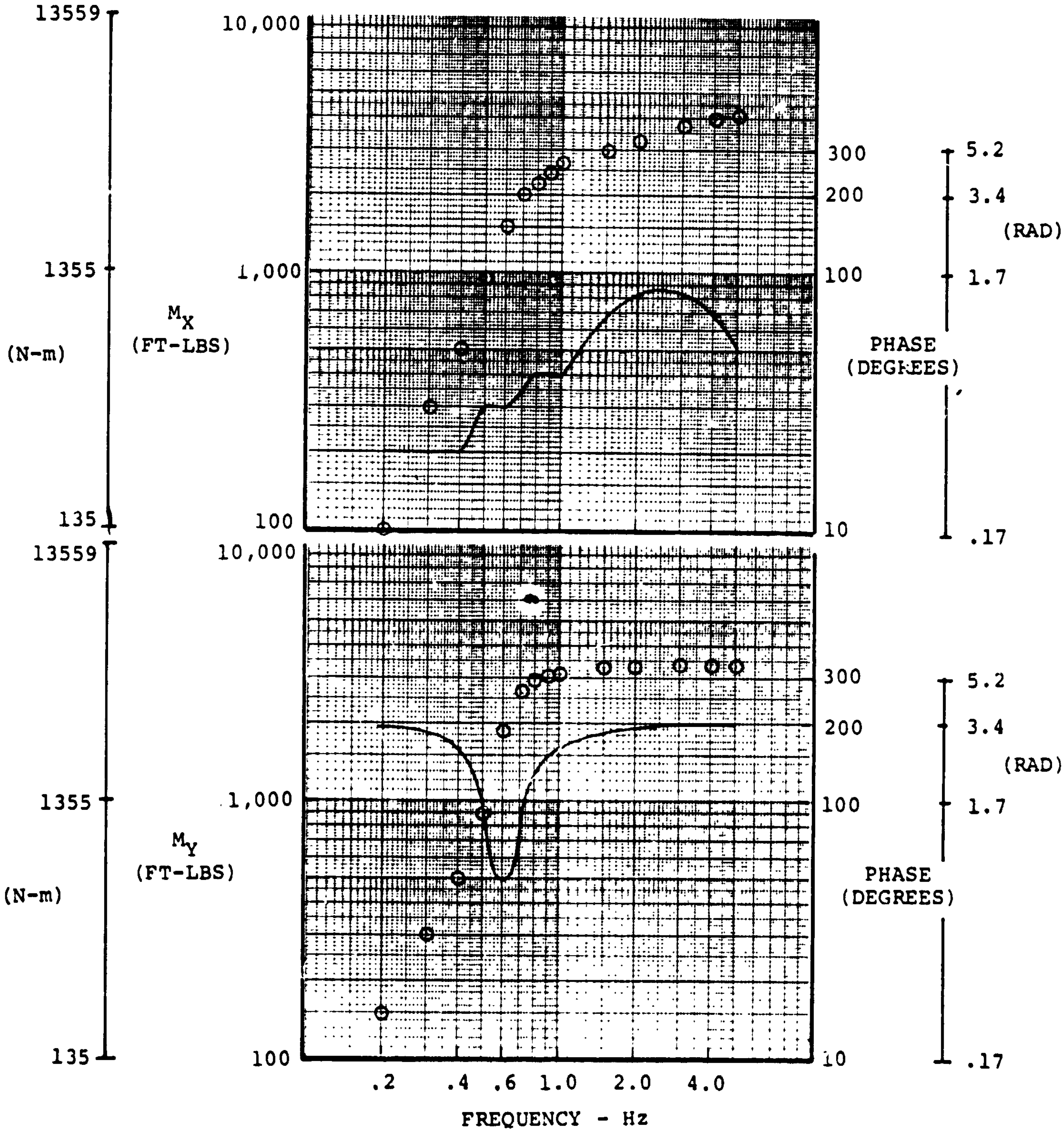

FIGURE B-42. FREQUENCY RESPONSE OF ROTOR HUB MOMENTS DUE TO B_1 CYCLIC (240 KNOTS, 3049 METERS, AFT CG)

