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FLIGHT EVALUATIONS OF THE EFFECT OF VARIABLE PHUGOID DAMPING IN A JTB-26B AIRPLANE

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FOREWORD

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ABSTRACT

A JTB-26B airplane, previously modified to permit in-flight variation of the dynamics of the phugoid motion, is used to quantitatively and qualitatively evaluate the effect of phugoid damping ratio in simulated instrument flying. One pilot's comments as to the relative acceptability of given damping configurations are presented and compared with corresponding quantitative measurements. It is established that phugoid damping is not a negligible parameter of good aircraft stability and control design, specifically when instrument flight is considered. Higher than present, inherent values of phugoid damping are beneficial.

PUBLICATION REVIEW

This report has been reviewed and is approved.

FOR THE COMMANDER:

Nathan L. Krisberg
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LIST OF SYMBOLS

V_i	Indicated airspeed, mph
U_o	Forward velocity, ft/sec
u	Incremental forward velocity, ft/sec
$\mathring{u}$	Rate of change of forward velocity, ft/sec^2
ρ	Atmospheric density, slug/ft^3
q	Dynamic pressure, $\frac{\rho}{2}U_o^2$ lb/ft^2
h_p	Pressure altitude, ft
C_{m_u}	Pitching moment coefficient per unit airspeed, $\frac{\partial C_m}{\partial \frac{u}{U_o}}$
$C_{m_{\mathring{u}}}$	Pitching moment coefficient per rate of change of airspeed, $\frac{\partial C_m}{\partial D\frac{u}{U_o}}$
$C_{m_{\delta_{AUX}}}$	Pitching moment coefficient per unit auxiliary surface deflection, $\frac{\partial C_m}{\partial \delta_{AUX}}$
δ_e	Elevation deflection, degrees or radians
δ_{AUX}	Auxiliary surface deflection, degrees or radians
$\frac{\delta_{AUX}}{u}$	Knob 9 (frequency) sensitivity, fraction of maximum
$\frac{\delta_{AUX}}{\mathring{u}}$	Knob 8 (damping) sensitivity, fraction of maximum
T	Period of oscillation, sec
ζ	Damping ratio; percent of critical damping
D	Non-dimensional operator $\tau\frac{d}{dt}$
τ	Aerodynamic time $\frac{m}{\rho S U_o}$, sec
m	Mass of the airplane, slugs
S	Wing area, ft^2

INTRODUCTION

For the past several years, the Flight Research Department of Cornell Aeronautical Laboratory, Inc. has been engaged in the theoretical and experimental investigation of artificial stability and airplane handling qualities. Briefly, this study has considered the statics and dynamics of both the longitudinal and lateral modes of motion, and has been performed using both fighter and bomber types of aircraft. The investigative technique employed has been to obtain both quantitative and qualitative data. The latter, in the form of pilot comments has become increasingly important as a measure of pilot-airplane performance.

Interest in the phugoid mode of longitudinal motion has been slow to develop, primarily due to its subtle effects. It is difficult for the pilot to recognize the motion as a distinct oscillation because of its inherent long period. Thus the inability of a pilot to maintain constant altitude and airspeed may be attributed to an effect (such as "poor trim characteristics") rather than the cause. It is likely that this inability may be accentuated on the basis of the design trend of future aircraft, since the reduction of airplane drag tends to further reduce phugoid damping.

Aside from inducing pilot annoyance and fatigue, poor phugoid damping may contribute adversely to an already critical flight situation. Flying IFR in areas of heavy traffic or making GCA and ILS approaches, which require maintaining minimum altitude variation, may result in hazardous situations. These situations may be aggravated by a combination of light phugoid damping, pilot fatigue, and navigational problems.

To investigate the above possibility, a theoretical investigation (Reference 1) and a preliminary flight investigation (Reference 2), were accomplished to determine the general feasibility of variable phugoid damping tests. It was determined that under VFR conditions, the pilot found it difficult to distinguish between the various amounts of phugoid damping provided. Therefore, simulated IFR flights were made with the pilot flying

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by instruments under a hood. In straight and level runs of one half hour per damping configuration under these conditions, the pilot could definitely distinguish between values of phugoid damping. Also, quantitative data in the form of power spectral densities of altitude deviation from the mean indicated definite differences in pilot-airplane performance as a function of phugoid damping. The effects of varying phugoid frequency over a range from approximately .01 to .05 cps were negligible.

With this preliminary investigation as a background, the present program was initiated for the purpose of refining test technique (both quantitative and qualitative) and extending the general range of investigation.

Specifically, then, the following items were investigated, the details and results of which appear in this report:

(a) Effect of phugoid damping on cross-country simulated IFR flight

(b) Effect of phugoid damping on GCA and ILS approaches.

In the presentation of the data, emphasis is placed on altitude and elevator input variations and pilot acceptability as a function of phugoid damping ratio. Correlation between quantitative data and a one pilot evaluation is shown.

EQUIPMENT

The majority of the equipment used in these tests has been described in detail in References 2 and 3. Therefore, only a brief summary of the basic instrumentation will be presented here. Additional equipment needed is described in detail.

A Douglas JTB-26B airplane, serial no. 44-34653 (Figure 1) was instrumented for the purpose of providing artificial stability which could be varied over a range sufficient to appreciably alter the dynamic characteristics (damping and period) of both the short period and phugoid modes of longitudinal motion. In addition, static stability, stick force and stick travel per g, and stick force and stick travel per airspeed may also be varied.

Variation of the phugoid characteristics required additional pitching moments as a function of u and $\dot{u}$. Theoretical considerations (Reference 1) indicated this could be accomplished by driving a small auxiliary surface (Figures 2a and 2b) with signals proportional to the sum of the incremental of the inverse of dynamic pressure ($\Delta \frac{1}{q}$) and $\frac{\dot{u}}{q}$. Instrumentation components required to do this are as follows:

1. Pitot tube - standard ship's system; pickup for dynamic pressure and airspeed.
2. Pressure transducers - convert aerodynamic signals to electrical signals
3. Airspeed Differentiator - provides $\dot{u}$ signal
4. q divider servo - provides the inverse of dynamic pressure
5. Balancing circuit to obtain $\Delta \frac{1}{q}$
6. Divider potentiometer to obtain $\frac{\dot{u}}{q}$
7. Gain controls for $\Delta \frac{1}{q}$, $\frac{\dot{u}}{q}$ and auxiliary surface position feedback.
8. Mixer-amplifier-discriminator - receives all signals for actuating the auxiliary surface

9. Auxiliary surface controller - servo amplifier and motor drives the auxiliary surface in response to the error signal from the mixer.
10. Rotary position potentiometer - provides auxiliary surface position feedback to the mixer.
11. Auxiliary surface - provides required additional moment.

A diagram of the system using the above components is shown on Figure 4. Reference 1 describes the use of $\Delta(\frac{1}{q})$ and $\frac{\dot{u}}{q}$ to approximate the artificial derivatives, C_{m_u} and $C_{m_{\dot{u}}}$.

Those quantities which form the basis for the quantitative data obtained during these tests were recorded from a photo observer panel located in the airplane bomb bay by a 16mm camera equipped with a CAL designed intervalometer capable of varying frame speed. The frame speed used in all but the exploratory data flights was one frame for each 6 second interval. This was based on consideration of length of flight, camera capacity and, in particular, the power spectral density method of data analysis. The following variables were recorded:

1. Altitude
2. Elevator position
3. Manifold pressure
4. Longitudinal trim changes
5. Angle between airplane and ILS glide path
6. Time

Elevator position, trim indication and ILS glide path information required additional instrumentation.

The elevator position pickup consists of a gear system coupled to an AY201D type synchro. The installation is shown on Figures 3a and 3b. The driver is fixed to the elevator horn bracket, concentric with the axis of rotation of the horn. The synchro with the driven gear fixed to its shaft is fixed to the elevator horn. Servomechanisms, Inc., No. A403 precision spring loaded gears with a 10 to 1 ratio are used. Thus a 1° elevator input produces a 10° rotation of the synchro shaft. The electrical signal produced is first fed to a repeater synchro (same type) which permits a zero adjustment before each run. The signal then proceeds through a demodulator to an overload circuit and finally to a 100-0-100 ma Simpson meter and modified Lewis meter. The overload circuit shunts the meters for large elevator deflections thus protecting them from damage. The Simpson meter is used for monitoring and is mounted in the observer's compartment. The Lewis meter is mounted on the photo observer panel. It is calibrated in degrees elevator deflection with a full scale of 2° (±1°). It has 100 divisions (±50) and is readable to 1/2 division. The meter itself has a full scale accuracy of 1/3 of 1%. Thus elevator deflections of .01° may be accurately obtained.

Changes in trim are indicated on the photo observer panel by a 100-0-100 ma Simpson meter. The signal is obtained from a 1000 ohm ten-turn helipot connected to a 3 inch diameter pulley driven by the airplane trim tab cable.

In the approach configurations, deviations from the ILS glide path were recorded by a standard ILS cross pointer meter mounted on the photo observer panel.

During the tests, elevator control friction greater than that of the normal airplane was present due to the "drag" friction of the hydraulic servos used during the previous short period program. The total friction was measured on the ground to be approximately 13 lb.

DATA REQUIRED - THEORETICAL CONSIDERATIONS

INTRODUCTION

The data required for evaluation of the effect of phugoid damping as presumed in these tests consist of two parts, qualitative and quantitative. The physical flight configurations tested consisted of simulated instrument straight and level flying at altitude and simulated instrument landing approaches, ILS (Instrument Landing System) and GCA (Ground Controlled Approach).

QUANTITATIVE DATA

A portion of the quantitative data presented is in the form of a statistical sample designed to show the effect of phugoid damping on the pilot's ability to hold a straight and level flight path. The statistical method chosen is the power spectral density method of analysis and is applied to altitude and elevator deflection variations with time. This method will be discussed here only insofar as it affects the execution of the flight tests. Details may be obtained from Reference 5. Further discussion appears in the data analysis section of this report.

Inherent characteristics of this method dictate to some extent the physical characteristics of the test. It is desired that the amount of relative power appearing at or near the phugoid frequency be truly representative of the case and not distorted by power of the short period frequency. If there is negligible power at any frequency above the phugoid frequency, then considerably more latitude is available in the choice of parameters which compose the statistical sample. If it is suspected that such power exists, then (if no test for it is made) those parameters must be chosen with care.

A short flight was made to determine the amount of displacement (altitude) power at the short period frequency (approximately .5 cps). A time interval of 1 sec was employed. This was sufficiently small to provide a power point at this frequency. The results showed that no power existed. Thus it was possible to design the sample on the basis of resolution of power points, desired accuracy of the analysis based on statistical degrees of freedom, data reduction problems, and the flight length of each sample.

