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NASA Technical Memorandum 85758

PROPOSED INPUT FOR DETERMINING LONGITUDINAL AERODYNAMIC PARAMETERS FOR THE SPACE SHUTTLE

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OCTOBER 1984

National Aeronautics and
Space Administration

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SUMMARY

A control input form to improve the identification of longitudinal aerodynamic parameters for the Space Shuttle, especially at low Mach numbers, has been proposed. This input combines features of several inputs currently used with the Shuttle to improve the response in angle-of-attack without exceeding pitch rate limits. The responses of the proposed input were generated using a simple three-degree-of-freedom simulation. An examination of the power spectral densities of these responses showed them to have more power near the vehicle natural frequency than doublet inputs previously used with the Shuttle.

When the responses to the proposed input were corrupted with noise and processed using a maximum likelihood parameter extraction program, the identifiability of the parameters was improved over the identifiability of the same parameters using actual Shuttle responses from doublet inputs of a similar magnitude. This preliminary study indicates that the proposed inputs form should result in improved identifiablity of longitudinal static and control parameters for the Shutttle vehicle.

INTRODUCTION

The identification of the longitudinal aerodynamic parameters of the Space Shuttle has been a limited effort because very few longitudinal maneuvers suitable for parameter extraction have been performed. In some of the more recent flights, doublet or pulse-type inputs have been used to excite the longitudinal modes. These maneuvers have been reasonably good for determining control derivatives, but because of the limited vehicle response allowed by safety constraints, the angle-of-attack derivatives have not been as consistent as desired.

At high Mach numbers several pull-up-push-over type maneuvers were performed and these seemed to give reasonable convergence of the parameter extraction algorithms and fair determination of the angle-of-attack derivatives. However, these maneuvers required 30 to 40 seconds and are too long to be used at the lower Mach numbers. A possible maneuver which would be usable at all Mach numbers and would be a combination of some of the features of both the doublet and pull-up-push-over type maneuvers will be considered. The purpose of this paper is to examine some of the characteristics of the two types of maneuvers in question and to use the information obtained to try to design a longitudinal maneuver to give good definition of the control and static stability derivatives when the vehicle responses to this maneuver are processed using parameter extraction algorithms.

SYMBOLS

Values are given in U.S. customary units.

a_x	acceleration along x-body axis, "G" units
a_z	acceleration along z-body axis, "G" units
M_Y	reaction control system moment about Y-body axis, ft-lbs
q	rate of pitch, rad/sec or deg/sec
$\|S_q\|$	power spectral density of the rate of pitch, $(\text{deg/sec})^2$ sec
$\|S_\alpha\|$	power spectral density of the angle-of-attack, $(\text{deg})^2$ sec
$\|S_{\delta_e}\|$	power spectral density of the elevon deflection, $(\text{deg})^2$ sec
α	angle-of-attack, rad or deg
β	angle-of-sideslip, rad or deg
θ	pitch angle, rad or deg
δ_e	elevon deflection, rad or deg

Examination of Sample Inputs

Four longitudinal inputs were chosen from some recent Shuttle flights to examine the features that are useful in parameter extraction. These maneuvers, two pull-up-push-over (PUPO) and two doublets (table 1), were used to generate the vehicle responses that gave good parameter definition. These inputs were chosen because they had rapid control deflections of reasonable magnitude and the vehicle responses resulted in fair identifiability of the static and control parameters. Figures 1 and 2 show the PUPO maneuvers and figures 3 and 4 show the doublet maneuvers. The PUPO maneuvers generally had angle-of-attack variations and z-body accelerations that were relatively large, but occurred over a span of about 20 seconds. Because the maneuvers were slow, the maximum pitch rate was less than ± 2 degrees/second. Also, at several times during the maneuvers there were elevon pulses with magnitudes in the order of 4 to 6 degrees which enabled the identification of the control derivatives.

The doublets had rapid elevon inputs of about ± 5 degrees with the elevon rate close to the maximum possible for the Shuttle. The two inputs chosen to illustrate the doublet maneuver had similar peak-to-peak variations but the responses were less in the case shown as figure 4. Since the dynamic pressures were similar for the two runs, the primary difference seemed to be that the elevon deflection went trailing-edge down first, then trailing-edge up for the case shown in figure 3. This sequence resulted in a greater response than where the elevon sequence was reversed as in figure 4.

The next step in the investigation of the inputs was to look at the power spectra of the input for the angle-of-attack and pitch rate responses. The power spectra for the example cases are shown as figures 5 through 8. Of interest is the power at frequencies close to the natural frequency of the short period mode for the Shuttle vehicle. Using an approximate expression for this frequency, it was found to vary between 5 to 10 seconds per cycle in the Mach 2 to Mach .6 range. Therefore, we are interested in the power in the .1 to .2 Hertz range.

As can be seen from figures 5 and 6, the greatest power for the PUPO maneuver was at frequencies below the short period frequencies of .1 to .2 Hertz. However, in the .1 to .2 Hertz frequency range, the PUPO maneuvers still had as much power as the doublet maneuvers discussed in this paper. Figures 7 and 8 show that in spite of the fact that the spectra of the doublet input shows a dual frequency of .45 and .7 Hertz for input 3, and of .32 and .6 Hertz for input 4, the maximum power for the responses to these inputs still occurs around .2 Hertz. Table II summarizes these conclusions from figures 5 through 8.

Extraction of Parameters

The parameter extraction program used to examine the Shuttle data generates, in addition to parameter values, parameter sensitivities and Cramer-Rao bounds (ref. 1). The sensitivities indicate which parameters can be most easily extracted, and the Cramer-Rao bound is an indication of how well the program has determined a specific parameter value. By using these indicators of parameter identifiability, the suitability of different inputs to generate data for parameter extraction can be assessed (ref. 2).

Table III shows the sensitivities and the Cramer-Rao bounds of each parameter extracted. In all cases the fit to the data was good with a difference between the estimated and the measured time histories of less than two percent of the peak-to-peak value of the measured responses. Since the parameters that are being estimated describe the short period mode of the vehicle, responses in the .1 to .2 Hertz range have the most influence on the identifiability of these parameters. The extra power seen in the PUPO-type maneuvers (table II) only increased the identifiability of C_{m_α} when compared with the doublet where the elevon went trailing edge down initially (maneuver 3). Overall, the limited response from the rapid doublet-type input is almost as effective for parameter extraction as the large response from the PUPO maneuvers. Since the latter maneuvers can only be performed at the higher Mach numbers because of the time required to complete them, a modified doublet that would improve the identifiability of C_{m_α} at the lower Mach numbers (Mach < 5) will be designed.

Input Design

Based on the four sample inputs, an elevon input consisting of a rapid input (initially trailing-edge down) to a specified magnitude, followed by a slower reversal to a trailing-edge up position of the same magnitude, and then a rapid return to zero deflection is proposed (fig. 9). Trailing-edge down was chosen as the initial direction for the elevon since this input resulted in greater responses than trailing-edge up initially (figs. 3 and 4). Also, an input performed initially at the maximum elevon rate gives the best change for good identification of the elevon effectiveness. The slower reversal allows the angle-of-attack and acceleration along the z-body axis to build up more than is possible with the standard doublet where the reversal part of the input is fast enough so that the vehicle does not have time to respond. Finally, the rapid return to zero again helps the identification of the control derivative.

The peak values of the input were chosen as ± .1 radian to be compatible with the peak values of the doublets shown as figures 3 and 4. The period of the input initially tried was about 4 seconds to be close to the vehicle natural frequency. The responses shown in figure 9 were obtained with a dynamic pressure typical of the Mach = .6 portion of the descent trajectory. This initial attempt with the modified doublet resulted in responses that exceeded the guidelines for responses to input for the Shuttle. The same input with dynamic pressure typical of the Mach 2 portion of the descent trajectory resulted in reduced responses, but these also exceeded the guidelines (fig. 10).

The most critical response is the maximum pitch rate which should be kept close to ± 3 degrees per second. To get acceptable responses at Mach = .6, the amplitude of the input would have to be reduced to approximately ± .05 radian. This reduced amplitude input with the modified doublet may not give good definitions of the elevon effectiveness. However, an incidental maneuver at Mach = .6 during STS-5 with less peak-to-peak amplitude and having a less rapid initial elevon input (fig. 11) gave sensitivities and Cramer-Rao bounds that implied a good definition of the control derivative.

Maneuvers with dynamic pressures typical of Mach = .6 and Mach = 2 were chosen to illustrate samples of the proposed second modified input. An examination of the responses for an input at Mach = .6 shows that the response for pitch rate is reasonable and the angle-of-attack response, although small, is larger than the response for the figure 11 run where the angle-of-attack derivatives were well-defined (fig. 12). The responses for the Mach = 2 maneuver showed the pitch rate to be larger than desired. At this point the choices for reducing the response were to shorten the period of the input or to reduce the amplitude. Both of these approaches were tried and the results are shown as figures 13 and 14. Since the input is larger, the responses shown in figure 14 are initially more rapid than those of figure 13, but the peak values of the angle-of-attack and z-body acceleration are not as large. However, the initial peak of the pitch rate is larger for the higher amplitude input shown in figure 14. This initial examination would imply that even though the control effectiveness may not be defined as well for the lower amplitude input, overall this could prove to be the best input for the Mach = 2 flight conditions.

The next check on the suitability of the inputs for parameter extraction was to examine the power spectra of the responses and the inputs. The plots of the spectra for angle-of-attack, pitch rate and elevon deflection from the two proposed inputs at Mach = 2 conditions are shown as figures 15 and 16, and the results are summarized in table IV. The comparison of the two inputs using the power spectra indicates the larger amplitude input has more power, but the increase in reversal time of the smaller input leads to greater response power. Also, the percent increase in the angle-of-attack power is greater than the percent increase in the pitch rate power. The most important comparison, however, is against the results from the doublet inputs. The power of the proposed inputs was greater than that of the doublets, and the frequency of the peak power for the proposed inputs was in the .3 to .4 Hertz range. The doublet inputs had power peaks in this frequency range and the resulting responses had maximum power in the .2 Hertz frequency range. Figures 15 and 16 show that the peak power of the responses are in the .15 to .2 Hertz frequency range and result in significantly larger responses than the doublets used for comparison. The implication is that the input magnitude could be reduced farther, and still the responses should be large enough for increased identifiability of the longitudinal static and control parameters.

The final check of the inputs was to take the responses from the two Mach = 2 runs, contaminate them with noise that was two percent of the peak-to-peak response to an input, and then use this data to extract the parameters used in the mathematical model which generated the data. The original parameters were offset by at least 20 percent for the initial parameter estimates. After applying the maximum likelihood parameter extraction program (outlined in ref. 1) to the simulated data, the parameters determined were within one and one-half percent of the parameter used to generate the responses initially. The sensitivities and Cramer-Rao bounds resulting from the extraction process are given in table V. These are the most significant values determined from the extraction process because when compared with the input 3 and 4 results of table III, they give an indication of the potential improvement in identifiability of parameters for the modified doublet input. The sensitivities and Cramer-Rao bounds both show an improvement of about a factor of 10 when using the modified doublet. These results imply the inputs of this type should result in responses that improve the identifiability of longitudinal static and control parameters.