FEEDBACK REQUIRED FOR SPECIFIED ALLEVIATION IN CABIN

240 KNOTS, 10,000 FEET (3049M), AFT CG

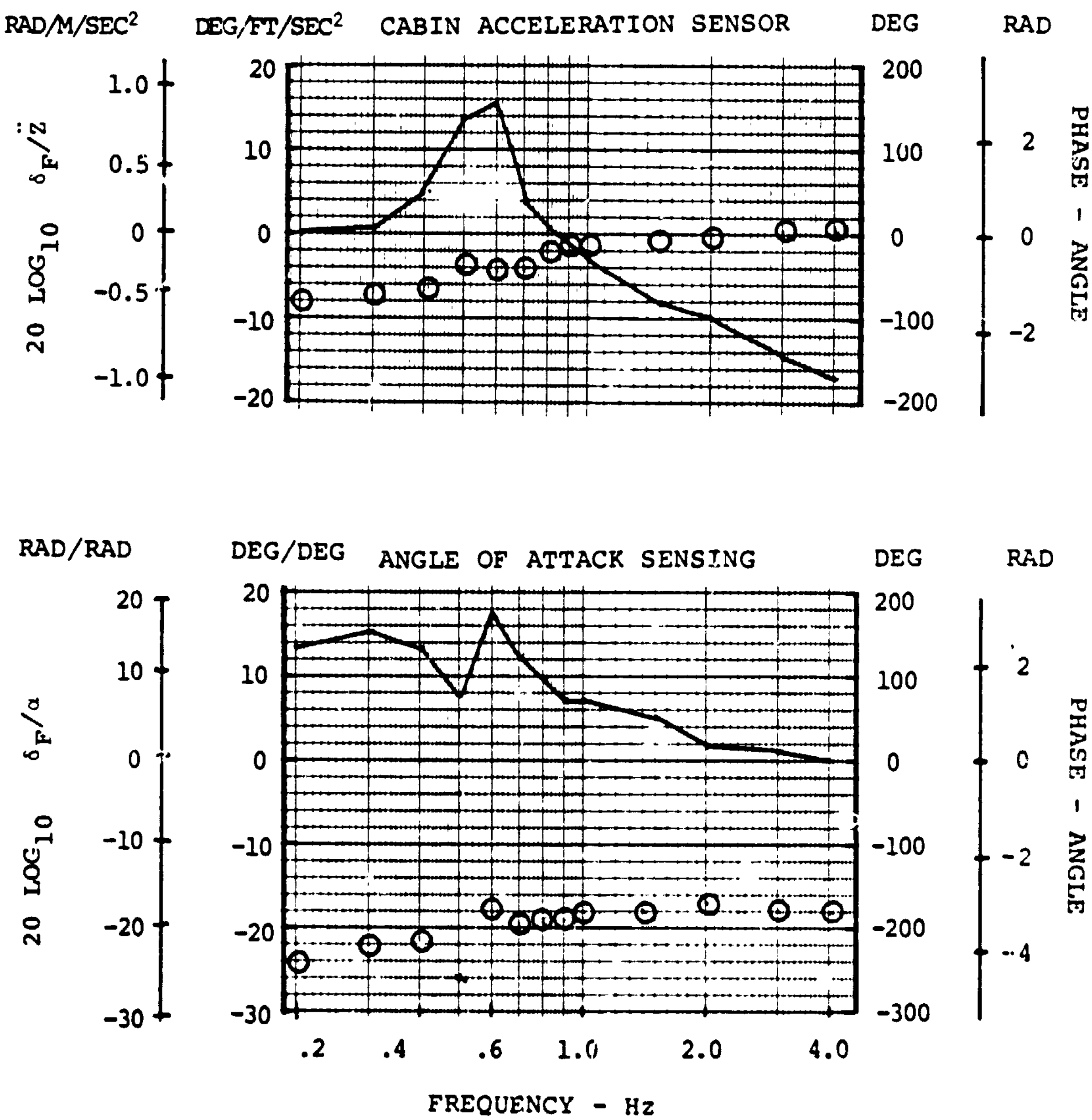

FIGURE B-43. FLAP FEEDBACK REQUIRED WITH ACCELERATION AND α SENSING RESPECTIVELY, 240 KNOTS 3049 METERS, AFT CG, NO A_1, B_1 FEEDBACK