The final parameters chosen for data analysis were:

a. Recording time interval, $\Delta t = 6$ seconds

b. Number of power estimates[1] $m = 40$

c. Record length; approximately 3600 seconds. This resulted in frequency spacing of $\Delta f = \frac{1}{m \Delta t} = .00416\ c/s$

On the basis of Reference 5, this appeared sufficiently small. The number of points recorded was approximately 600. Hence, the degree of freedom[2] for a single damping configuration is

$$k = \frac{N}{\frac{m}{2}} = 30$$

Degrees of freedom are increased if a given configuration is repeated and the points at each frequency are averaged.

$$k = n\left(\frac{N}{\frac{m}{2}}\right) \quad \text{where } n \text{ is the number of runs.}$$

During this study data was obtained at least four times for each damping configuration, resulting in 120 degrees of freedom. For 90% confidence, this results in a band width of from .9 to 1.10. This will be discussed further in the section "Data Analysis".

QUALITATIVE DATA

The qualitative data required are those of pilot opinion. It is of interest not only to obtain an over-all indication of whether or not a configuration is preferred, but also to determine why such an opinion results. The latter is accomplished by requesting the pilot to comment on a variety of conditions existing during the tests. These items appear in the following section.

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[1] *m = the number of power estimates and represents the number of lagged products chosen in the calculation of the autocorrelation function, R_p .*

[2] *Degree of freedom is, in general, a measure of the accuracy of the analysis. It is a function of the number of recorded points, desired frequency spacing and time interval.*

METHODS OF TEST

INTRODUCTION

The previous section indicated the data required to successfully evaluate the effects of phugoid damping. The methods used to obtain these data are presented below.

PROGRAM

The range of variable phugoid damping chosen for study was from approximately -23% of critical to approximately 50% of critical. This essentially represents the suitable range of the installed equipment and was determined during the calibration phase of the tests. Further, it was felt that this range adequately represented the extremes, from a definitely undesirable point to one which could be little improved upon. Seven nominal values of phugoid damping ratios were chosen for test including the extremes above. They are -.23, -.15, -.05, +.05, +.15, +.30 and +.50. Essentially constant normal airplane period of 50 seconds was maintained throughout.

Since the results of these tests depend a great deal on the human pilot factor, each damping configuration was tested at least four times. Three configurations were done per flight; eleven flights of satisfactory data were considered sufficient for evaluation. Damping configurations were arranged throughout these flights such that, insofar as possible, each configuration was run at least once in each run position; and each configuration was run after a different configuration each time. The time allowed for each configuration was one hour. This was based on the time necessary for the pilot to adequately formulate his opinion, and on the time required for a representative sample of statistical data. A symbolic summary of the flight program follows on the opposite page.

At the conclusion of the altitude phase of each flight, a simulated instrument approach was planned for a given damping configuration, using the ILS method. Later in the program, the GCA method was also used.

FLIGHT NO. (RELATIVE)	RUN 1	RUN 2	RUN 3	KEY	
					ζ
1	e	c	a	a	+.50
2	d	b	g	b	+.30
3	f	d	a	c	+.15
4	b	e	g	d	+.05
5	c	f	b	e	-.05
6	a	g	d	f	-.15
7	a	c	e	g	-.23
8	e	a	f		
9	g	b	c		
10	d	a	b		
11	f	b	a		

The damping ratio range covered in the approach phase was (nominally) from -.15 to +.55. This range, also determined from flight calibration, differed from that of the altitude phase because of the inherently greater drag (hence greater damping ratio) due to flaps down, gear down configuration. Nominal values of damping ratios employed were: -.15, -.10, -.05, .05, .15, .30, and .50. As in the case of the altitude tests, approaches were made "under the hood".

In order to obtain a detailed estimate of a given damping configuration, the pilot was instructed to comment on the following items:

1. Ability to trim
2. Stick forces
3. Stick motion
4. Control feel
5. Ease of attaining desired altitude and airspeed after a procedural change in altitude or heading has been made
6. Turbulence; smooth, light, moderate, heavy, very heavy

7. Have you been doing what you could call (excessive, moderate, normal little) work in order to do a (poor, normal, excellent) job of instrument flight?
8. Is it frustrating to fly this airplane?
9. Has there been a change in your technique of monitoring the instruments?
10. Over-all rating of the configuration
    a. Very good
    b. Acceptable good
    c. Acceptable
    d. Acceptable poor
    e. Unacceptable

Definitions of the above ratings appear in the Data Analysis section.

Calibrations

Previous to the data flights, several flights were made to calibrate the airplane, i.e., obtain a variation of damping and period as a function of input knob settings. In addition, calibration check points were obtained during the data flights. Figures 5 and 6 show the calibration curves for the altitude and approach configurations. It was impossible to attain the extremes of the damping range without a slight variation of period. Since the pilot is relatively insensitive to small changes in period, this condition was tolerated in the interest of extended damping range.

Performance Techniques

In general, calibration and data flights were performed at 5000 ft and 200 mph indicated airspeed. Since smooth air was of primary importance during calibrations, altitudes were chosen to meet this requirement. Calculations indicated little effect on damping ratio of the test altitude variations.

Approach calibrations were performed at 150 mph indicated airspeed with gear down, flaps down 20° and power setting as required.

Calibration technique consisted of displacing the nose upward until an approximate 10 mph out-of-trim decrease in airspeed was realized. The stick was then rapidly returned until the elevator was in the initial trimmed position. It was necessary to slightly overshoot the pilot's control in order to negate the effect of servo friction in the control system. For the negatively damped points a 0 to 5 mph out-of-trim airspeed was used. Time histories of δ_e , δ_{AUX} , u and $\dot{u}$ were oscillograph recorded. An attempt was made to obtain at least 2 cycles of the motion. The u trace was analyzed by established techniques (Reference 4) based on the assumption of a second order system, to obtain the damping ratio and period.

During the one hour data runs, the pilot was instructed to maintain constant altitude and airspeed. Navigation, radio checks and all normal instrument flying procedures were handled by the pilot. Variables previously mentioned were camera recorded. After each hour configuration the pilot presented his comments which were tape recorded in the airplane.

ILS approaches were made in the following manner. The glide path and localizer beams were intercepted at approximately 2700 ft above and about 11 miles from touchdown. Descent and camera recording were started immediately. Thus, approximately 4.5 minutes of recorded data were obtained. Knob settings (damping ratio)usually corresponded closely to those of the last altitude run of the flight.

The GCA runs at each of the seven damping configurations were made in succession on a flight for this particular purpose. Recording was begun upon ground controller contact, 8-10 miles from touchdown at approximately 1800 ft. The glide path was started 3-3.5 miles from touchdown. Ground controller's talkdown and pilot's comments were tape recorded for each configuration, as were the photo observer panel variables.

DATA ANALYSIS

INTRODUCTION

Two forms of data are available for analysis. They are the pilot comment data and the quantitative data deduced from oscillograph records and from photographic records of flight instruments. These two forms of data are independent but should correlate with each other. The analysis of each and the correlation between them is discussed.

PILOT COMMENT DATA

The manner of obtaining these data have been discussed. What has been done with it is as follows.

In Table I, pilot comments and ratings obtained in the flight evaluation have been grouped according to configuration. These formulations of the data exhibit several related trends in the pilots' opinions as the phugoid damping is varied. Most discernible are those trends concerning "the ability to trim the airplane", "the amount of pilot effort required to fly the airplane on instruments", and the extent to which "the airplane is frustrating to fly". In essence these trends all show, that for the pilot, more agreeable airplane characteristics exist at the higher values of phugoid damping. For example, at -23% of critical damping the airplane is "very difficult" to "impossible to trim" whereas at +50% of critical damping the airplane trims "quite well" to "very well". A corresponding change occurs in pilot effort required to fly the airplane on instruments. For example, at -23% critical damping a fairly extensive to excessive amount of effort is required as contrasted with a normal amount of effort at the higher values of damping. At the negative values of damping the pilot feels that he accomplishes a "fairly poor" to "poor" job of instrument flying despite his effort, and he feels that the airplane is frustrating to fly. With positive damping the pilot feels he does much better at instrument flying with less effort and that the airplane is "not particularly frustrating" to "not at all frustrating" to fly.

For the negative values of damping the pilot often concentrates more than he feels is normal upon the gyro-horizon pitch-bar. This becomes necessary for the pilot to feel confidently informed of the pitch attitude of the airplane and make the required control corrections to maintain the desired pitch attitude without getting badly out of phase with the airplane.

A study of the pilot ratings was made to determine if they might be noticeably affected by the order of configurations in each flight. If such an effect is present,it is too small to be detected among the other variations present. Excluding the strong trends with phugoid damping, the remaining variations present are probably a result of turbulence coupled with the pilot's desire to rate some things independently of turbulence and other things dependent upon turbulence.

Perhaps the most significant comparison of pilot comments is that between " effort required" and " self rating of instrument flying ". As damping increases the effort required becomes less and the rating of instrument flying becomes best. It is not known, but possibly these two parameters interact in such a manner that in heavy turbulence the highly positively damped configurations would be markedly better than any of the other configurations and to an extent greater than has been displayed in the essentially smooth to light-moderate turbulent air prevalent during this program.

The pilot rates his ability to trim as independently of turbulence as he can. In turbulence the amount of time required to ascertain the proper trim settings is increased, but the basic ability to trim the airplane remains unchanged. Another aspect of the ability to trim the airplane is the ability of the pilot to find the "groove". There are two ways in which the airplane can be grooved. One is to stabilize each of the flight reference instruments within limits established by the pilot. The other groove is referred to as a "mechanical groove" and is the characteristic shown by some airplanes to return positively to assigned attitude after a disturbance. This characteristic is sometimes described by referring to some form of mechanical latch which automatically and positively seeks its detent whenever it has been unlatched. Whenever the mechanical groove exists the pilot might speak of being able to "bore holes, hands off" which means he is confident enough of the airplane characteristics to allow the craft to fly itself with only infrequent pilot control applied. This is a perfectly normal manner for flying some airplanes and the "mechanical groove" is the more important form of groove in this program.

Ratings of the attainment of altitude and airspeed after a procedural turn are affected by turbulence if the attainment takes place through a patch of turbulence.

Effort required to fly the airplane on instruments was considered by the pilot to mean that physical and mental effort which he expended only as a result of the phugoid characteristics of the airplane. The pilot rates this effort by considering the turbulence and trying to discard its effect. However, at no time during any of the test flights did the pilot know any of the quantitative parameters which described the phugoid characteristics with which he was coping. He ascertained the phugoid characteristics in a qualitative manner from his concentration upon the rate-of-descent, the altimeter and the airspeed indicator. His determination of the phugoid characteristics and the effort expended solely because of the phugoid motion are based upon the situations he was forced to overcome after the airplane had been disturbed.