CONCLUDING REMARKS

Control inputs that were used with the Shuttle have been examined. The two types of inputs used that were most successful in the parameter identification were the pull-up-push-over (PUPO) and the doublet. Considering convergence, fit, Cramer-Rao bounds and sensitivity of the parameters as indicators of the identifiability of parameters, the PUPO maneuvers were found to give good definition of the parameters but required too much time for the low Mach numbers. The doublet maneuvers used in this paper also gave good definition for most parameters.

When comparing the power spectra of the response from the various maneuvers, the PUPO maneuvers not only had much more power at frequencies less than .1 Hz but also had more power in the .1 Hz to .2 Hz range than the doublet with the greatest power. However, the parameter identifiability was not significantly better for the PUPO maneuvers when compared to the best doublet maneuver, since only the responses close to the natural frequency of the short period mode influenced the identification of parameters describing that mode.

The proposed maneuvers were designed to give responses with as much power, as determined by the power spectral density, as the PUPO maneuvers in the .1 to .2 Hertz frequency range. Also, inputs that were initially as rapid as possible to help the identification of the control effectiveness were desired. The proposed inputs met these design criteria. When simulated data generated by these maneuvers were processed using a maximum likelihood extraction program, the parameter values determined were within one and one-half percent of the true values, the fit to data was good, and the sensitivities and Cramer-Rao bounds were improved by a factor of 10 over the sensitivities and Cramer-Rao bounds of the doublet maneuvers. This preliminary study indicates that the proposed inputs should result in improved identifiability of longitudinal static and control parameters for the Shuttle descent trajectory.

REFERENCES

1. Murphy, Patrick C.: An Algorithm for Maximum Likelihood Estimation Using an Efficient Method for Approximating the Sensitivities. NASA TP-2311, June 1984.

2. Cannaday, Robert L.; and Suit, William T.: Effects of Control Inputs on the Estimation of Stability and Control Parameters of a Light Airplane. NASA TP-1043, December 1977.

TABLE I.- SAMPLE FLIGHT INPUTS

Input 1	Mach = 14	Pull-Up-Push-Over
Input 2	Mach = 7	Pull-Up-Push-Over
Input 3	Mach = 20	Doublet
Input 4	Mach = 1.8	Doublet

TABLE II.- SUMMARY OF POWER SPECTRUM FOR FREQUENCY GREATER THAN .1 HERTZ

INPUT	VARIABLE	PEAK VALUE OF SPECTRUM IN RANGE GREATER THAN .1 Hz AND FREQUENCY AT WHICH PEAK OCCURS
1	α	24 at .12 Hz and 4.0 at .20 Hz
	q	2.7 at .15 Hz
	δ_e	14 at .19 Hz
2	α	80.0 at .1 Hz and 4.0 at .18 Hz
	q	5.60 at .1 Hz and 1.0 at .14 Hz
	δ_e	7.0 at .16 Hz
3	α	1.2 at .19 Hz
	q	.42 at .20 hz
	δ_e	.2 at .12 Hz, 3.7 at .45 Hz and 4.0 at .7 Hz
4	α	.77 at .19 Hz
	q	.47 at .19 Hz
	δ_e	.5 at .13 Hz, 3.4 at .32 Hz and 3.2 at .6 Hz

TABLE III.- SENSITIVITY AND CRAMER-RAO BOUND FOR PARAMETERS FROM RUNS USING INPUTS 1-4

INPUT	PARAMETER	SENSITIVITY	CRAMER-RAO BOUND
1	C_{z_o}	$.47 \times 10^7$	.0027
2		$.2 \times 10^8$	.0011
3		$.14 \times 10^7$	.00076
4		$.39 \times 10^7$	.0012
1	C_{z_α}	$.165 \times 10^5$	.041
2		$.3 \times 10^5$	.056
3		$.508 \times 10^4$	.053
4		$.163 \times 10^5$	.130
1	C_{m_α}	$.142 \times 10^6$	.0002
2		$.85 \times 10^5$	.00078
3		$.467 \times 10^6$	.0014
4		$.214 \times 10^6$	.0045
1	$C_{m_{\delta e}}$	$.45 \times 10^5$	.0012
2		$.2 \times 10^6$	.00081
3		$.7 \times 10^6$	.00113
4		$.184 \times 10^6$	.0014

TABLE IV.- SUMMARY OF SPECTRUM FOR FREQUENCIES GREATER THAN .1 HERTZ USING MODIFIED DOUBLET INPUTS

INPUT	VARIABLE	PEAK VALUE OF SPECTRUM IN RANGE GREATER THAN .1 Hz AND FREQUENCY AT WHICH PEAK OCCURS
± .1 rad.	α	82.0 at .17 Hz
	q	33.0 at .17 Hz
	δe	9.6 at .4 Hz
± .06 rad.	α	126.0 at .17 Hz
	q	44.0 at .17 Hz
	δe	6.7 at .28 Hz

TABLE V.- SENSITIVITY AND CRAMER-RAO BOUNDS FOR PARAMETERS FROM DATA GENERATED USING MODIFIED DOUBLETS

INPUT	PARAMETER	SENSITIVITY	CRAMER-RAO BOUND
± .1 rad.	C_{z_o}	$.285 \times 10^8$	$.170 \times 10^3$
± .06 rad.	C_{z_o}	$.143 \times 10^8$	$.177 \times 10^3$
± .1 rad.	C_{z_α}	$.346 \times 10^6$	$.407 \times 10^2$
± .06 rad.	C_{z_α}	$.508 \times 10^4$	$.316 \times 10^2$
± .1 rad.	C_{m_α}	$.200 \times 10^7$	$.622 \times 10^4$
± .06 rad.	C_{m_α}	$.443 \times 10^7$	$.530 \times 10^4$
± .1 rad.	$C_{m_{\delta e}}$	$.536 \times 10^7$	$.310 \times 10^3$
± .06 rad.	$C_{m_{\delta e}}$	$.851 \times 10^7$	$.238 \times 10^3$

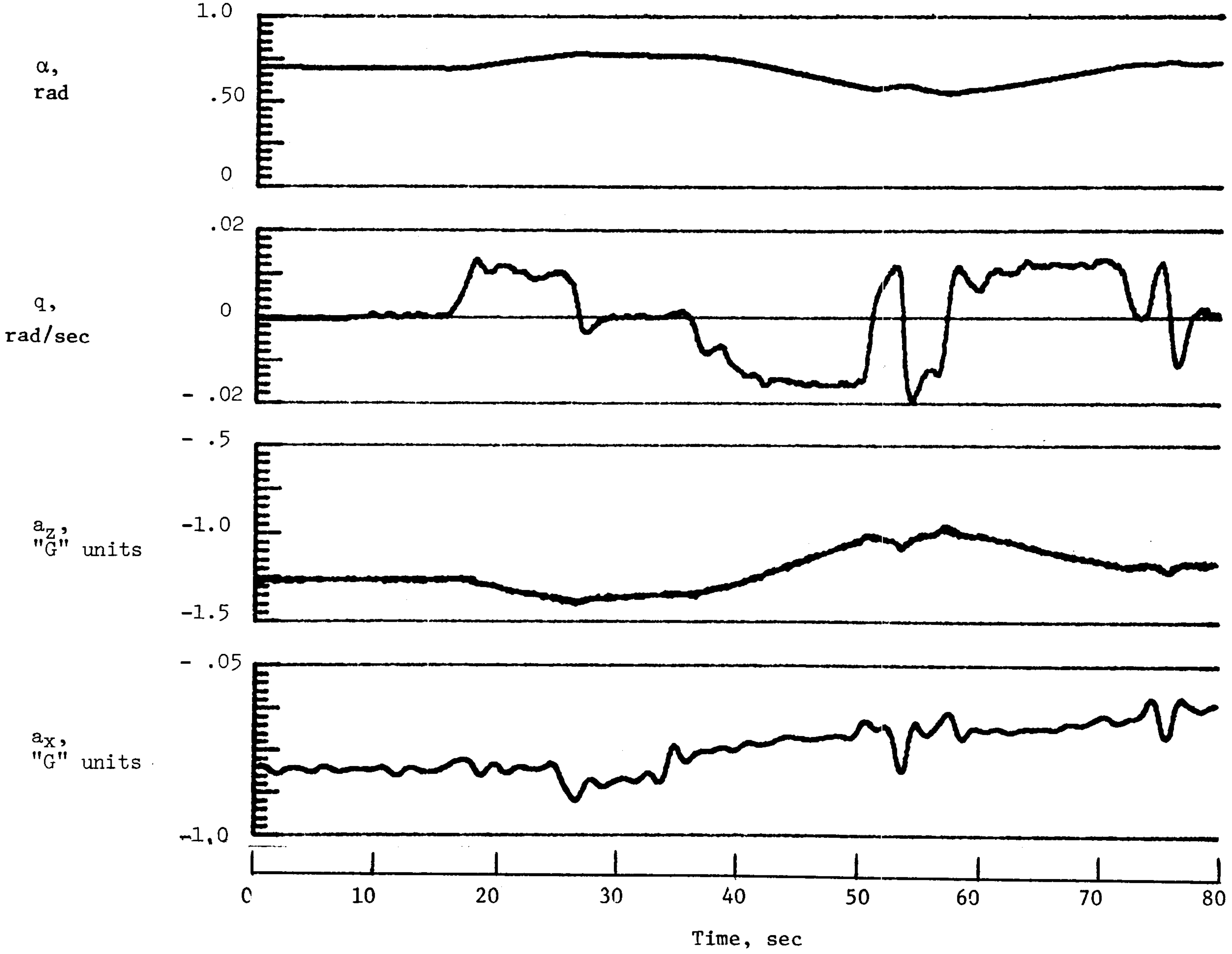

Figure 1.- Time history of pull-up-push-over maneuver listed as input 1 in table I.