FEEDBACK REQUIRED FOR SPECIFIED ALLEVIATION IN CABIN

240 KNOTS, 10,000 FEET (3049M), AFT CG

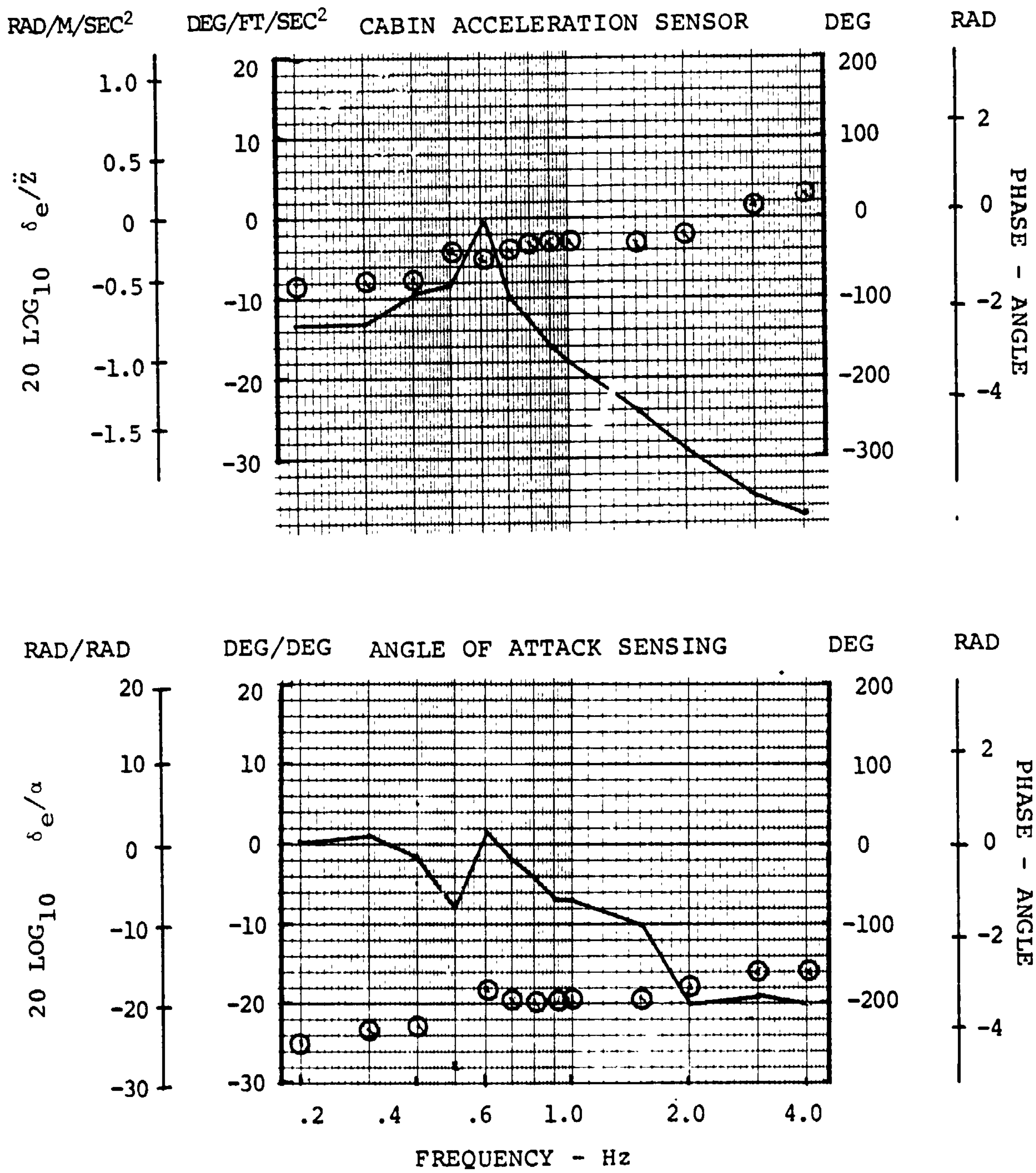

FIGURE B-44. ELEVATOR FEEDBACK REQUIRED WITH ACCELERATION AND α SENSING RESPECTIVELY, 240 KNOTS, 3049 METERS, AFT CG, NO A_1, B_1 FEEDBACK