The ratings of the instrument flying job done are based upon the ability to maintain a desired altitude and are affected by turbulence. To maintain within ±100 ft of the desired altitude is considered to be good or normal by the pilot; ±200 ft is considered acceptable but by no means good; beyond ±300 ft is questionable and rapidly approaches being unacceptable.

The ratings of how frustrating the airplane is to fly are based upon the pilot's ability to be in constant positive control of the airplane to the extent that the airplane allows him to fly as well as he believes he should be able. Turbulence affects these ratings. It does so particularly through its interaction with the ability to trim the airplane. It becomes very frustrating to the pilot when he believes he has the airplane trimmed and turns to another duty, to have the airplane respond to some disturbance in an apparently divergent manner or at least in some manner deemed unsatisfactory by the pilot.

Whenever the pilot makes a major change in his mode of monitoring the flight instruments he always monitors the gyro-horizon to an extent he considers to be quite a bit more than normal. The purpose of this change is excited by the characteristics which makes the airplane appear to have a divergent reponse which the pilot fears might get ahead of him. By concentrating more than normal upon the gyro-horizon for pitch changes the pilot can better anticipate changes in the airspeed, altimeter and rate-of-climb or descent indications and keep himself more in phase with them and better informed for coping with them.

Each of the ratings of turbulence is a qualitative one given by the pilot. Although these ratings are the result of flying by instruments through the turbulence, they were each supported by the safety pilot who had visual contact with all flight references, external as well as internal to the airplane. No direct quantitative measures of turbulence were made and hence possible daily variations in the qualitative ratings are undefined but it is felt that the pilot's ability to rate turbulence remains quite constant.

An over-all rating was the last comment given by the pilot for each configuration and is shown as a function of phugoid damping ratio on Figure 7. These ratings represent levels of acceptability of each configuration flown and are given immediately after flying the configuration. Because the majority of the flights were done in smooth air or light turbulence the over-all ratings are limited to these conditions. It is not known what shift, if any, would occur in these ratings were the turbulence level increased.

The over-all rating scale, and its definitions, was developed by the pilot and is based upon the tendency of the airplane to return to trimmed flight after a pilot input or atmospheric disturbance, and the resulting pilot effort required to maintain a desired altitude and airspeed. This tendency is determined by observing the altimeter, the rate-of-descent or climb and the airspeed indicator. The gyro-horizon was excellent for determining if a change in pitch attitude was under way but was limited in determining magnitudes and did not enter directly into the pilot's over-all rating mechanism. The flights were all instrument flights since it was determined in a previous program that, in contact flying, the pilot is much less sensitive to the effects of phugoid damping. The over-all rating scale is defined as follows:

Rating	Definition
Very good	All pertinent parameters are excellent in all respects. (This rating was never given by the pilot who feels he has no right to establish a par excellence when in the future something of which he has not thought might be superior.)
Acceptable good plus Acceptable good	After a disturbance the airplane noticeably seeks and obtains rather quickly the trimmed flight condition. The pilot is able to maintain altitude within ±100 feet.
Acceptable good minus Acceptable plus	
Acceptable	After a disturbance the airplane seeks trim rather slowly. The pilot is able to maintain altitude within ±200 ft.
Acceptable minus Acceptable poor plus	
Acceptable poor	This airplane stops where you put it or where a disturbance leaves it; i.e., it doesn't diverge but it maintains the attitude, as determined from the altimeter, the rate-of-ascent or descent and airspeed in which a disturbance leaves it. This airplane requires constant and very definite pilot effort and the pilot has difficulty maintaining the desired altitude within bounds less than ±200 feet.
Acceptable poor minus Unacceptable plus	
Unacceptable	This airplane is definitely divergent after a disturbance.

Certain of the ratings just defined are ostensibly paired. These are: acceptable good minus with acceptable plus, acceptable minus with acceptable poor plus, and acceptable poor minus with unacceptable plus. The pairing arises because there is no clear distinction between the two members of each pair. The use of those plus and minus ratings was initiated by the pilot to rate those configurations that could not be definitely placed in either of two adjacent major rating groups. This precise distinction between ratings is felt to be possible on a given flight, but it may not be consistent from one flight to another.

The data were classified with respect to damping ratio, flight, order of configuration in a flight, turbulence rating, and configuration over-all rating. Numbers were assigned to the pilots' ratings in a consistent fashion. After several different approaches of analysis, it was determined that the main variation in configuration over-all ratings is with phugoid damping. The remainder of the variations are considered experimental error since they can not be assigned to definite factors. Because this is the case a comparative analysis of the pilots' comments yields the total of the information available from the comment data. The conclusion from such an analysis is that phugoid damping does affect a pilot's opinion of his performance of instrument flight and a substantial positive damping makes possible the more desirable opinions.

This conclusion is mandatory from the consistent trends toward higher levels of acceptance and/or efficiency vs. phugoid damping that appear in each of the classes of pilot comments.

During the majority of the test program, the pilot frequently spoke of desiring and not having a "mechanical groove" (this term has been previously referred to on p. 13). Study of the problem and subsequent flight tests revealed that by removing the u input from the artificial stability system, the "groove" was noticeably produced for .30 and .50 damping ratio. The u input is used in the basic system as necessary to maintain constant frequency as the damping is varied. In addition, however, the artificial ΔC_{m_u} thus produced contributes an unstable component which reduces the stability for flight at constant lift. This is particularly true at the higher values of positive damping. Thus, by reducing this static instability by removing the u input, a "grooving" tendency is produced which is desired by the pilot. A slight variation of phugoid period with damping also results.

Although the pilot was very enthusiastic about having this groove, the configuration on which he noticed it did not appear to be any different in over-all quality from other configurations of the same damping but without the groove. Insufficient data were obtained to realize a significant estimate of the effect of this phenomena.

QUANTITATIVE DATA

The quantitative data obtained were for power changes per hour, trim adjustments per hour, altitude variance spectrum and total variance, and elevator variance spectrum and total variance. The variance spectra are determined by power spectral density techniques. The total variance is determined from plotting the data on arithmetic probability paper. Variance is, essentially, the value obtained by squaring the rms of a distribution provided the rms is determined about the true mean of the distribution. Such an rms value is also the standard deviation of the distribution.

The procedures used in reducing the recorded data to the above are outlined in the Appendix.

TRIM AND POWER DATA

Measurements of elevator trim adjustment were made every six seconds by recording the elevator trim knob angular position. However, the majority of the trim changes made by the pilot were exceedingly smaller than anticipated and were hidden within the resolution of the instrumentation. It also may have occurred on some runs that the pilot had completed the majority of his large trim adjustments before the recording equipment was turned on. These factors combine so that the average trim changes per hour are very unreliable.

Measurements of power changes were made by recording the manifold pressure for one engine every six seconds throughout the run. Since the manifold pressure gauge is effectively an altimeter and is disturbed by vibration and possibly by acceleration forces, changes of manifold pressure of approximately 0.5 inches were expected as a function of these parameters.

In counting the number of 0.5 inch changes, absurd numbers of power changes were obtained. Hence, the number of changes of 1 inch up to but not including 2 inches were counted and the number of changes of 2 inches and greater were counted. The numbers of both of these changes are very low and preponderantly zero. There is no correlation between the numbers of changes, when they are greater than zero, and per cent of critical damping of the phugoid of the airplane. Thus, if the measurements of manifold pressure changes of 1 inch or greater are valid estimates of power changes, then it is concluded that the pilot does not expend different amounts of effort on power settings among the configurations.

THE ALTITUDE VARIATION DATA

Changes of the phugoid damping result in different altitude response to pilot and gust inputs. The differences are in the frequency at which the amplitude ratio of the transfer function is a maximum and in the magnitude of the amplitude ratio throughout the frequency range. Hence if the flight conditions are restricted such that there are, besides pilot-input disturbances, no disturbances that result in altitude changes (e.g. gusts) and such that the pilot-input disturbances are congruous from one damping condition to another, then the rms of the altitude time histories is a direct measure of the effect of the different damping conditions.

Several variations from the restrictions exist in the data and are explainable but not particularly measurable. One variation is the turbulence level which was qualitatively measured but not precisely or accurately determined, and the turbulence level was not constant throughout the test. A second variation is that the pilot in actuality performed as relaxed instrument flying as he could and the amount of effort expended depended upon the characteristics of the configuration. This results in the possibility that the rms of altitude for a poor configuration that requires a great deal of effort is the same as the rms of a good configuration that requires very little effort. All this suggests the possibility of flight-to-flight variations. From the rms data as displayed in Table II and shown in Figure 8, it is obvious that flight-to-flight variations are as large as the variations due to configurations. These variations coupled with the relatively few repetitions in this program result in weak significance tests and the trend of decreasing altitude rms with increasing phugoid damping cannot be supported with this data alone. Some of the numbers in this table are for turbulent air, but no conclusion can be determined as to a definite effect due to turbulence. It also is reasonable to suggest that the table may indicate that altitude rms alone is, for an experiment of such limited size, a very weak measure of the effect of phugoid damping upon pilot ability to fly instruments.

The pilot-opinion data and co-pilot-observer in-flight comments become very important for establishing in a comparative fashion some differences among the configurations. Aspects of the opinion data have previously been discussed.

One relation that exists between the altitude rms and pilot-comment data is between the measured rms values and the altitude variations specifically included in the pilot's definitions of the over-all-rating scale. The altitude variations noted in the definitions were expected by the pilot to be average variations, not total variations, and this expectation was reiterated several times during and after the tests. In actual fact, for each configuration associated with a given rating, the variation as defined by the pilot very closely includes 95% or greater of the corresponding altitude data. That is, for those configurations rated AG the altitude variation of ±100 ft, associated by the pilot with that rating, includes 95% or greater of all of the measured altitude variations from configurations rated AG. These comparisons are shown in Table II included in which is an illustration of the relationship between the rms and the percentage of data included if the data is normally distributed. It is seen that very few of the altitude variations associated with the ratings (4 to be exact) include 100% of the data. In detail the majority of the configurations have a range a good bit wider than 6 σ (±3 σ) and in them there is significantly more data in the tails of the data distribution than there would be if the data distributions were precisely normal. The relation between the data and a normal distribution will be discussed further later on, but from the initial analysis described above it is concluded that the pilot bases his opinion on variations of altitude greater than average and that if so relaxed a criterion as is given for altitude variations in the rating scale is used, there is good correlation between the ratings given and the measured rms of altitude.