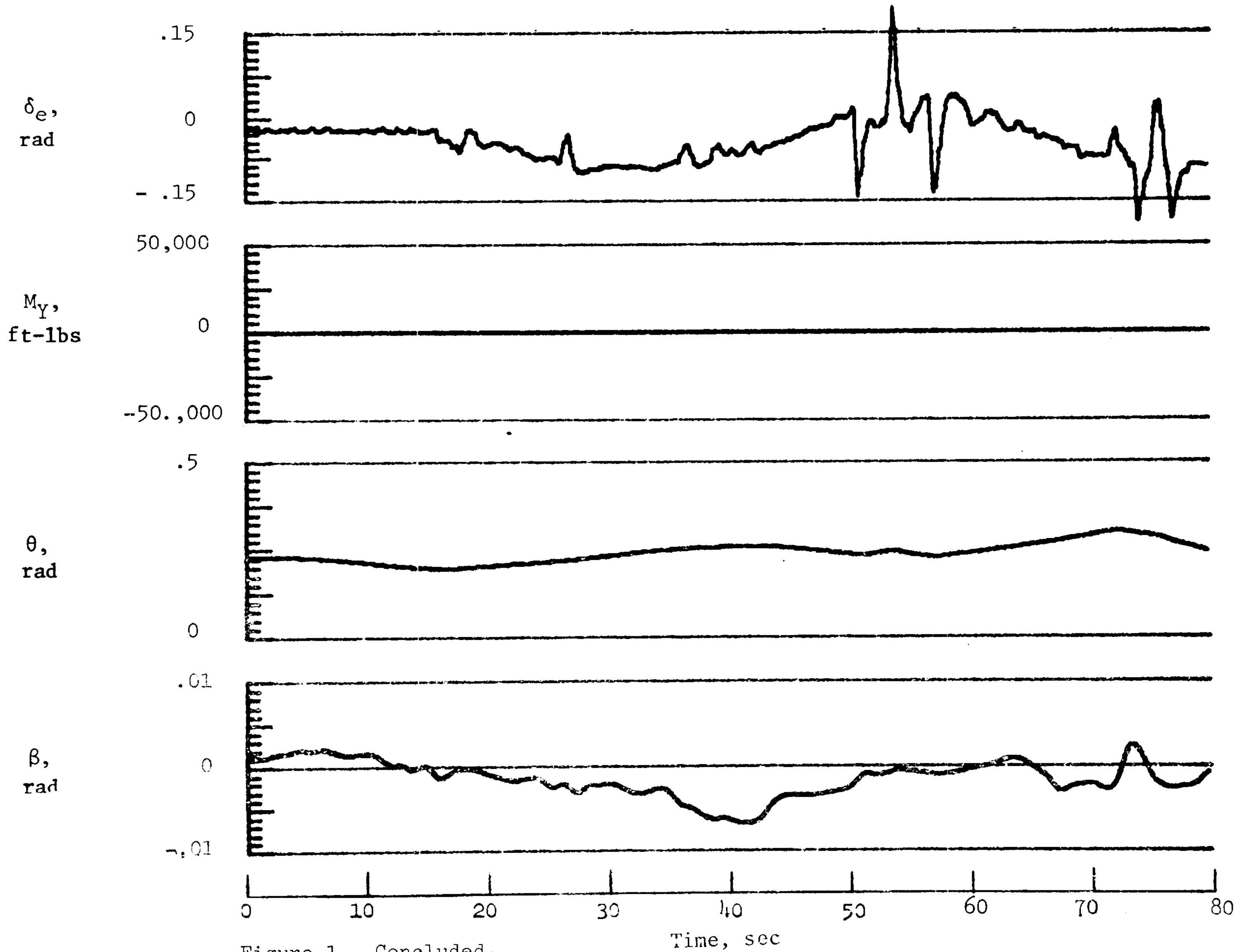

Figure 1.- Concluded.

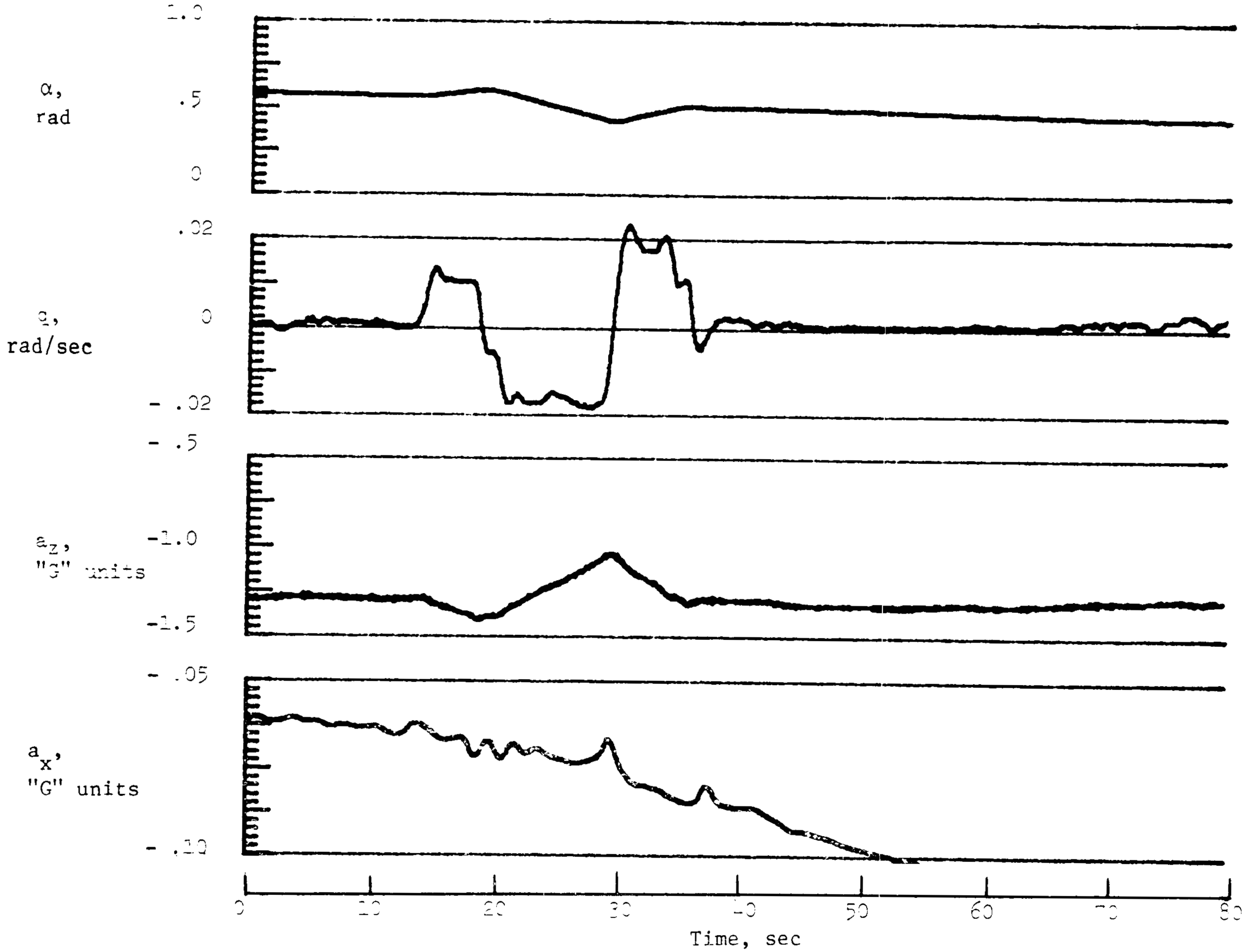

Figure 2.- Time history of pull-up-push-over maneuver listed as input 2 in table I.

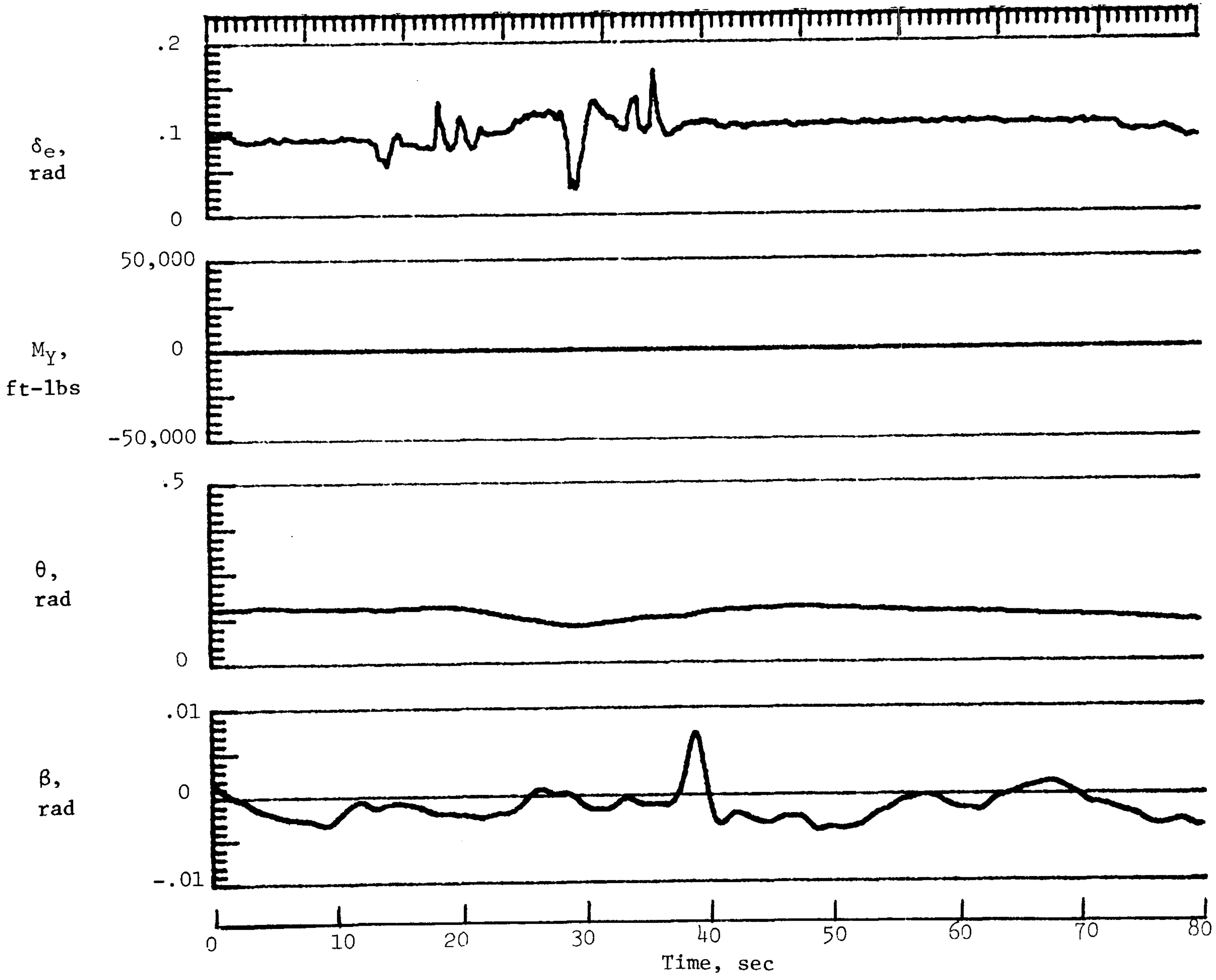

Figure 2.- Concluded.