FEEDBACK REQUIRED FOR SPECIFIED ALLEVIATION IN CABIN

240 KNOTS, 10,000 FEET (3049M), AFT CG

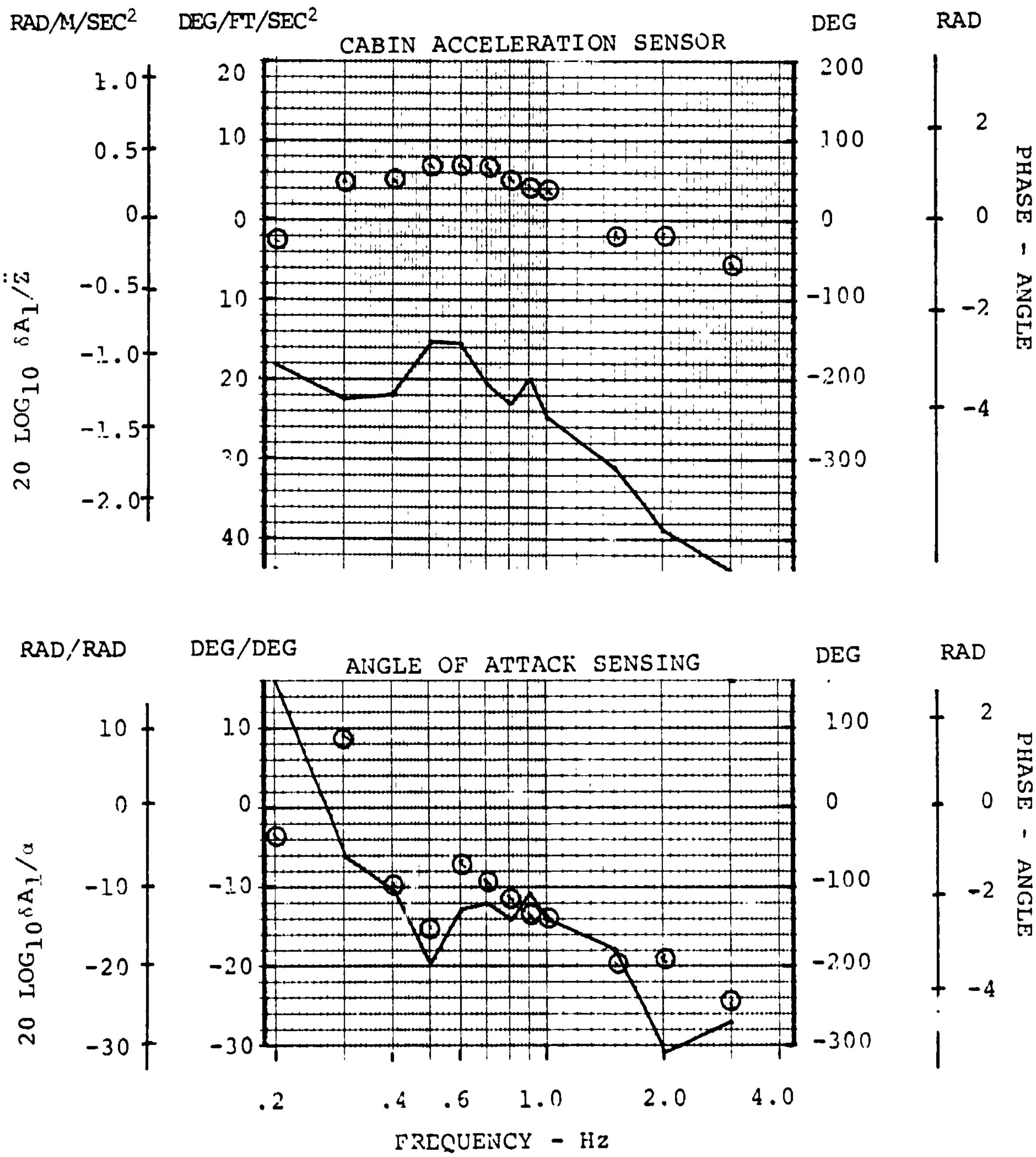

FIGURE B-45. A1 FEEDBACK REQUIRED WITH ACCELERATION AND α SENSING RESPECTIVELY, 240 KNOTS, 3049 METERS, AFT CG

FEEDBACK REQUIRED FOR SPECIFIED ALLEVIATION IN CABIN

240 KNOTS, 10,000 FEET (3049M), AFT CG

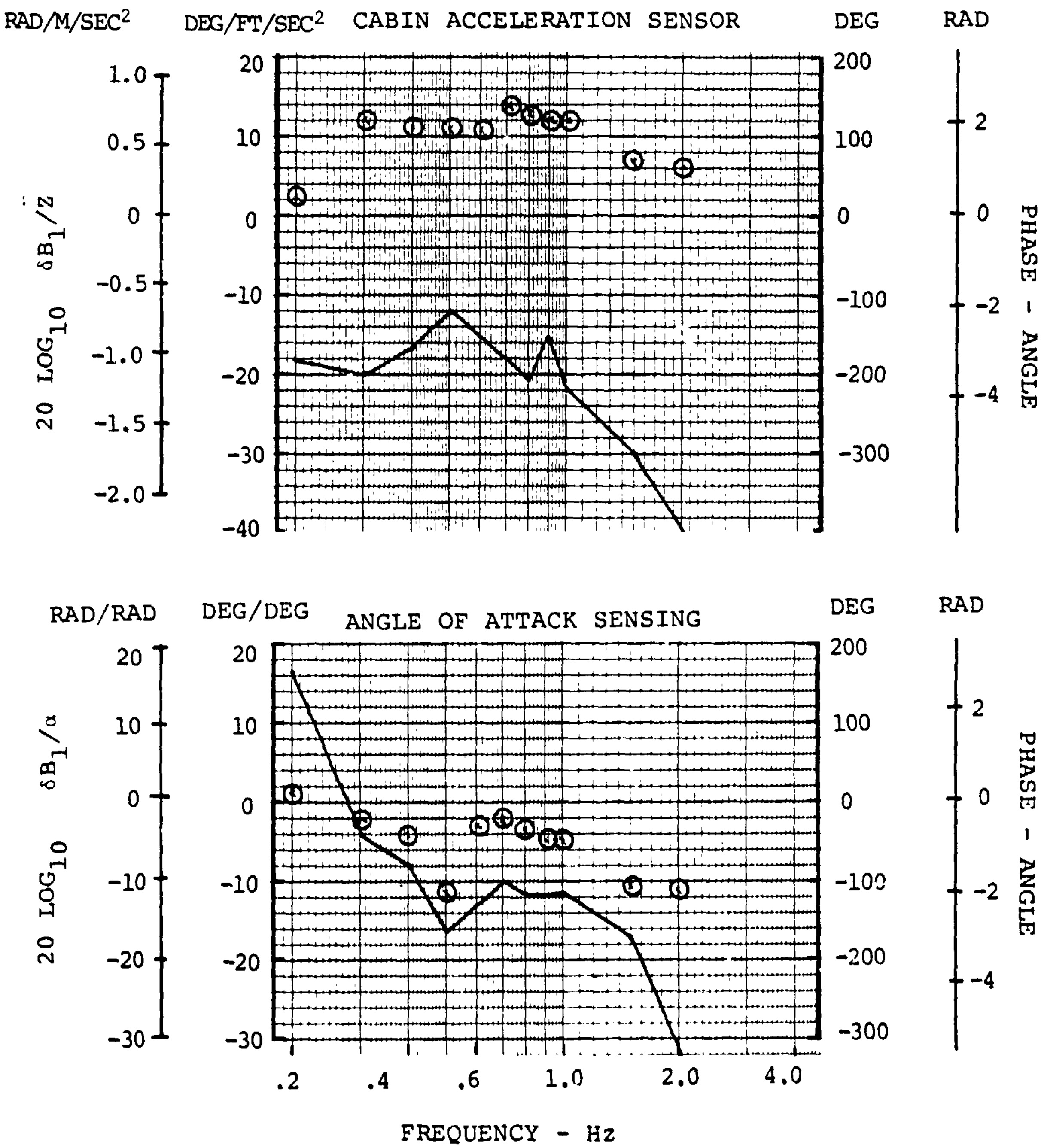