It has so far been established that the pilot-opinion data are in agreement with the rms data. A remaining question is whether the rms data are more or less definitive than, or the same as, the opinion data. There is so much variation from flight to flight that the query is difficult to resolve, but this difficulty is, itself, a partial answer.

To answer the question more completely consider that the rms is a sensitive and consistent measure of the differences among the damping configurations. Let, also, the variation from flight to flight be the same as using different zero points on the scale of measurement. On this basis determine if there are consistent separations, in terms of the measured rms,among the over-all ratings and if there are consistent separations, in terms of the measured rms, among the configurations. If there are consistent separations in these two manners then the configurations and over-all ratings can be paired and this result can be compared to the pairing by the pilot of ratings with configurations. The conclusion from such an analysis is that the pilot comment and rating data are superior to the rms data.

It has been shown that the rms data do not necessarily exhibit a trend in the phugoid damping, whereas the pilot comment data do. In discussions with the evaluation pilot it was determined that pilot confidence in airplane handling characteristics increases with increased phugoid damping. The manner in which the handling characteristics affect the pilot may be summarized as the degree of confidence in the ability of the airplane to fly itself, which the pilot derives from the flight characteristics. It is possible that the rms values are more measures of this confidence than of the ability of the pilot to fly instruments. This can be exemplified by a discussion of piloting technique.

Piloting technique for one pilot flying instruments includes performing all radio, navigation and engine instrument checks as well as watching, interpreting and making decisions from the flight instruments. The pilot must continually compromise his attention among these tasks. If the pilot acquires between two configurations relatively different amounts of confidence, for the one in which he has more confidence he may be relatively lenient in making altitude corrections and direct his attention more upon the other tasks. A result of this can be a larger rms of altitude for the better configuration. The pilot himself has made a statement to this effect and also that had he been on actual IFR flight rather than simulated instrument flight with a safety pilot, he would have flown all configurations, particularly the poorer ones, more tightly. He flew all of the poorest configurations with an amount of effort which, to him, was excessive. What would happen, precisely, to the rms under actual IFR flight is unknown because it is not known whether the pilot would increase his effort by some constant increment or by some increment dependent upon the configuration and its characteristics. It is known only that for all configurations some greater amount of effort might be expended.

The conclusions from the preceding discussions and analyses are the following:

1. The results of the test are limited to aircraft which possess phugoid properties consistent with those tested.
2. The results pertain to smooth air or light turbulence and there is no basis for the extrapolation of them to heavier turbulence.
3. The rms data is no more enlightening than the pilot-comment data but it does establish that what the pilot refers to as average altitude variations are considerably larger than average.
4. The flight-to-flight variations of altitude rms are large, but the pilot-opinion data seem to be more stable, implying that the pilot does not consider the rms of altitude as too important, and that the other characteristics are at least as important.
5. Other than the magnitude of altitude variations, the pilot considers the manner in which the airplane deviates, which greatly determines the confidence he has in each configuration.
6. It is very possible that altitude variations in a more extensive program would still be only a weak measure of the effect of phugoid damping. As the pilot gained confidence he allows the airplane to

fly itself to a greater extent with the higher values of phugoid damping and thus obscures the effect of phugoid damping on altitude variations. However, this is a positive effect as determined by the pilot's comments.

DISCUSSION OF POWER SPECTRAL DENSITY APPROACH TO THE DATA

Power spectral density methods were applied to the altitude and elevator motion data. The altitude and elevator power spectra are presented in Figures 9 and 10. These data at each value of phugoid damping are the averages of four runs. From them, for frequencies higher than the phugoid (.02 cps), the relative altitude power content is greatest at the worst value of phugoid damping and progresses approximately as a function of phugoid damping to the least power content at the highest value of damping. These results agree qualitatively with the pilot's opinion and are among themselves quite consistent. However, for them to be direct quantitative measures of the effectiveness of the different values of phugoid damping, then either the airplane must not respond to gusts or else there must be no gusts. The second of these conditions is the only realistic one and the evaluation pilot and his check pilot both agreed that many runs were in smooth air.

To determine if gusts were present calculations with the power spectra from runs of normal airplane characteristics flown in air rated as smooth by the pilot were made to obtain the amplitude portion of the altitude to elevator transfer function. This transfer function does not agree, as shown in Figure 11, with the amplitude portion of the transfer function for the normal airplane as determined from an harmonic analysis of the altitude response of an elevator pulse. A simple and direct approach establishes that the difference shown might be expected as a result of even those long period gusts which are not discerned by pilots.

GCA AND ILS APPROACH DATA

The following quantitative data were analysed in an effort to obtain correlation between phugoid damping and parameter variation during descent.

1. Altitude as a function of time - GCA and ILS

2. Indicated air speed as a function of time - ILS
3. ILS cross-pointer meter deflection as a function of time - GCA and ILS
4. Elevator deflection as a function of time - GCA and ILS

None of the above data show any significant trend with damping ratio. The altitude and airspeed time histories shown on Figures 12, 13 and 14, represent single-run data. Large relative changes in altitude (as indicated by deviation from an approximate mean path) are not evident. However, deviation from the airplane glide path cannot be estimated because of insufficient glide-path data. Initial and final altitudes are noted. On the basis of the data obtained,it is estimated that considerably more approach runs at each damping configuration than were possible in this program are necessary to determine whether any variations in vertical distance from the glide slope and airspeed exist as a function of phugoid damping. A sufficient number of runs at each configuration would indicate whether such trends do exist or whether pilot input is such that altitude variation (for example) is maintained constant with damping ratio. The latter situation could be verified from pilot opinion in terms of additional work required at the lighter (or negative) damping ratios.

As in the case of the quantitative data, pilot opinion shows no significant trend with phugoid damping ratio. The scatter of the over-all rating points indicates that practical difficulties may tend to mask the apparent subtle effects of damping. For example, the pilot felt that the GCA runs were of too short duration to adequately form an opinion. Such difficulties may be directly related to pilot experience. A higher level of experience than used here (in terms of the number of approaches made in daily pilot activity) could conceivably provide a degree of observation sufficient to adequately detect small differences in the airplane-pilot system.

From the above, it may be seen that the approach data presented here represent only a preliminary look at the problem of phugoid damping in the approach configuration.

SUMMARY OF TEST DATA LIMITATIONS

There are several important limitations to the test data as presented in this report on which the succeeding conclusions are based. They are:

1. Restriction to phugoid frequencies near .02 cps. The pilot monitors the actual airplane response, where the phugoid response to a pulse input is of the form $Ke^{-\zeta\omega_n t}\cos(\omega t+\phi)$. For long periods the pilot sees only the $\cos(\omega t+\phi)$ term. Therefore, it appears possible (for example) that a very low frequency and light damping ratio would appear initially to the pilot as .02 cps and very high damping ratio. However, this possible combination (and others) may manifest themselves to the pilot by handling qualities different from those obtained.
2. Restriction to smooth air. The majority of runs were made in smooth air. In those cases where turbulence was encountered, the pilot attempted to rate on the basis of smooth air. Lack of sufficient quantitative data invalidated any rational means for extrapolation to turbulent air. The results are therefore limited to smooth air.
3. Limited instrument flying experience. Since the pilot has had limited opportunity to extend his instrument-flying experience level, he felt that this might be a limitation on the results.
4. Simulated instrument flight. All of the results are most directly applicable to simulated instrument flight. The pilot felt that for actual instrument flight he would fly each configuration more tightly and pass secondary duties to the copilot. Also, there may have been some psychological effect of having a safety pilot on visual flight. These differences from actual instrument flight are not expected to particularly affect the pilot's comments other than to possibly make a rather minor shift in the ratings of the configurations, but they would affect the altitude rms values in smooth air.
5. There was only one evaluation pilot. It is doubted that this is any severe limitation. Three different instrument pilots with active certificate ratings acted as safety pilot on different occasions and they each felt the evaluation pilot was using perfectly normal

procedures and that he was doing a complete, objective, and reasonable job of evaluation. It is expected that from other pilots similar comments would be obtained, but that variations in rating and especially altitude rms might be found.

6. The approach information for both ILS and GCA is limited by the short time spent on each actual letdown. Such short times were not sufficient for the pilot to feel confident of his evaluations, and were not sufficient to adequately determine consistent differences among the recorded time histories of the approaches. This limitation is most severe for the GCA approaches.

CONCLUSIONS AND RECOMMENDATIONS

CONCLUSIONS

Because of the low inherent drag of modern, high-performance aircraft, a trend toward lower values of phugoid damping exists. Pilot opinion of instrument-flight characteristics is considerably affected by phugoid damping. The comments obtained in this investigation indicated the following adverse effects of decreasing phugoid damping:

1. The ability to trim at a desired air speed deteriorates.
2. With increasing "negative damping" the deviations due to disturbances of the airplane from the desired equilibrium become increasingly annoying.
3. The attention and effort required for "just flying" increases.
4. The pilot's instrument-flying technique changes. He monitors air speed, altitude, and rate of climb increasingly more, with a resulting decrease on other instruments. With extreme "negative damping" he found it necessary to monitor the horizon bar of the gyro horizon very critically as well as the rate of climb to maintain altitude.
5. The magnitude of the altitude variation increases.

The quantitative altitude variation information obtained corroborates the pilot's opinion of the magnitude of the variations. Also, there is an apparent trend of altitude variation with phugoid damping similar to the trend of pilot-opinion ratings.

The pilot-opinion data and the quantitative data obtained indicate no great improvement is realized if phugoid damping is increased beyond 15 to 30%. If damping decreases below this value, both pilot opinion and measured pilot-airplane performance fall off rapidly.

Insufficient approach data (both quantitative and qualitative) were obtained to indicate any trend as a function of phugoid damping.

RECOMMENDATIONS

It is recommended that:

1. The validity of rms as a criterion for measurements of the type made during this program be definitely established. In particular, as applied to phugoid-damping-ratio effect on altitude variation presented here, this might be done by obtaining more runs per damping configuration, using several pilots. Such a program should include pilots having a high instrument-flying experience level, i.e., airline and military air transport service personnel.
2. Further study of the application of the power-spectral density technique be made, with emphasis on the reasons for apparent differences between airplane frequency response obtained by this method and that obtained from the pulse transient method.
3. Further study be made to improve methods of test technique for instrument approaches so that the effect of phugoid-damping ratio will be reasonably defined.
4. Because the pilot commented that the spiral mode had an apparent influence on the motion of the airplane at the same time the phugoid motion was being evaluated, a study be made of the spiral mode and possible spiral-phugoid coupling.