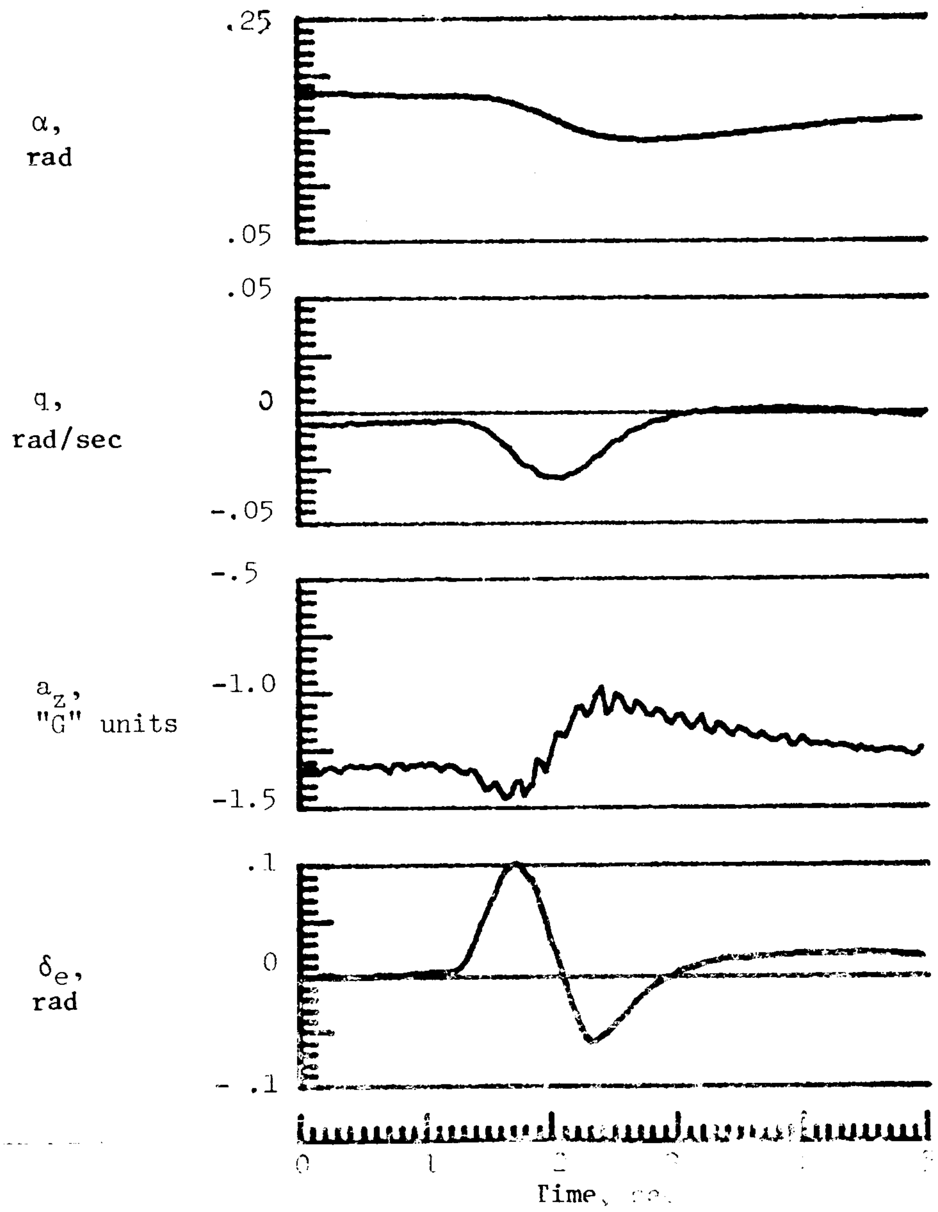

Figure 3.- Time history of doublet maneuver with elevon deflection initially positive. Listed as input 3 in table I.

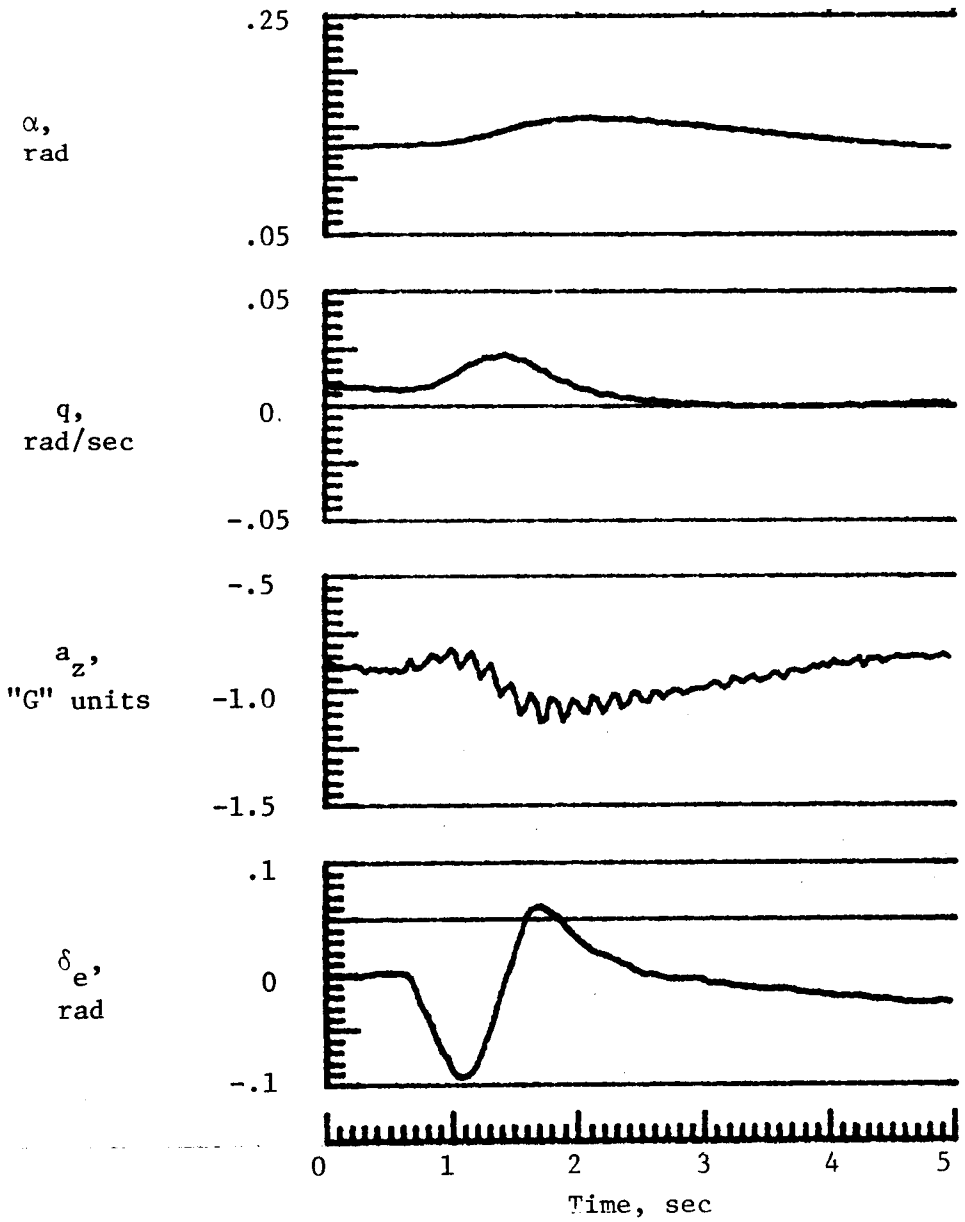

Figure 4.- Time history of doublet maneuver with elevon initially negative. Listed as input 4 in table I.

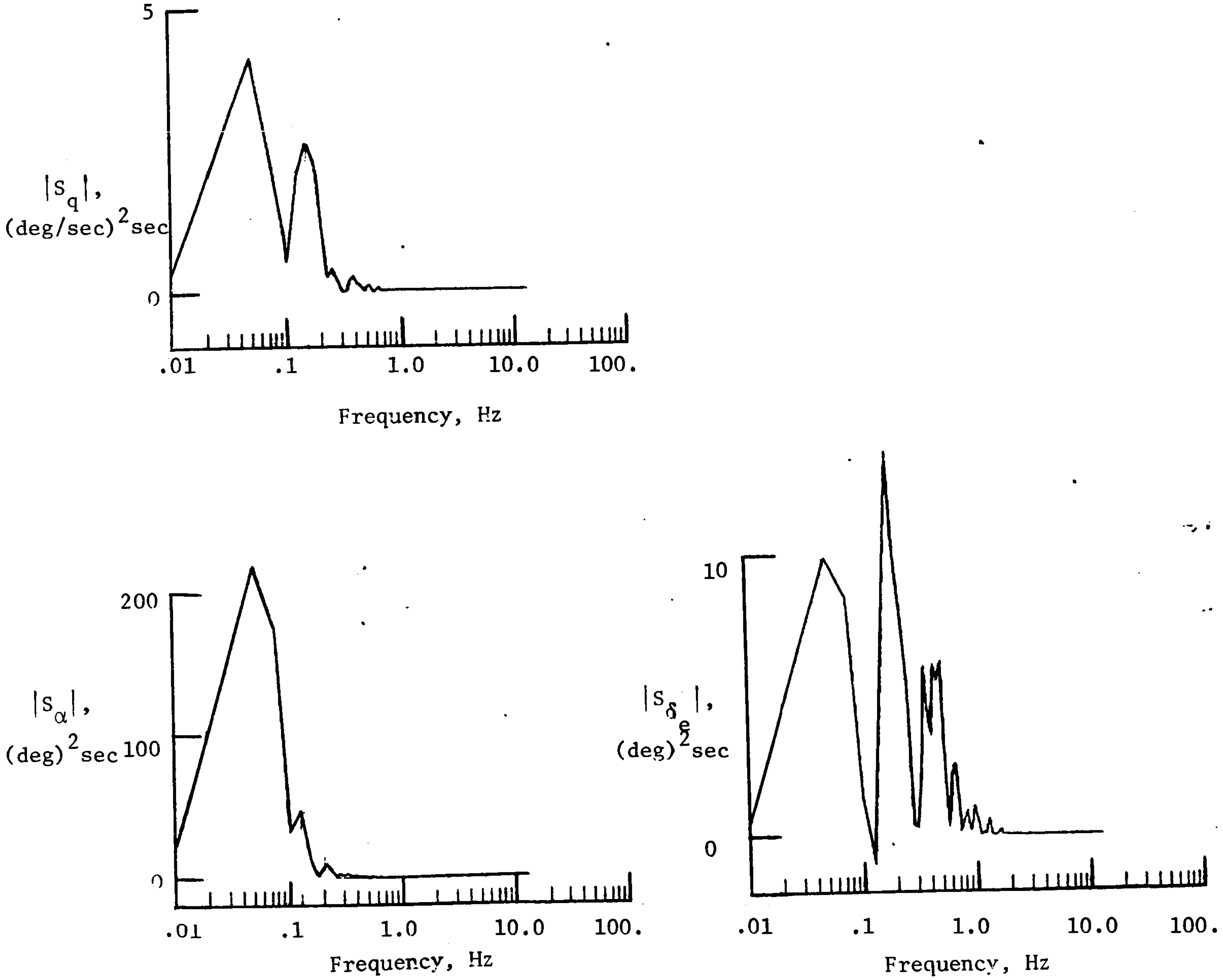

Figure 5.- Power spectra of input and responses for input 1 of table I.