FIGURE B-46. B_1 FEEDBACK REQUIRED WITH ACCELERATION AND α SENSING RESPECTIVELY, 240 KNOTS, 3049 METERS, AFT CG

FEEDBACK REQUIRED FOR SPECIFIED ALLEVIATION IN CABIN

240 KNOTS, 10,000 FEET (3049M), AFT CG

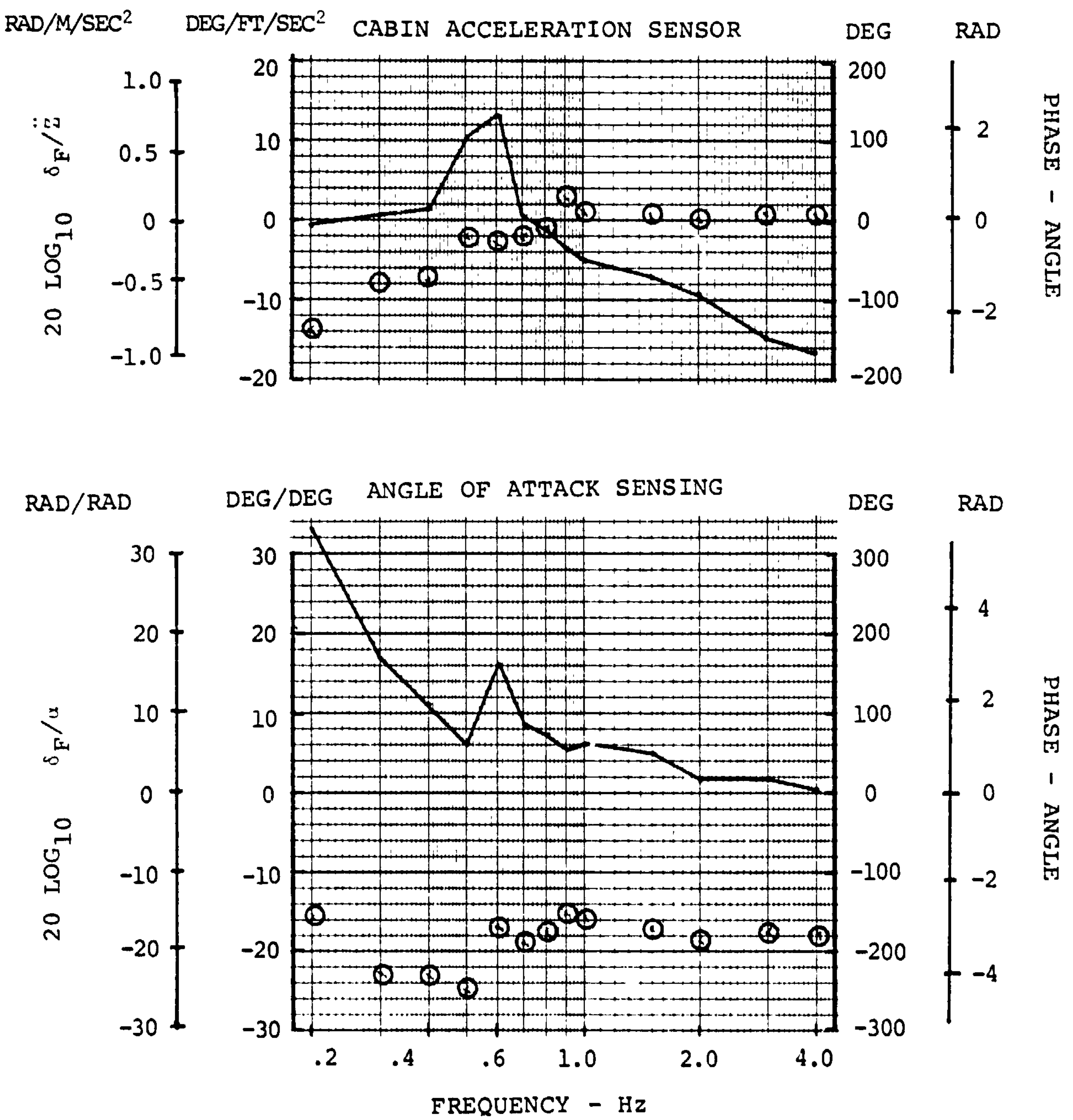

FIGURE B-47. FLAP FEEDBACK REQUIRED WITH ACCELERATION AND α SENSING RESPECTIVELY, 240 KNOTS, 3049 METERS, AFT CG, A_1 & B_1 FEEDBACK