REFERENCES

1. Heilenday, F. and Campbell, G., Artificial Stability and Control of Longitudinal Motion of the B-26 Aircraft - Theoretical Investigation. Air Force Technical Report 6703, Cornell Aeronautical Laboratory Report TB-757-F-2 November 1951
2. Newell, F. and Campbell, G., Flight Evaluations of Variable Short Period and Phugoid Characteristics in a B-26. Wright Air Development Center Technical Report 54-594, Cornell Aeronautical Laboratory Report TB-757-F-11 December 1954
3. Kidd, E. A., Artificial Stability Installations in B-26 and F-94 Aircraft. Wright Air Development Center Technical Report 54-441, Cornell Aeronautical Laboratory Report TB-757-F-9 September 1954
4. Draper, C. S., McKay, W., and Lees, S., Instrument Engineering Volume II, McGraw-Hill Book Co., Inc. September 1952
5. Lappi, U. O., A Direct Method of Utilizing Flight Data to Determine Space and Spectrum Gust Velocity Distributions and Airplane Gust Performance Function. Cornell Aeronautical Laboratory Report GM-776-T-45 August 1955

FIGURE I JTB-26B AIRPLANE SERIAL NO. 44-3453

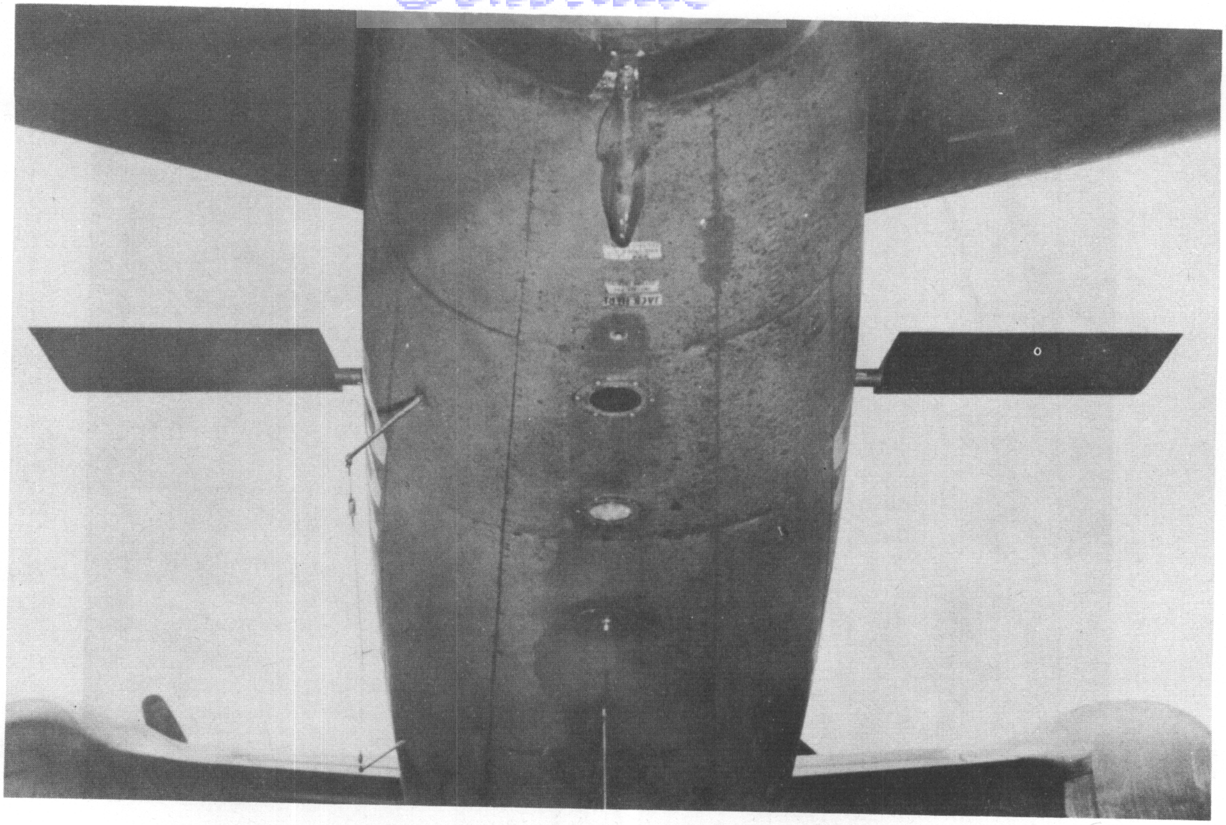


FIGURE 2a AUXILIARY CONTROL SURFACES - REAR VIEW

FIGURE 2b LEFT AUXILIARY CONTROL SURFACE

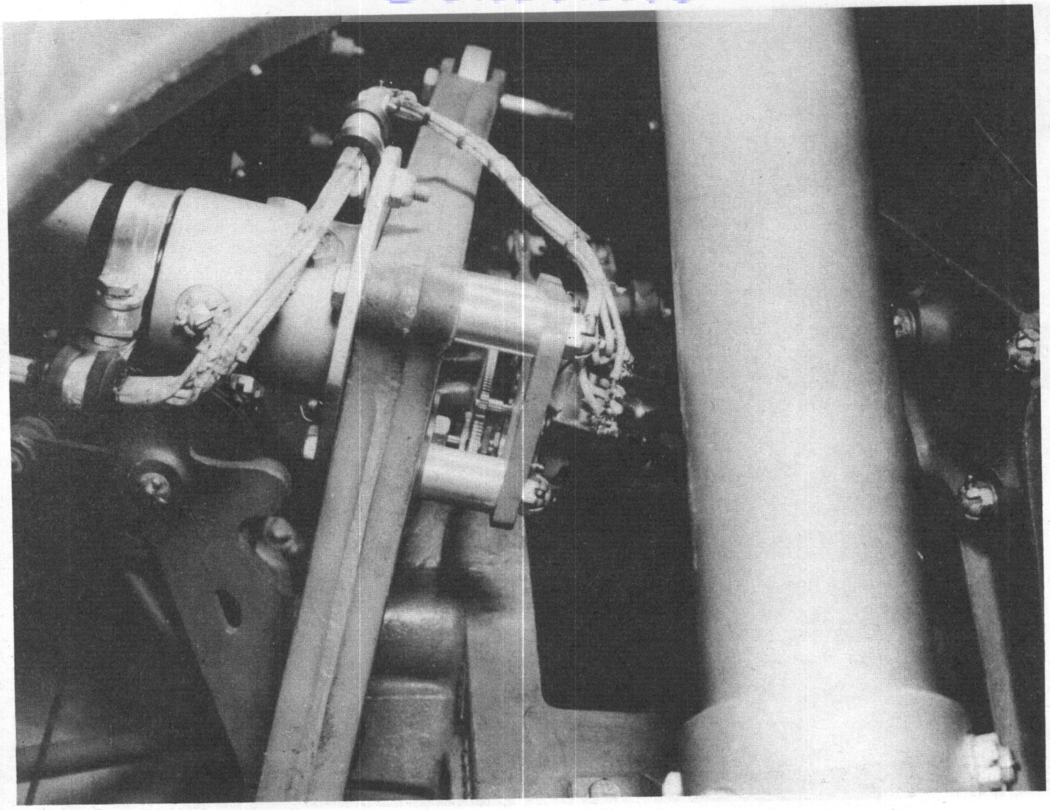


FIGURE 3a ELEVATOR DEFLECTION PICKUP - FRONT VIEW

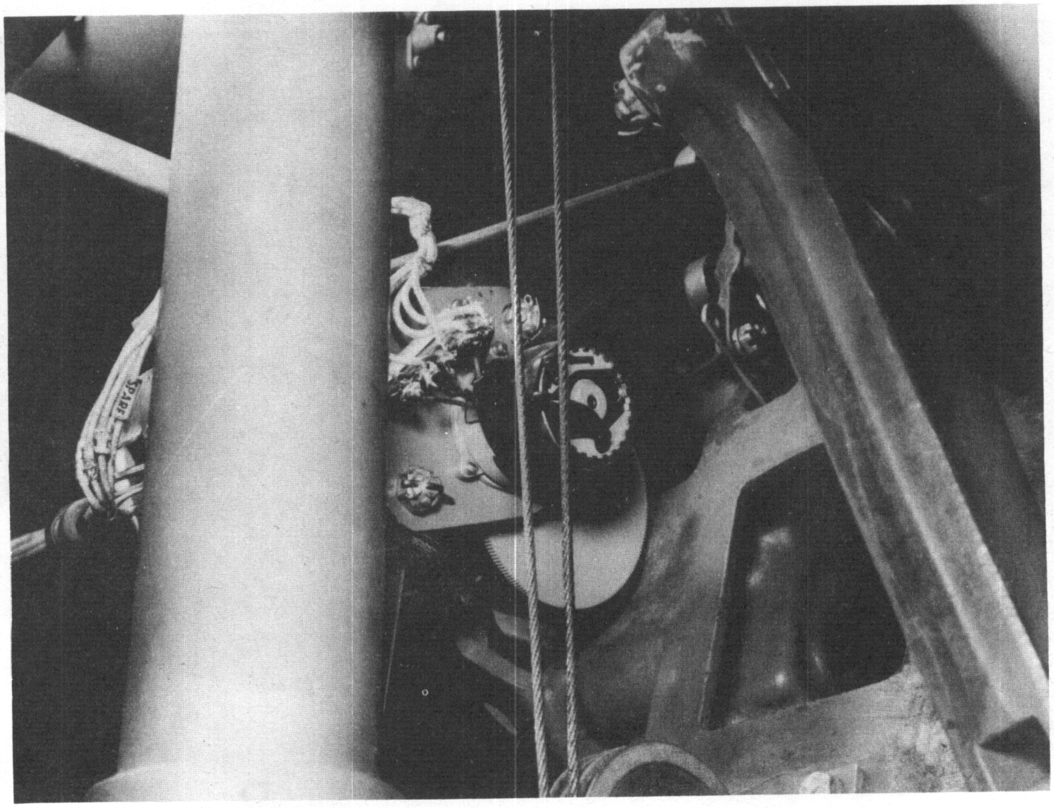


FIGURE 3b ELEVATOR DEFLECTION PICKUP - THREE-QUARTER FRONT VIEW

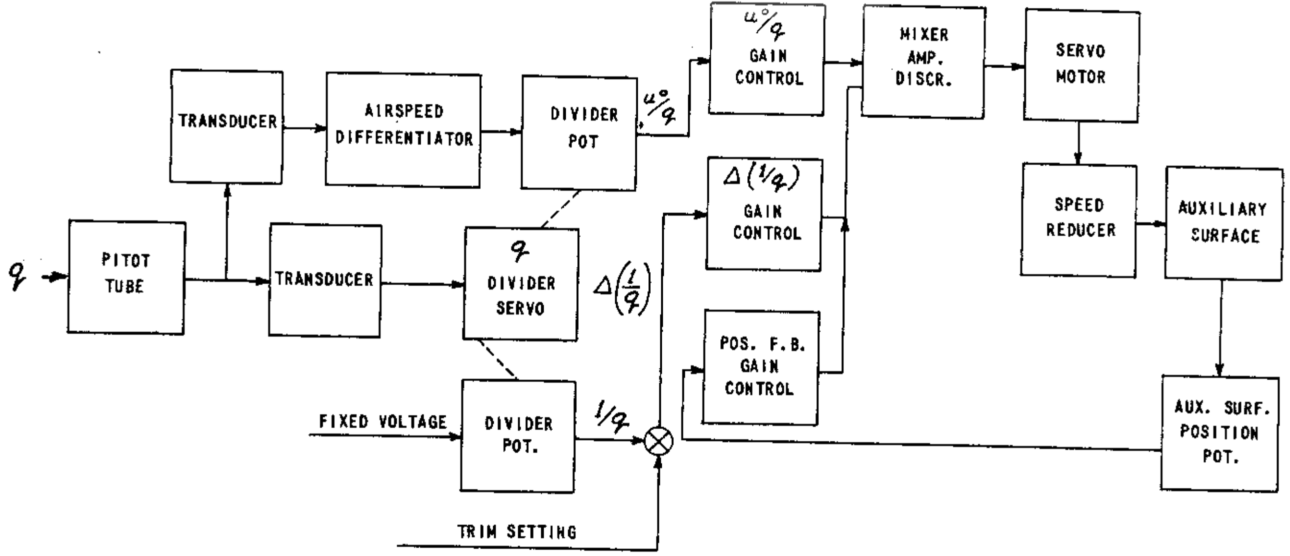


FIGURE 4 BLOCK DIAGRAM OF B-26 PHUGOID VARIABLE STABILITY CONTROL SYSTEM

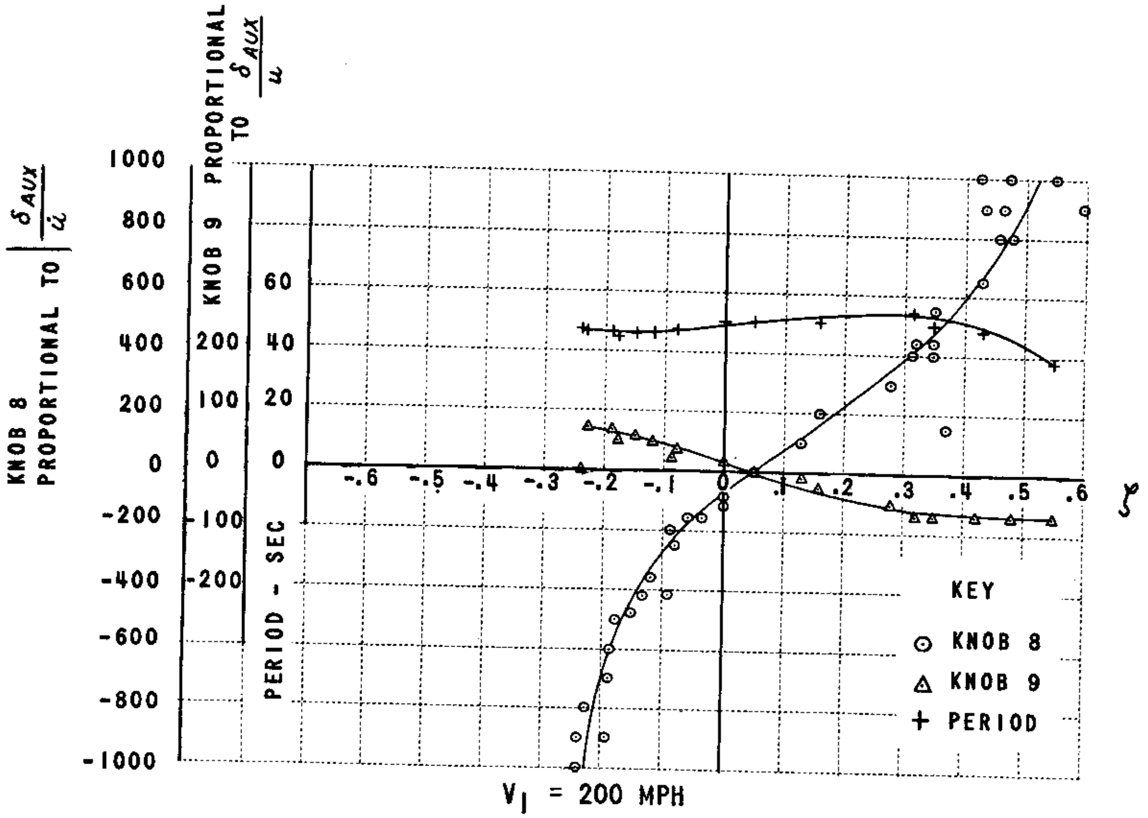


FIGURE 5 ALTITUDE CONFIGURATION FLIGHT CALIBRATION

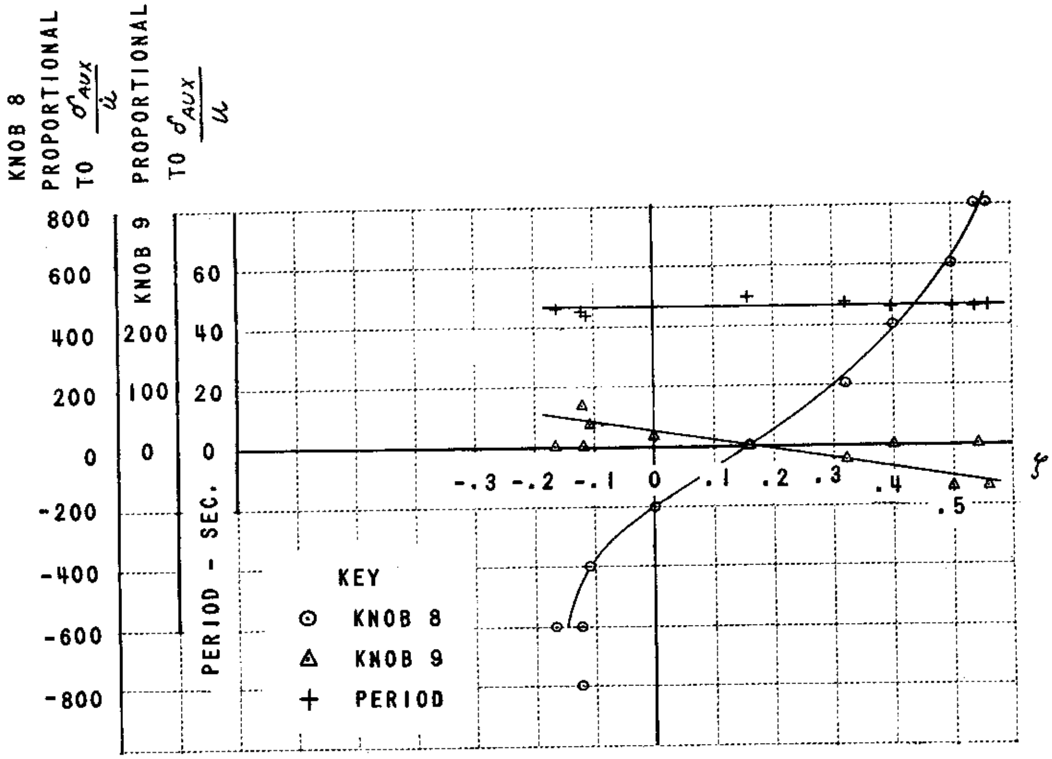


FIG. 6 APPROACH CONFIGURATION FLIGHT CALIBRATION V_I = 150 MPH

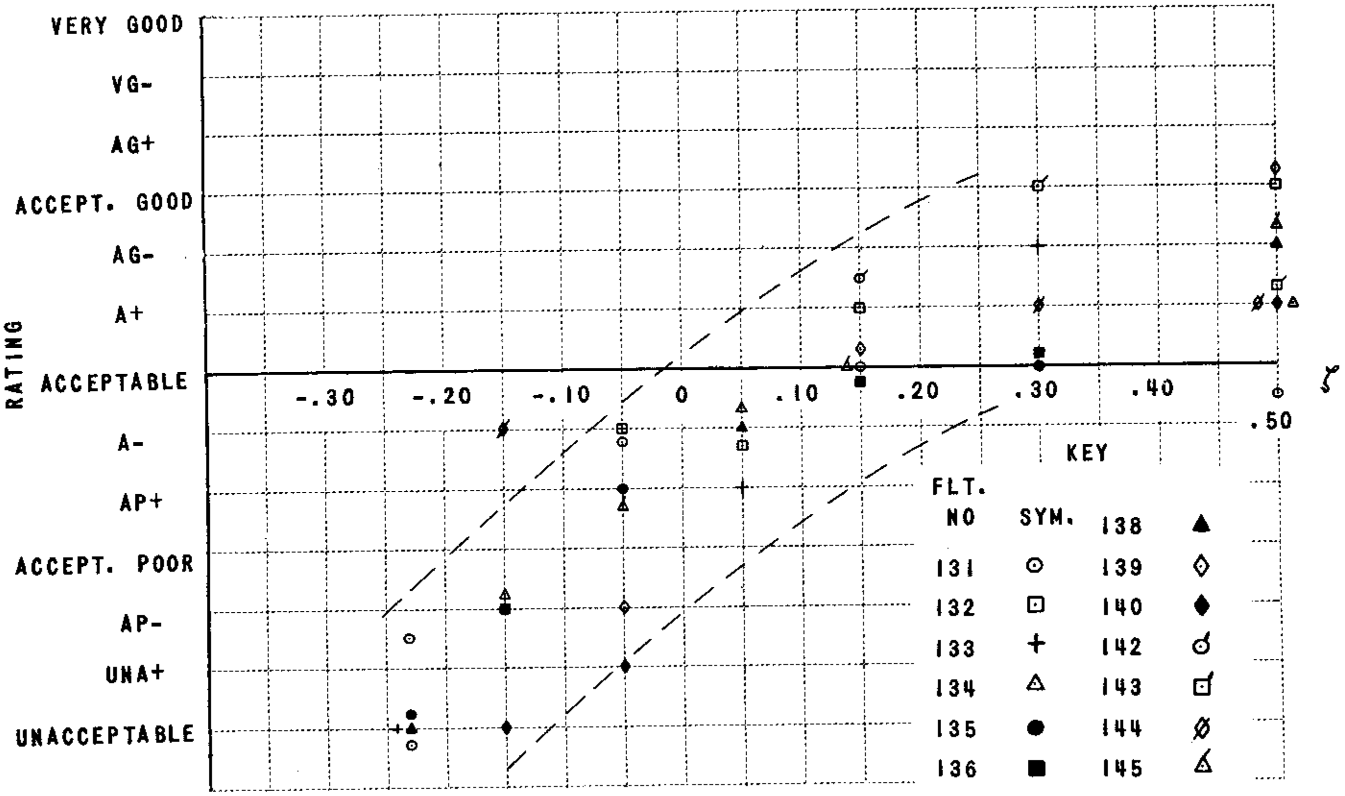


FIGURE 7 PILOT'S OVER-ALL RATING VS. PHUGOID DAMPING RATIO

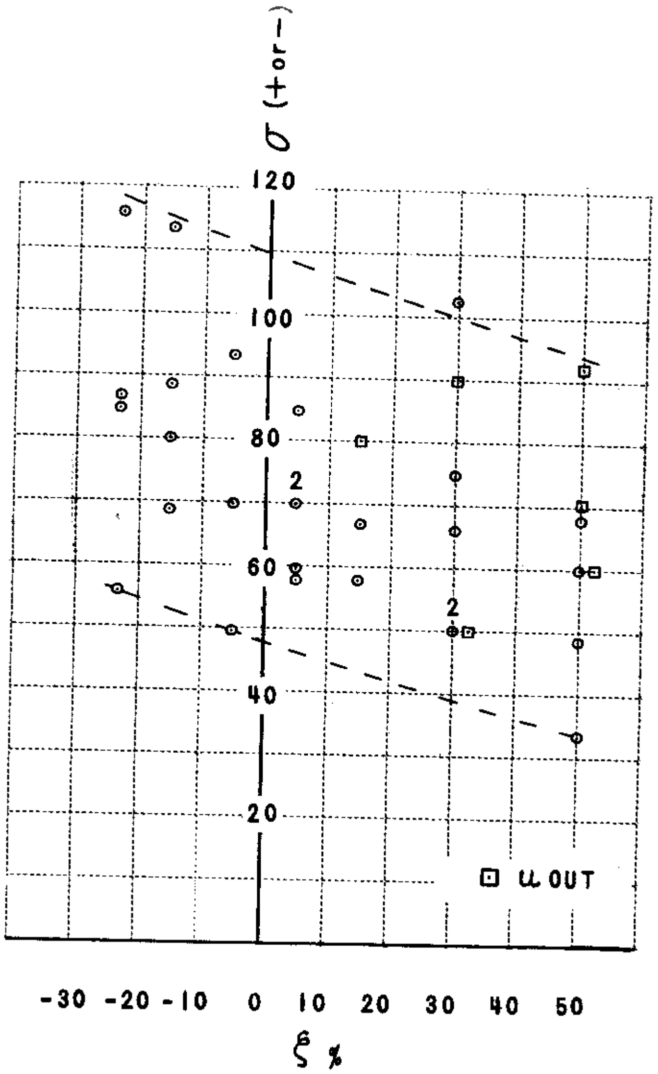


FIGURE 8 ALTITUDE VARIATIONS VS. PHUGOID DAMPING (FROM TABLE II)