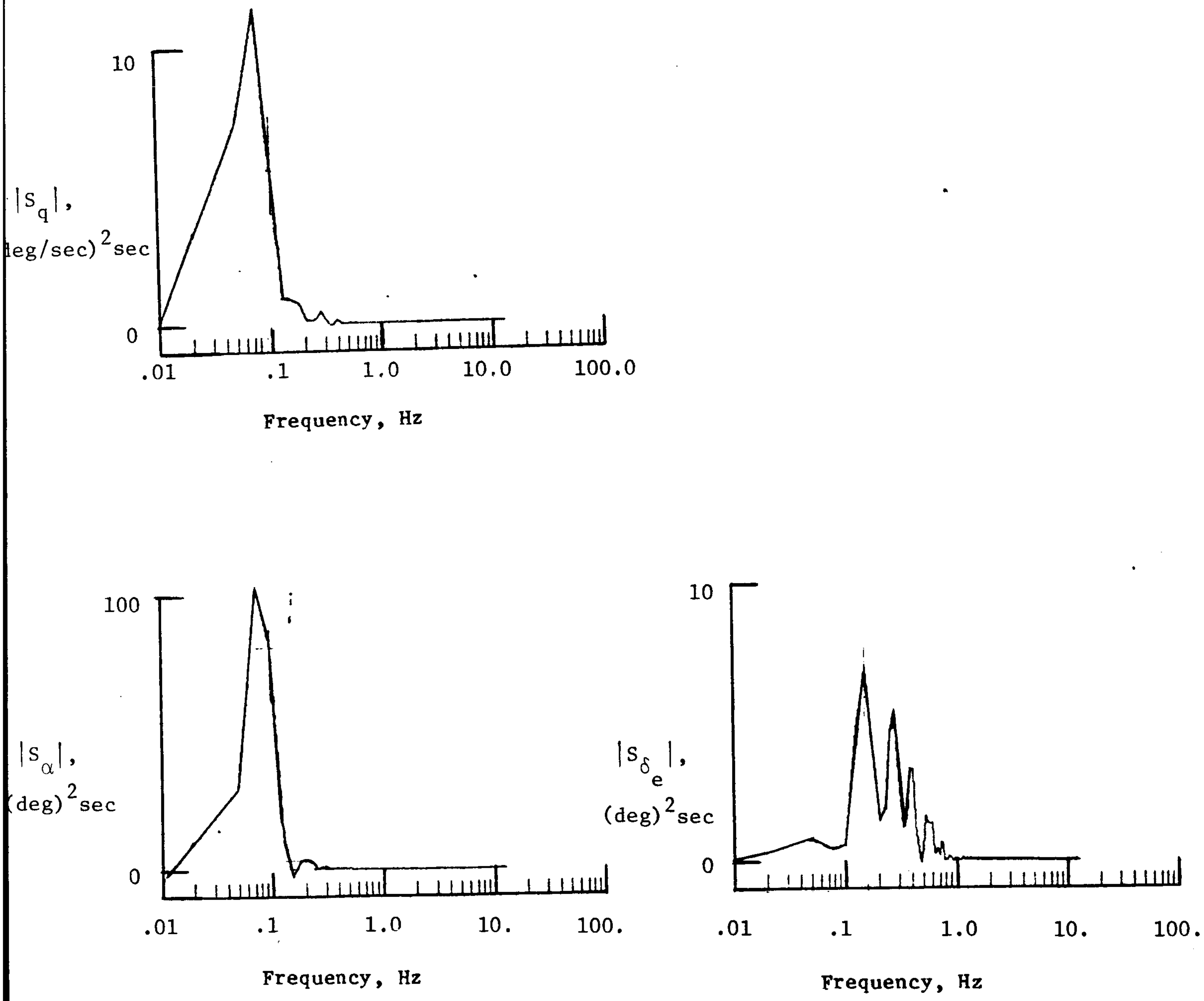

Figure 6.- Power spectra of input and responses of input 2, table I.

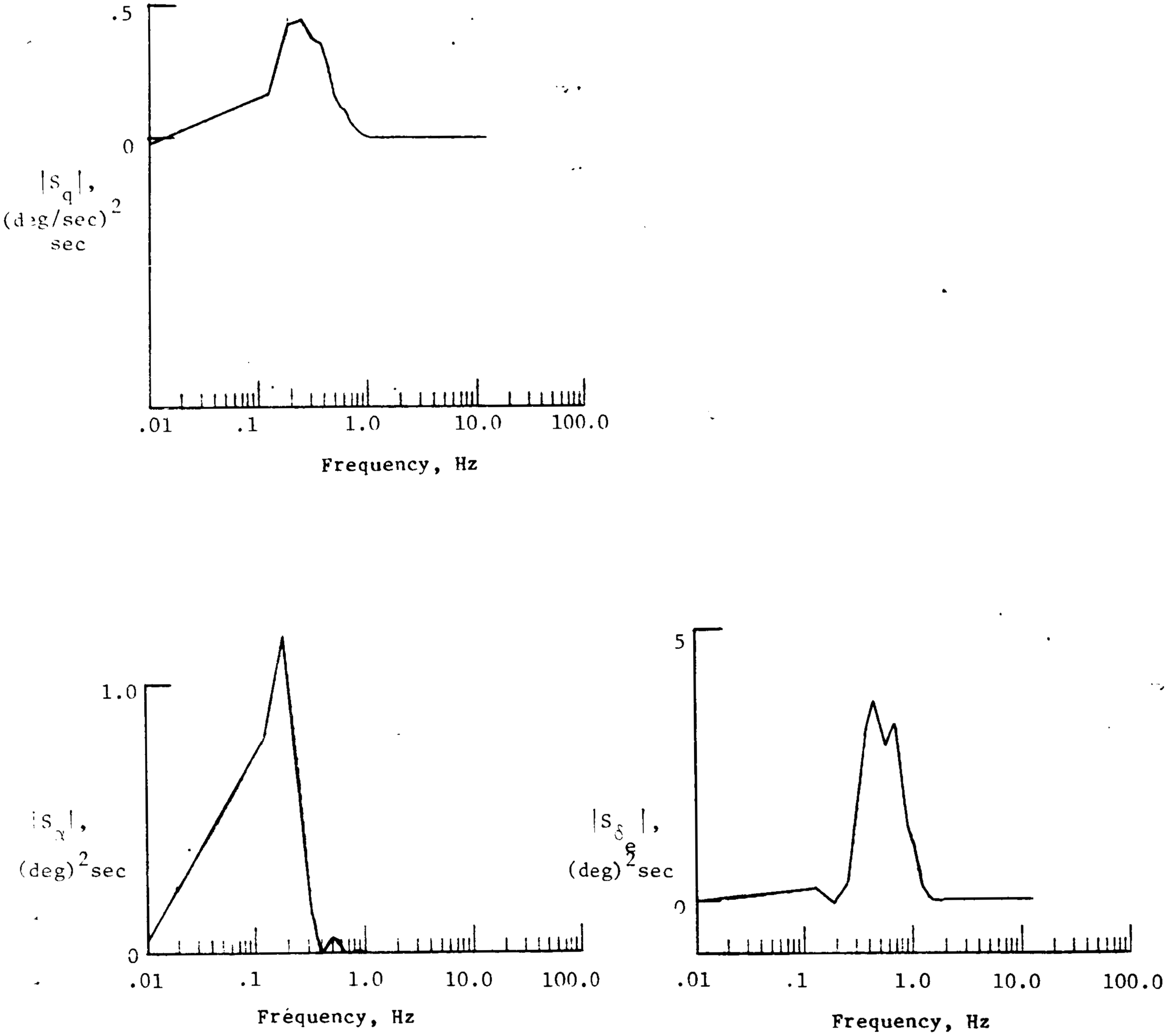

Figure 7.- Power spectra of input and responses of input 3, table I.

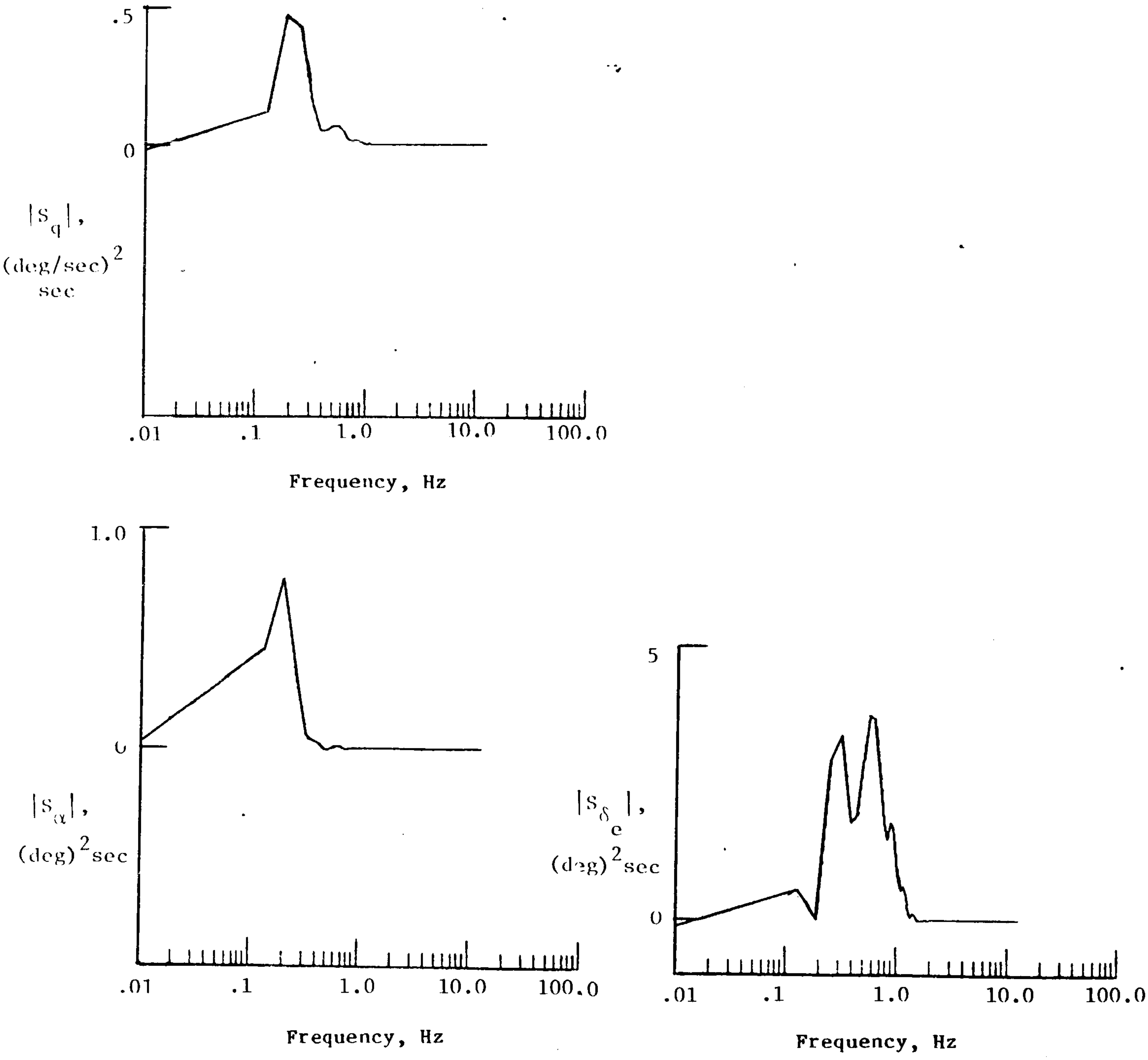

Figure 8.- Power spectra of input and responses of input 4, table I.