FEEDBACK REQUIRED FOR SPECIFIED ALLEVIATION IN CABIN

240 KNOTS, 10,000 FEET (3049M), AFT CG

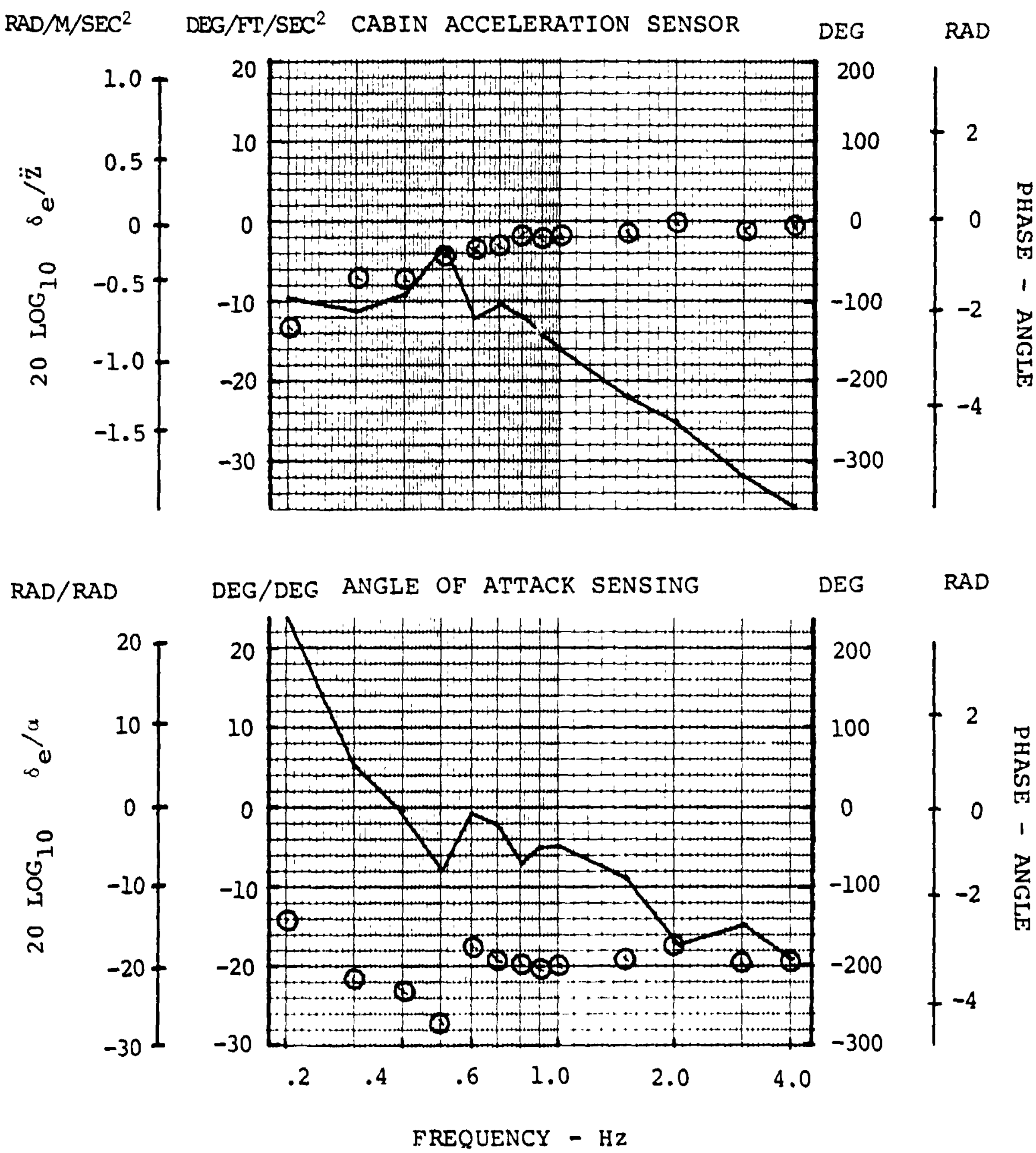

FIGURE B-48. ELEVATOR FEEDBACK REQUIRED WITH ACCELERATION AND α SENSING RESPECTIVELY, 240 KNOTS, 3049 METERS, AFT CG, A_1 & B_1 FEEDBACK

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FLIGHT CONDITION: 240 KNOTS, 10,000 FEET, (3,049m), AFT CG