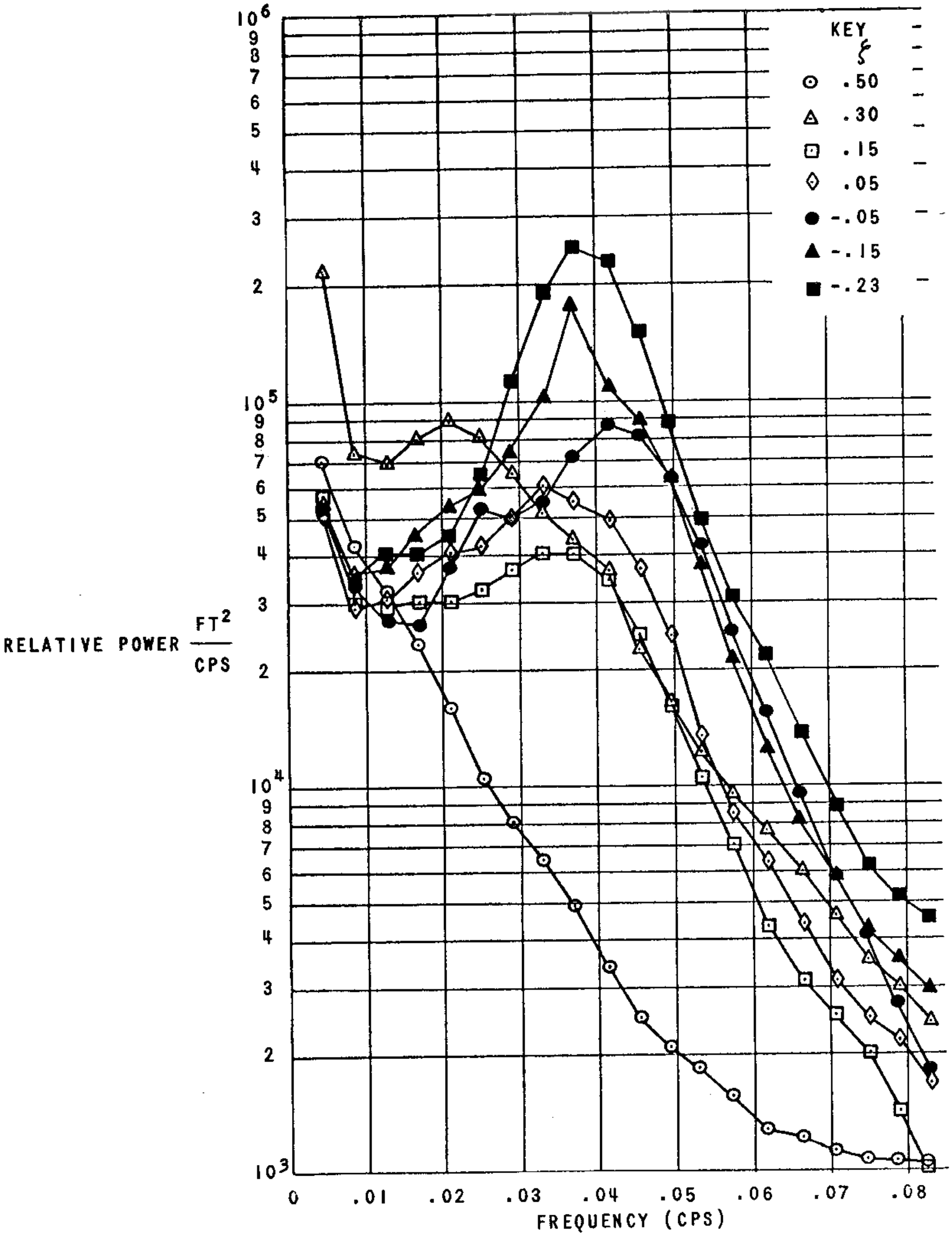


FIGURE 9 POWER SPECTRAL DENSITY OF ALTITUDE

AVERAGES OF 4 RUNS

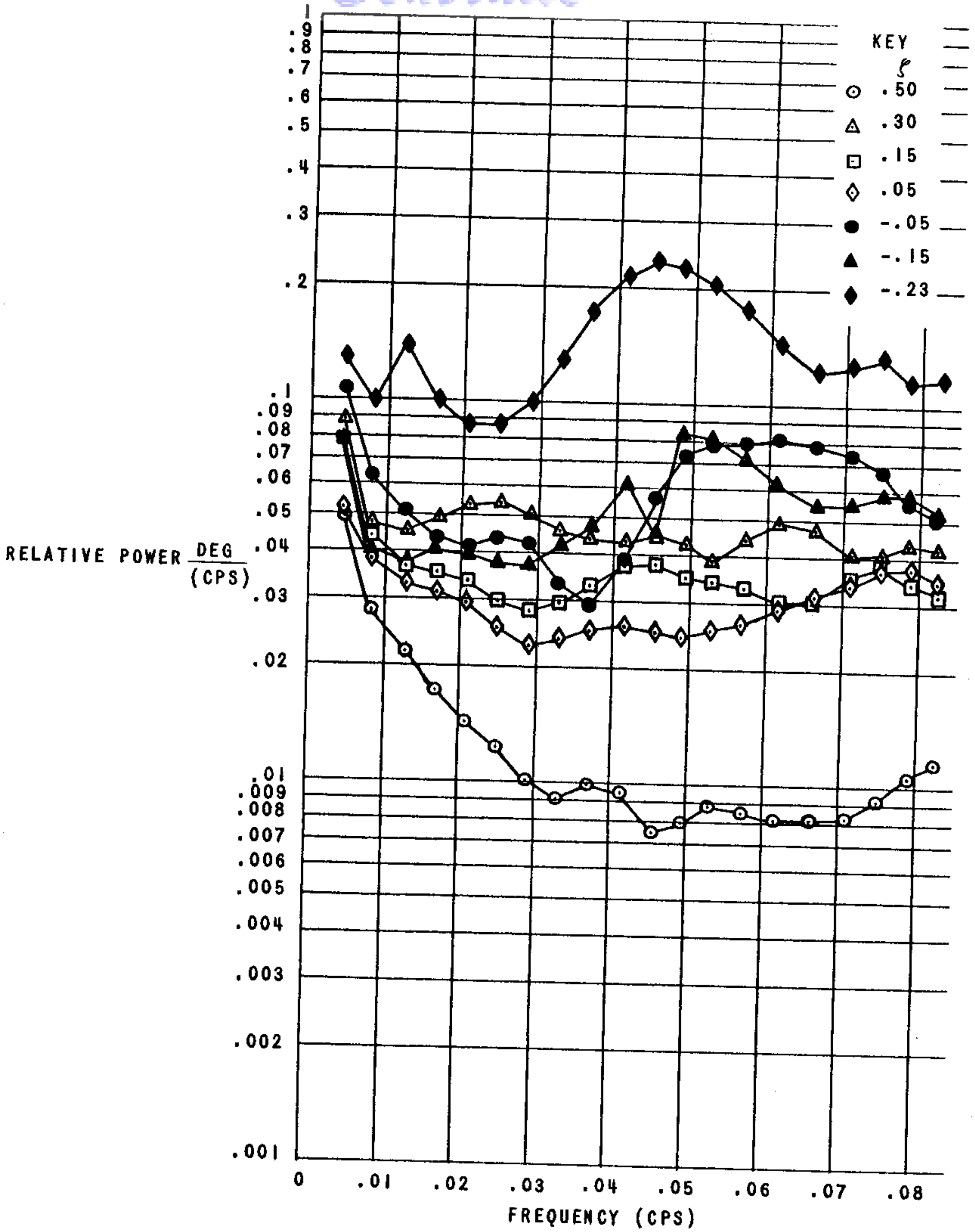


FIGURE 10 POWER SPECTRAL DENSITY OF ELEVATOR DEFLECTION
AVERAGES OF 4 RUNS