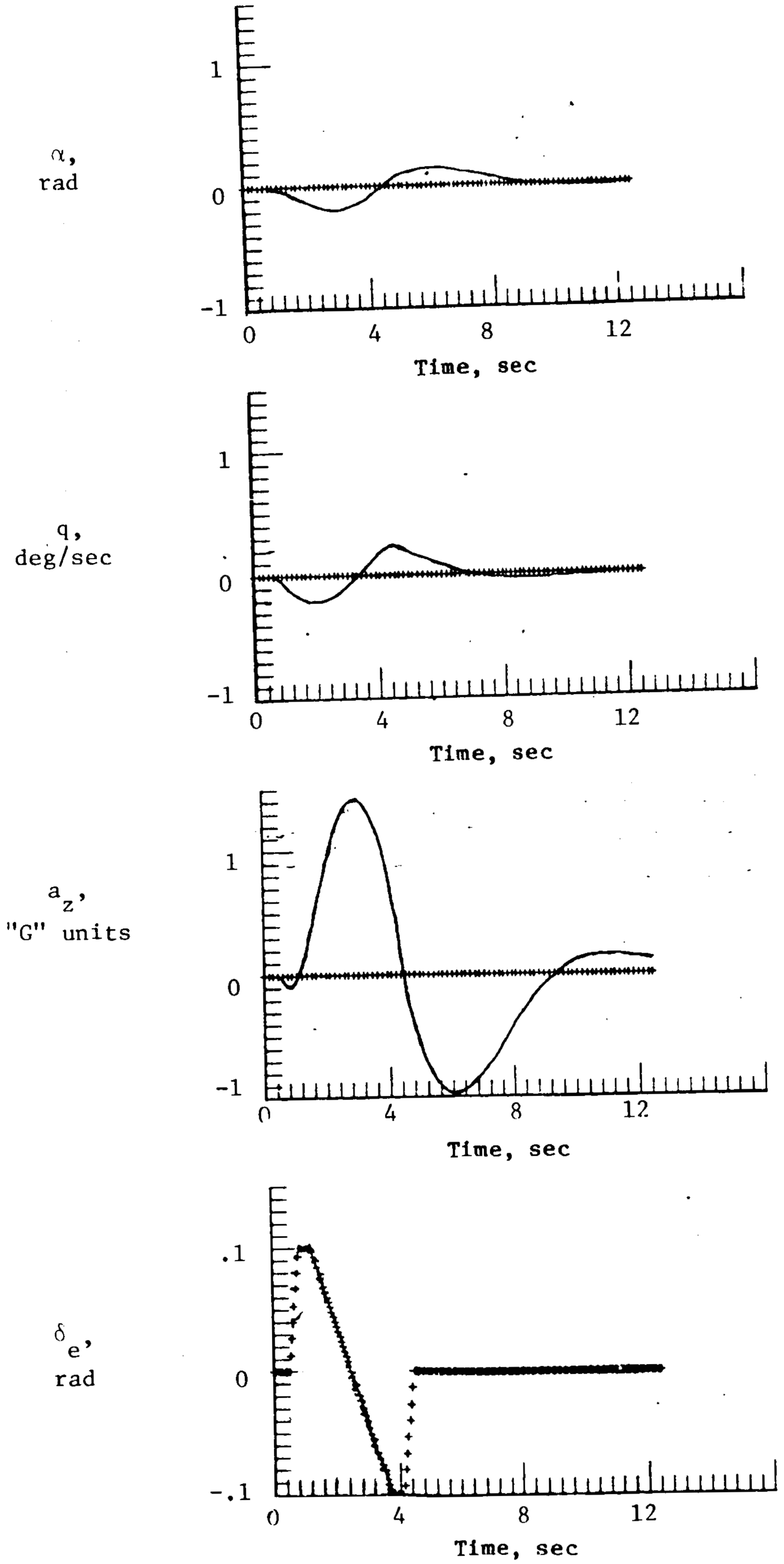

Figure 9.- Time histories of input and responses for first modified input checked at a dynamic pressure typical of the M = .6 portion of a Shuttle descent trajecto

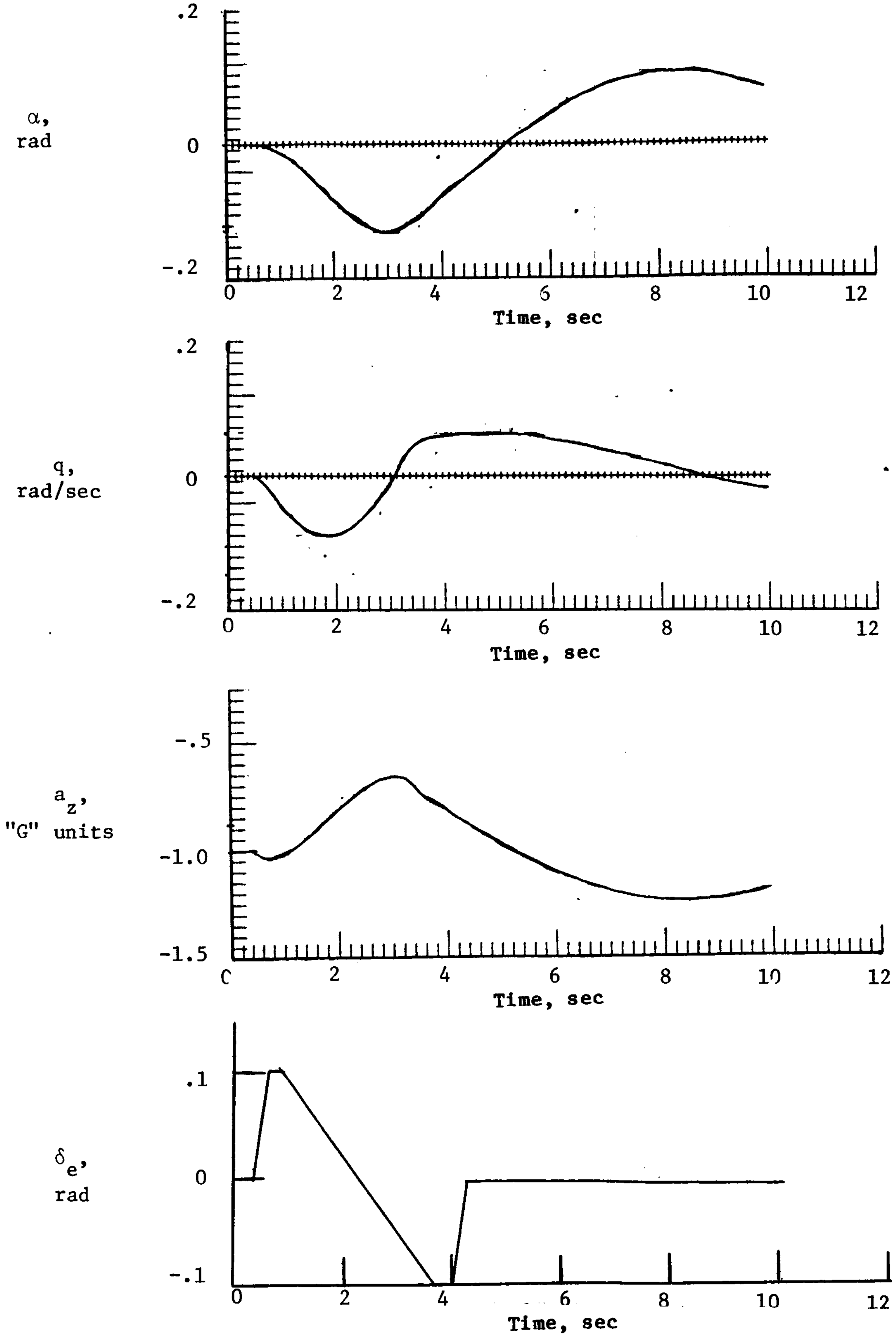

Figure 10.- Time history of responses to the input of figure 9 run at a dynamic pressure typical of the M = 2.0 portion of a Shuttle descent trajectory.

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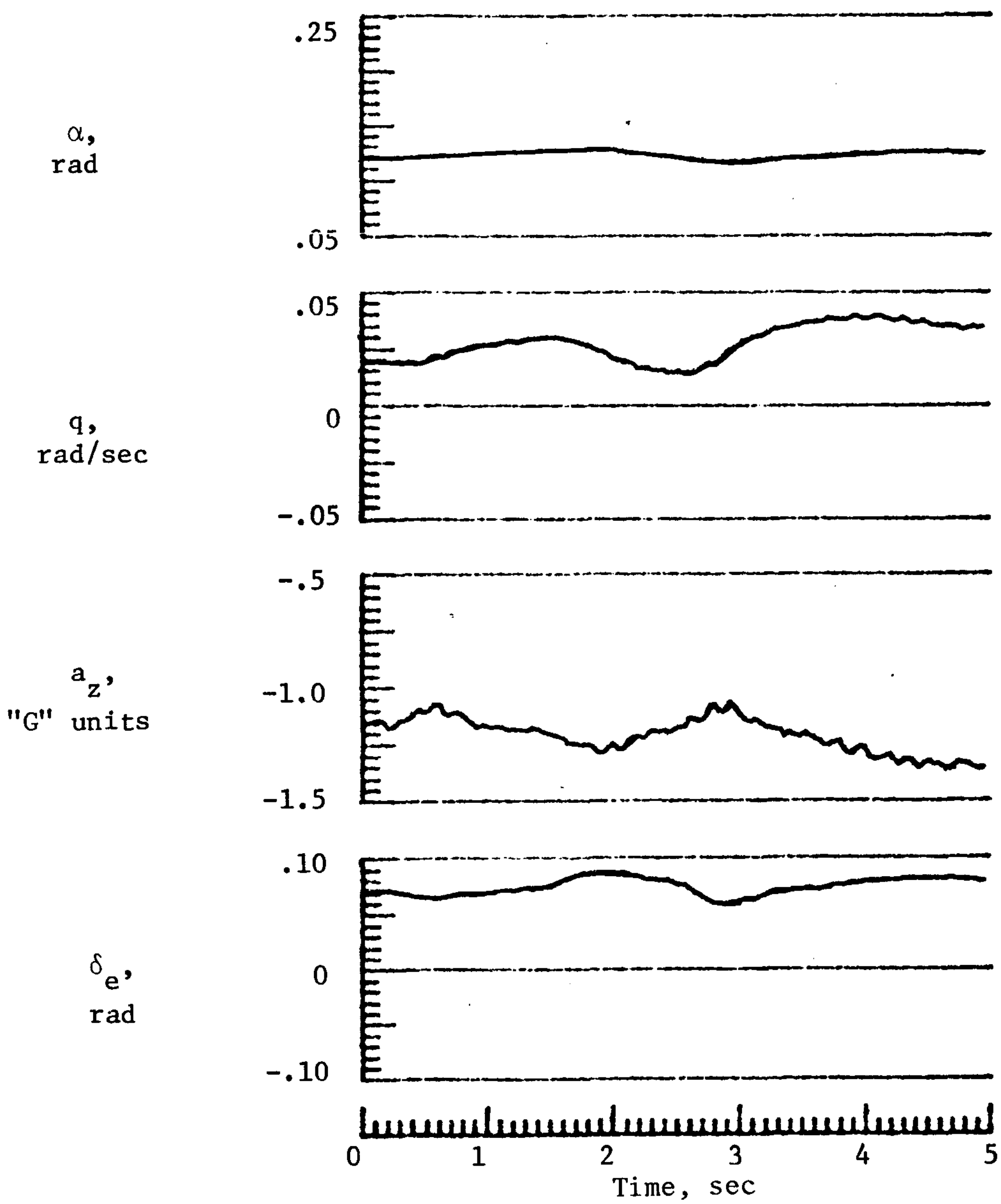