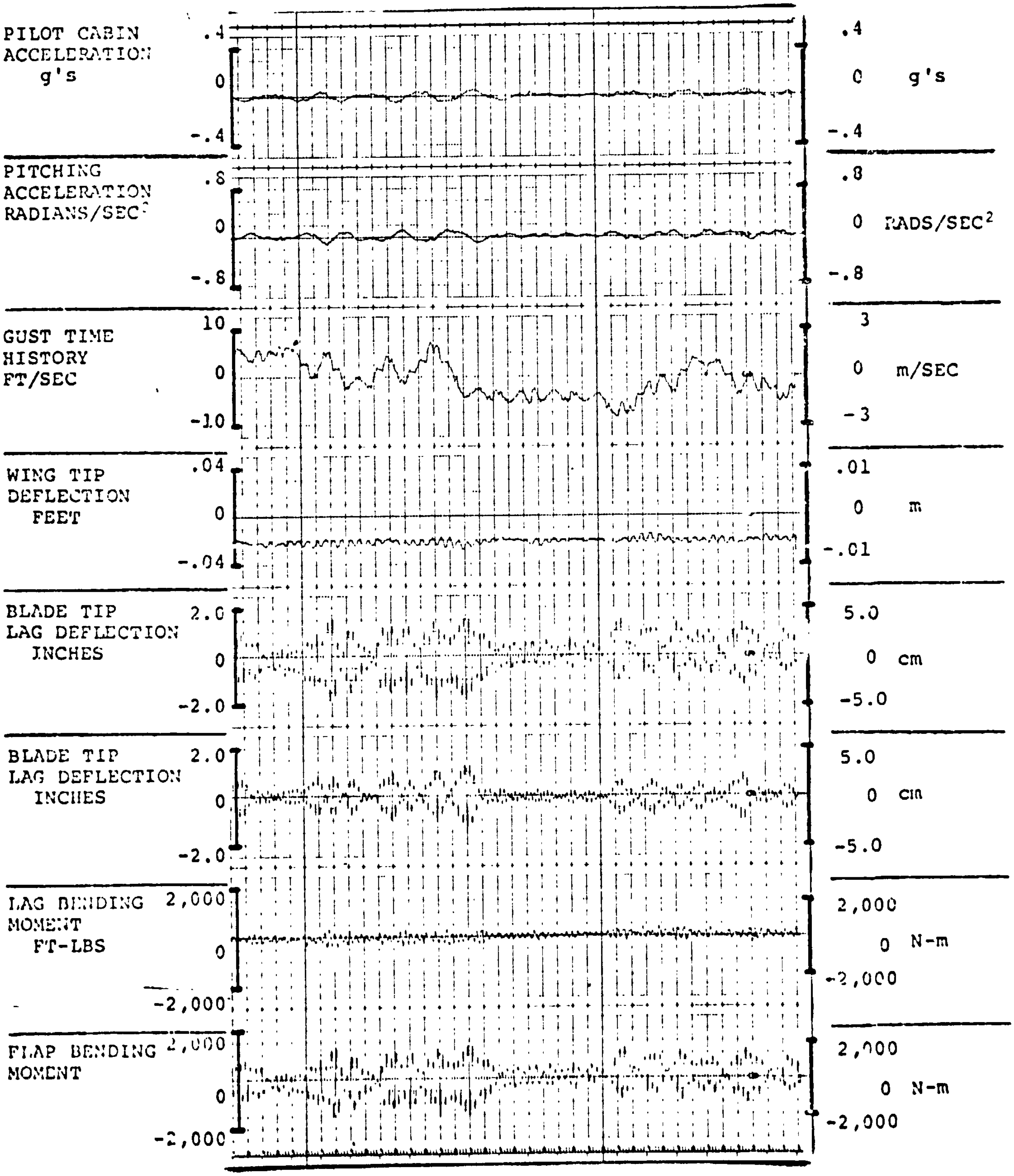

FIGURE B-49. RESPONSES FOR GAIN F = 4.0, GAIN E = .6

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FLIGHT CONDITION: 240 KNOTS, 10,000 FEET, (3,049m), AFT CG