Figure 11.- Time history for incidental input at Mach = .6.

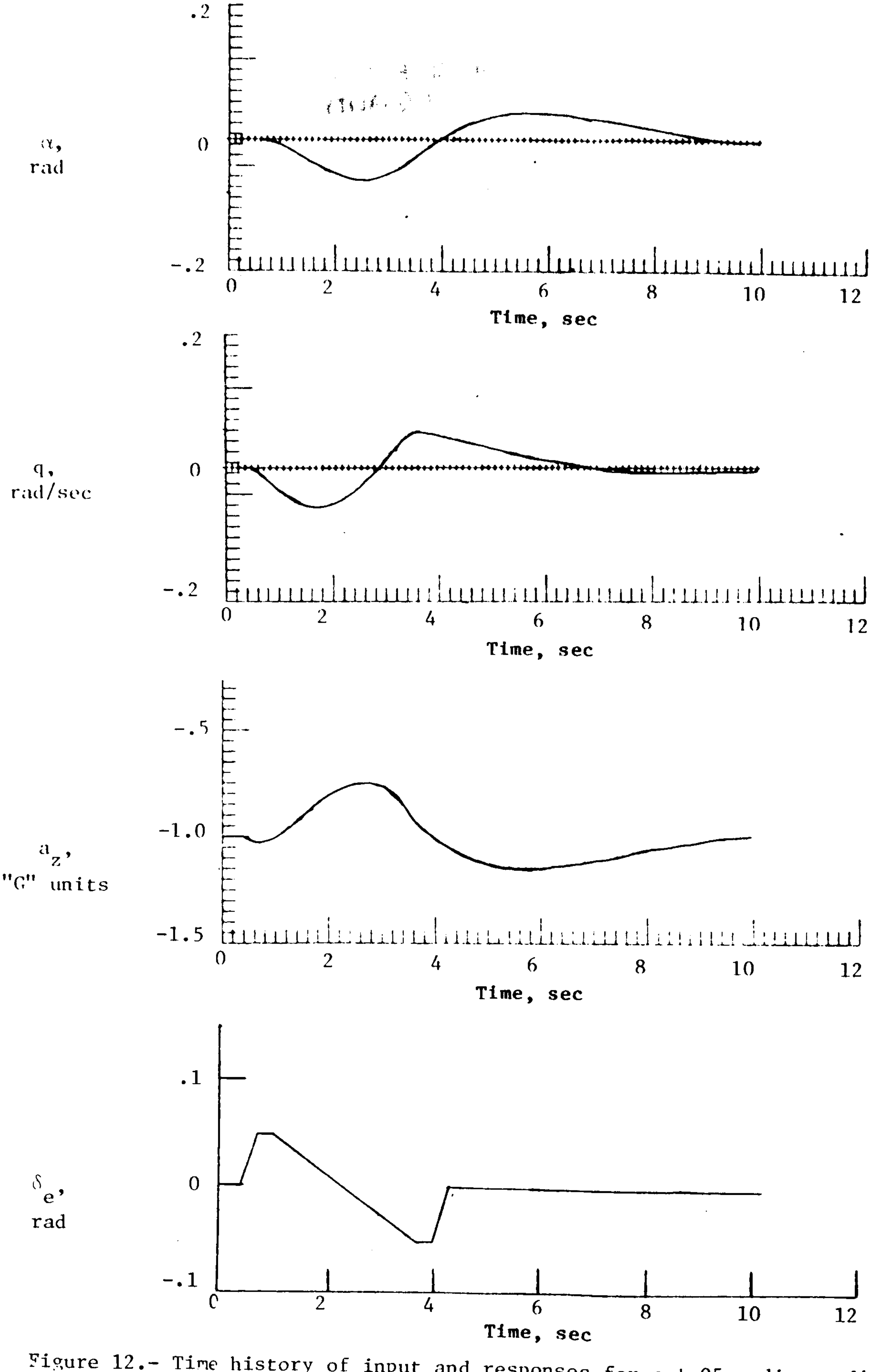

Figure 12.- Time history of input and responses for a ±.05 radian modified doublet run at a dynamic pressure typical of the M = .6 portion of a Shuttle descent trajectory.

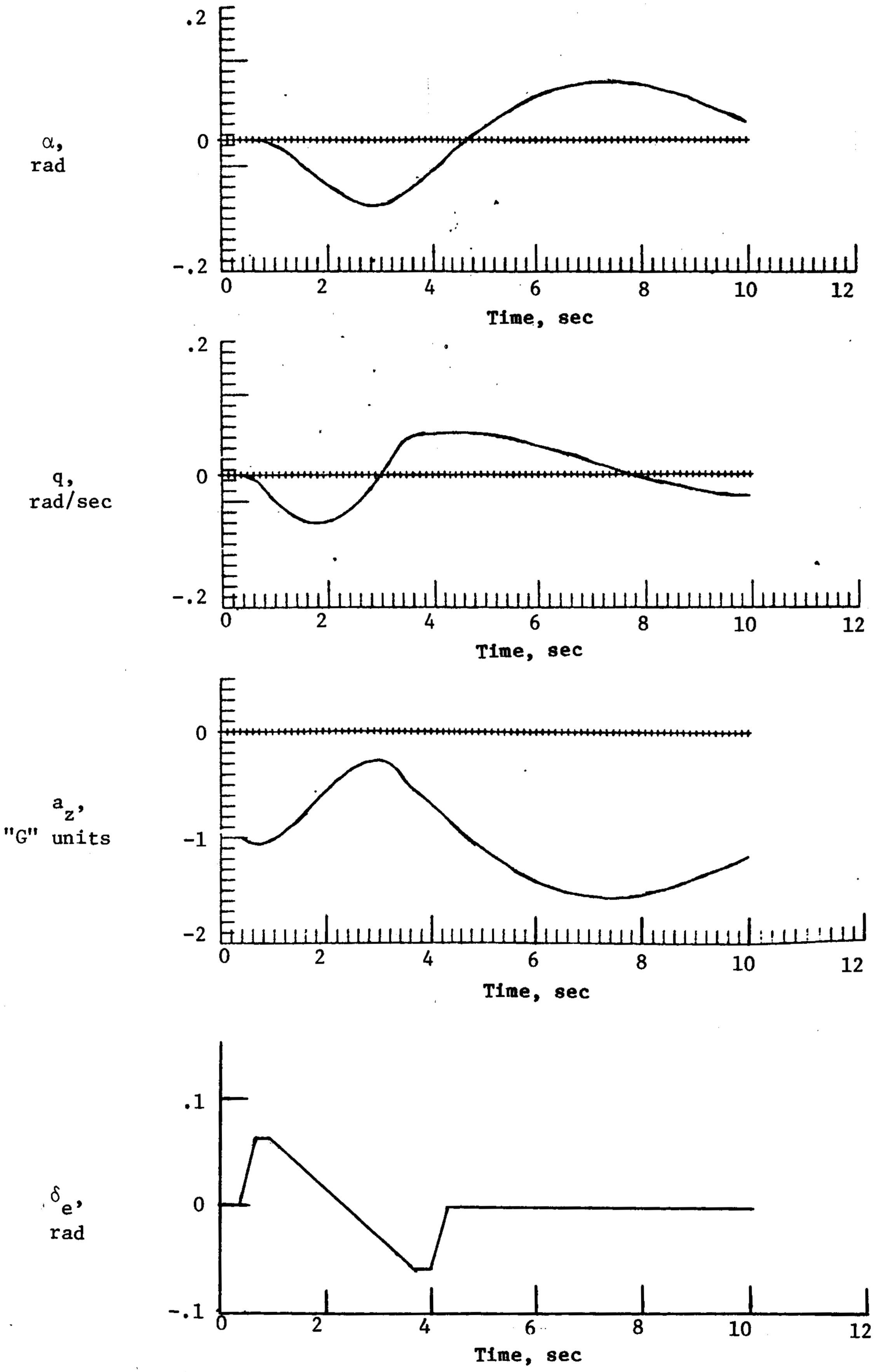

Figure 13.- Time history of input and responses for a ± .06 radian modified doublet run at a dynamic pressure typical of the M = 2.0 portion of a Shuttle descent trajectory.