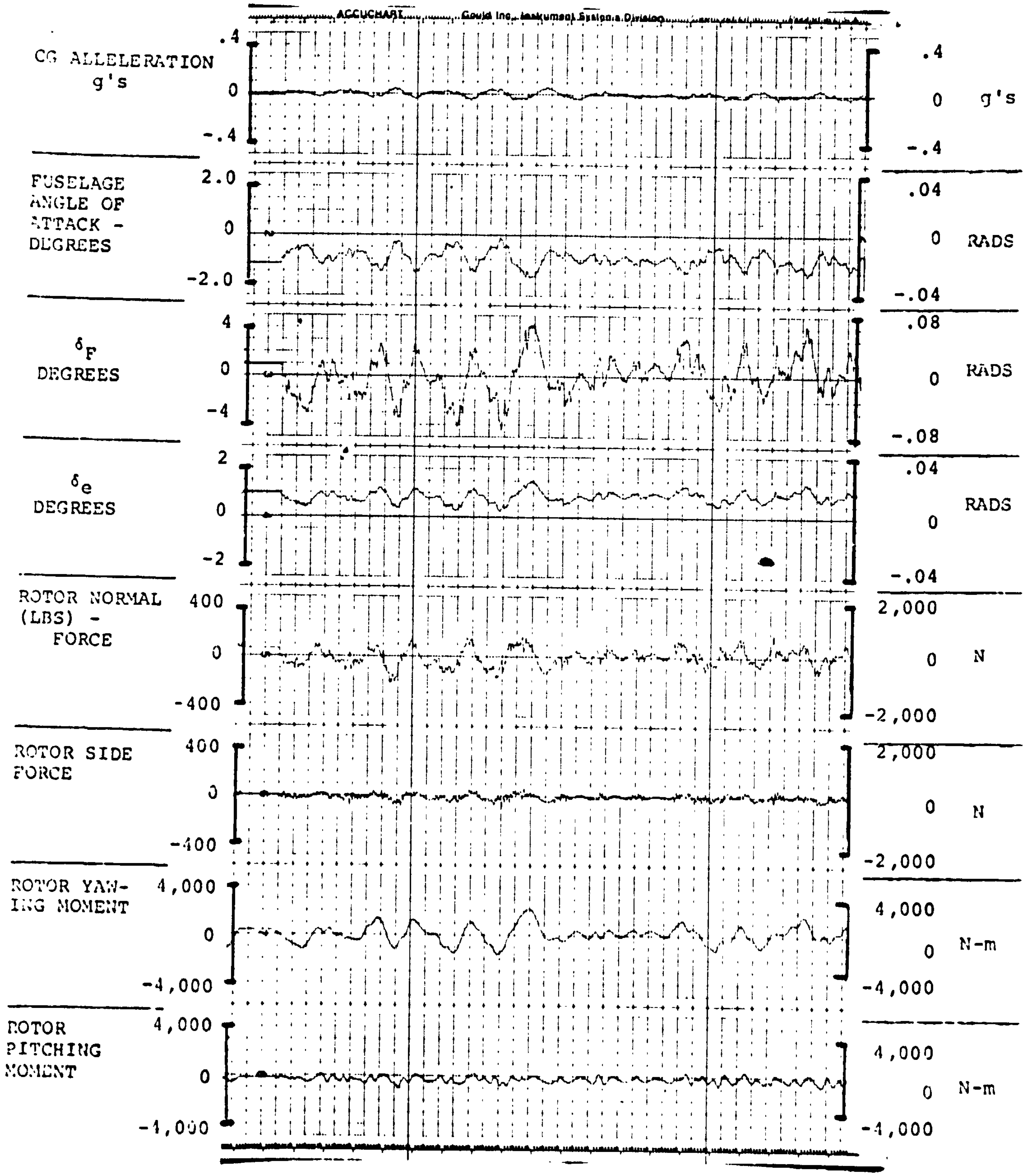

FIGURE B-50. RESPONSES FOR GAIN F = 4.0, GAIN E = .6

FLIGHT CONDITION: 240 KNOTS, 10,000 FEET, (3,049m), AFT CG

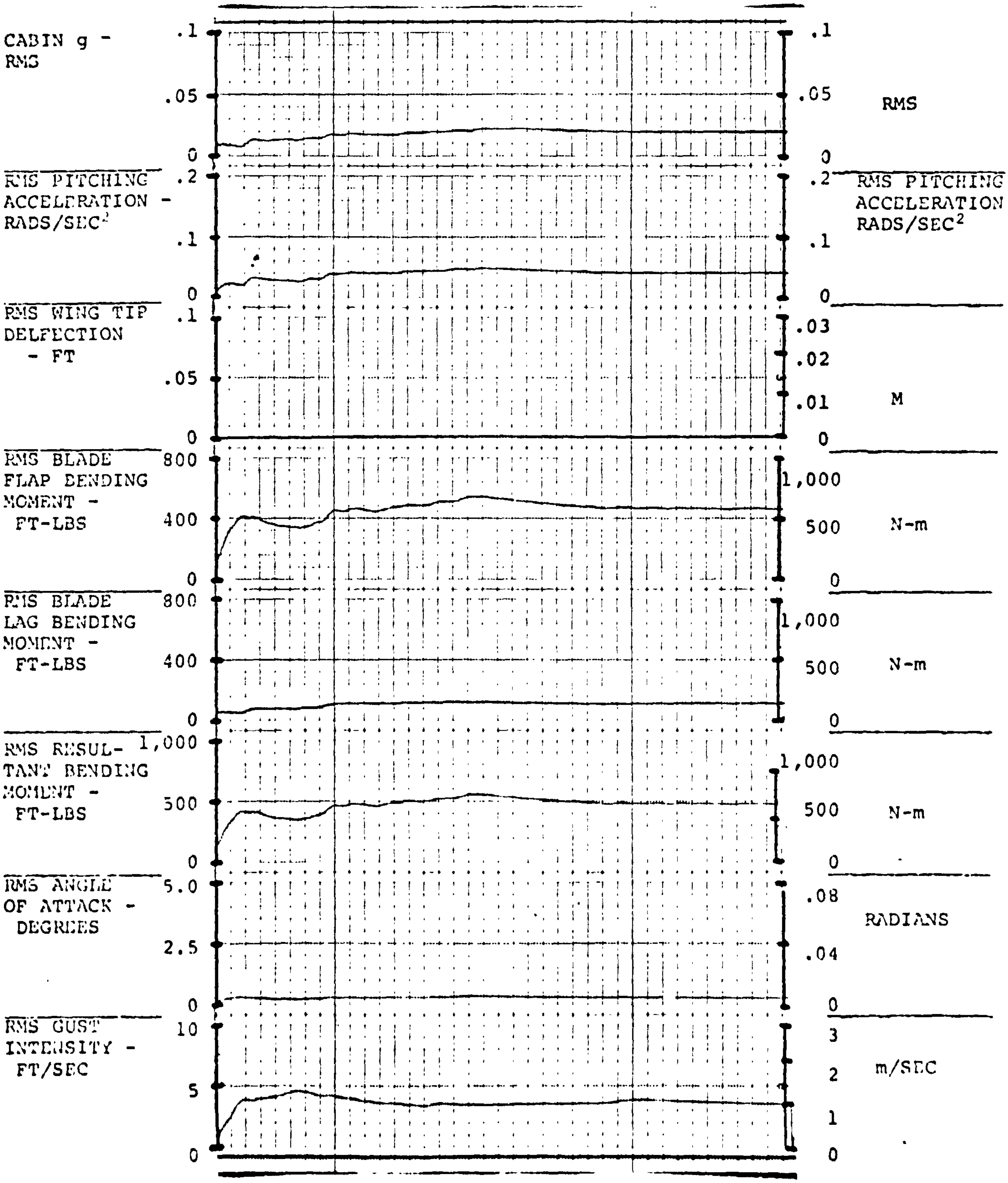

FIGURE B-51. RESPONSES FOR GAIN F = 4.0, GAIN E = .6