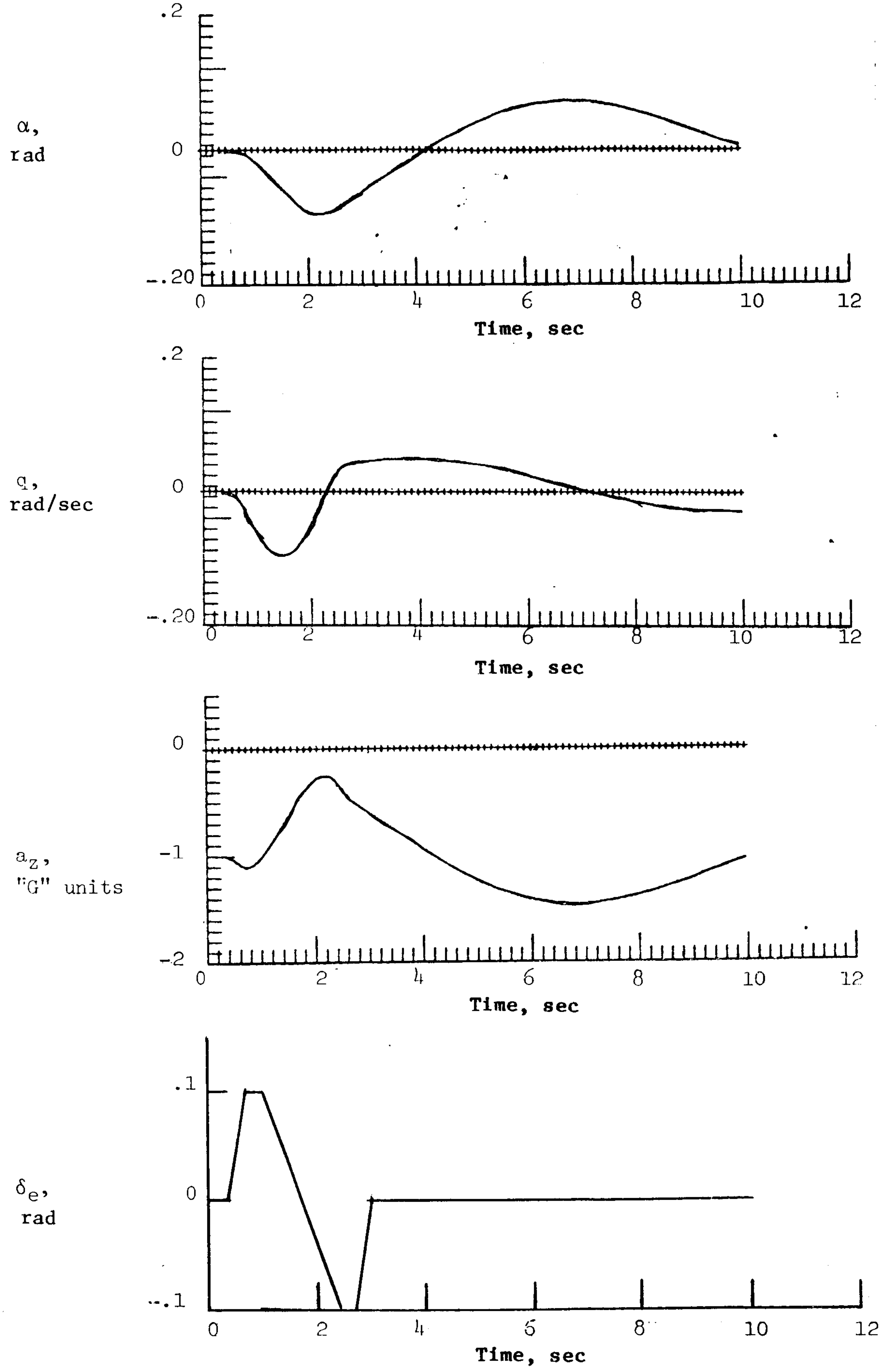

Figure 14.- Time history of input and responses for ± .1 radian modified doublet run at a dynamic pressure typical of the M = 2.0 portion of a Shuttle descen trajectory.

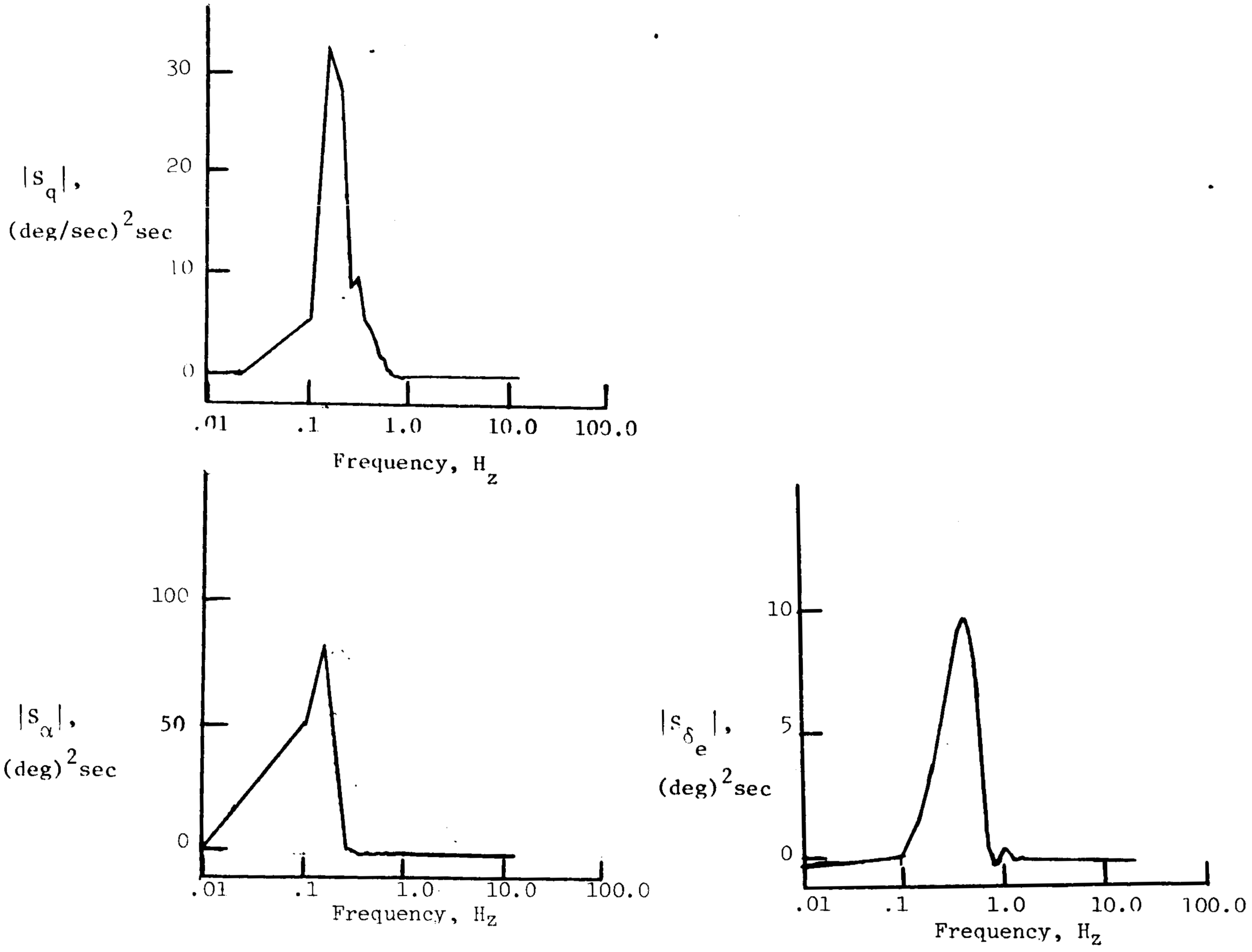

Figure 15.- Power spectra of the input and responses for a modified doublet of ± .1 radians run at a dynamic pressure typical of the M = 2.0 portion of a Shuttle descent trajectory.

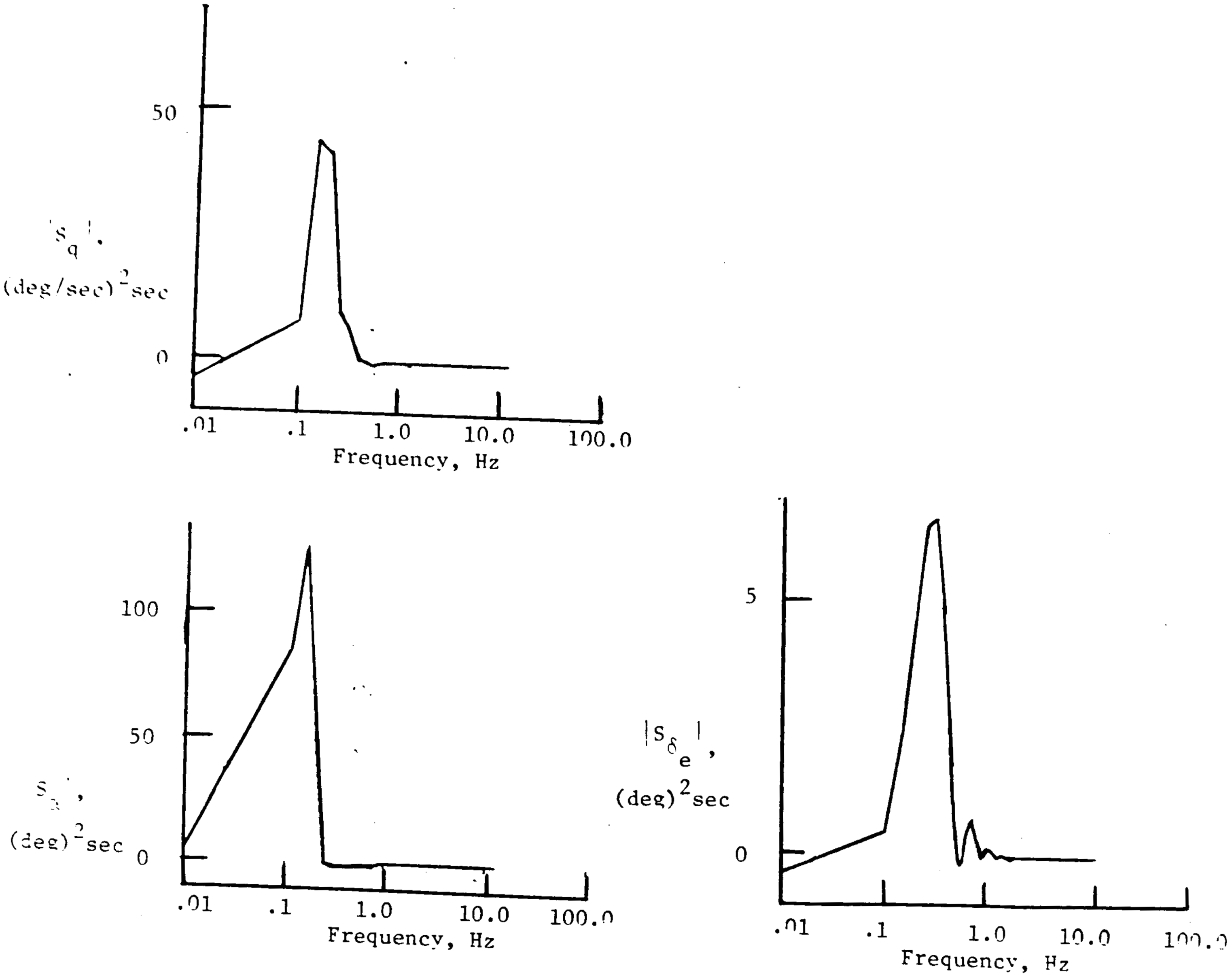

Figure 16.- Power spectra of the input and responses for a modified doublet of ± .06 radians run at a dynamic pressure typical of the M = 2.0 portion of a Shuttle descent trajectory.