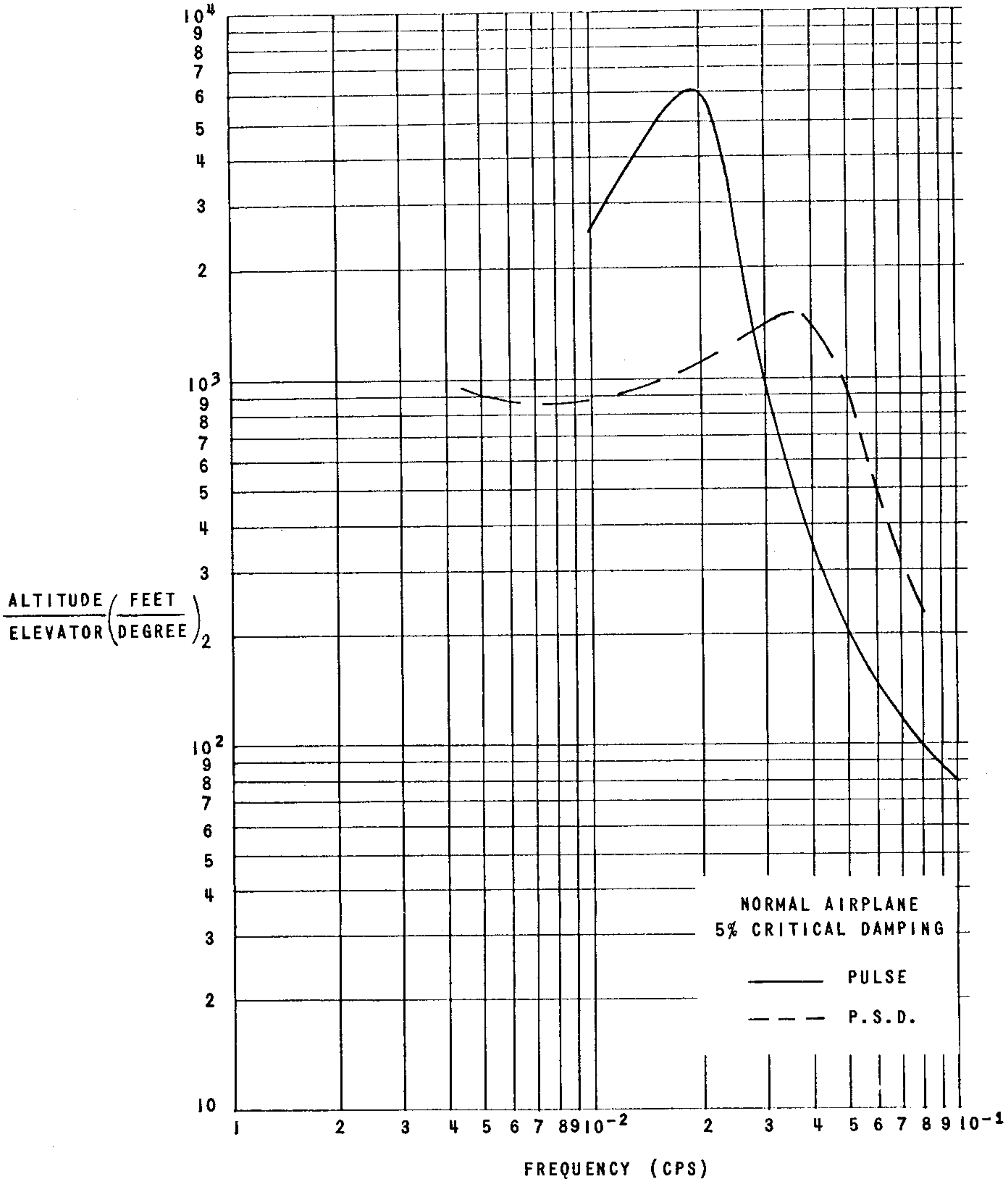


FIGURE 11 ALTITUDE FREQUENCY RESPONSE AMPLITUDE RATIO

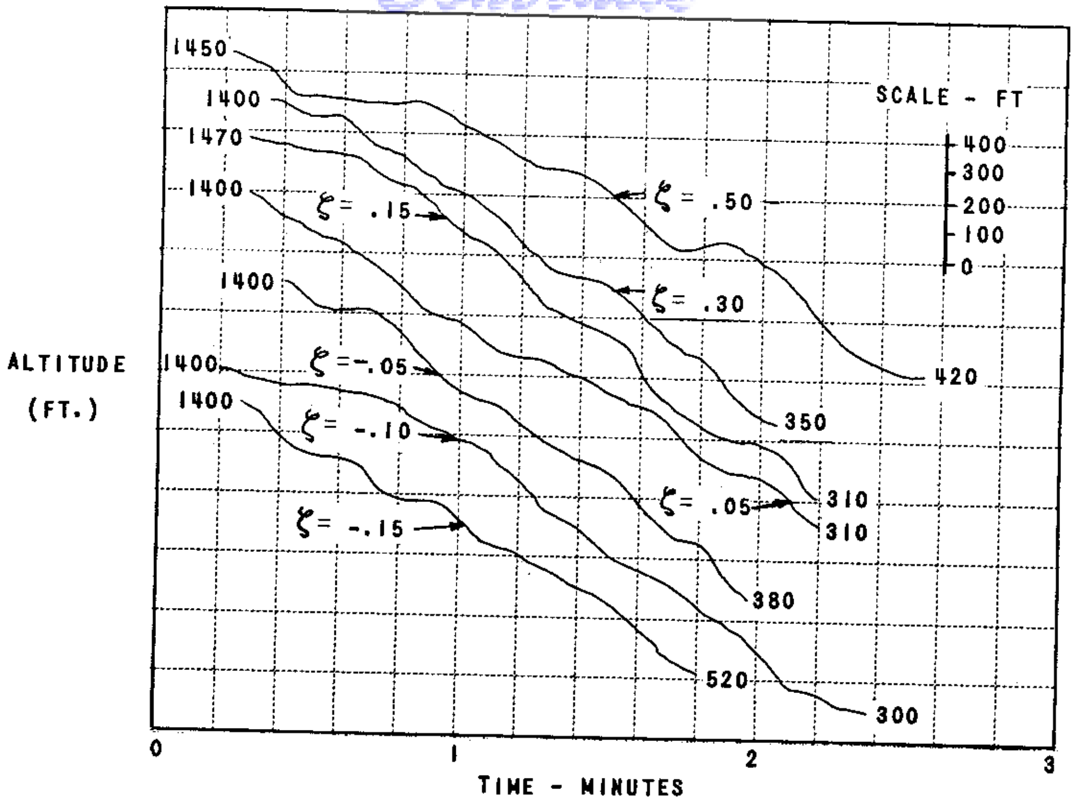


FIGURE 12 ALTITUDE TIME HISTORIES OF GCA APPROACHES

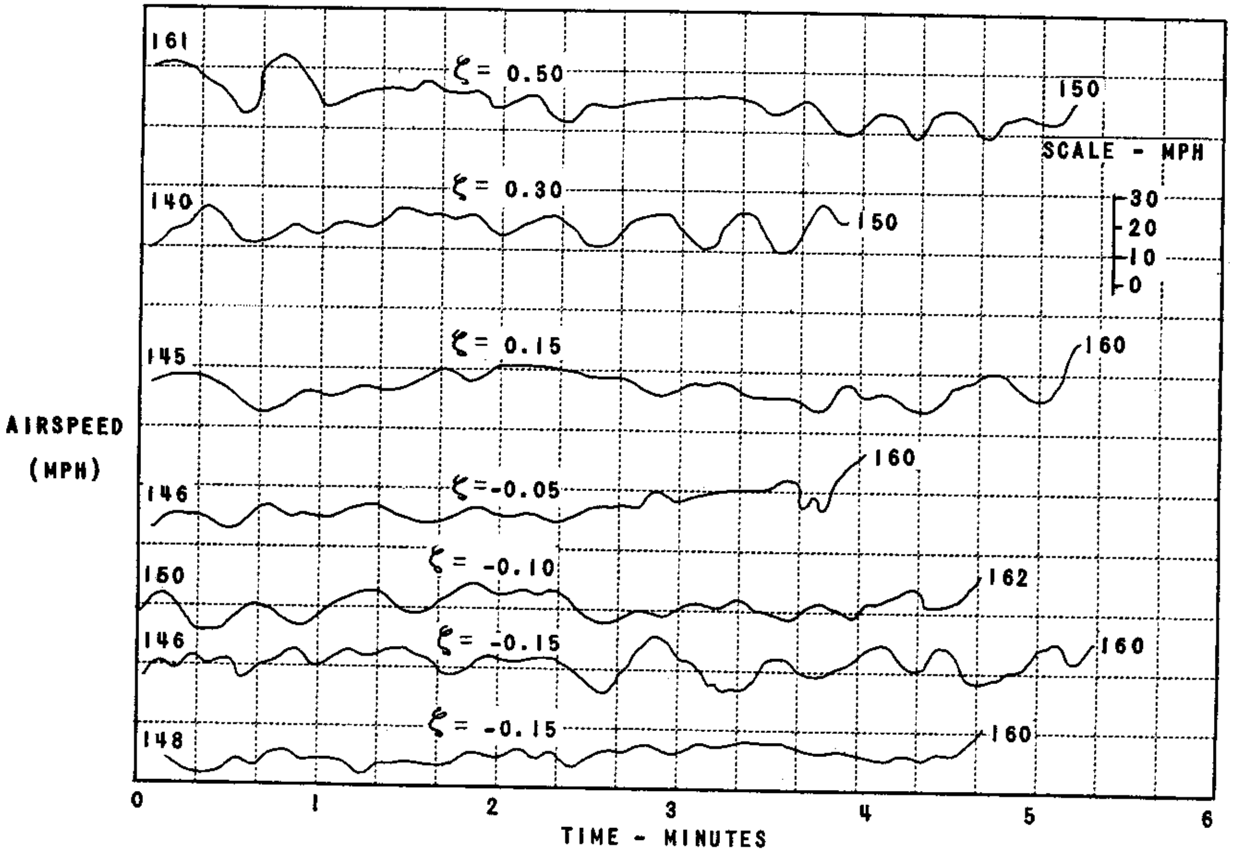


FIGURE 13 AIRSPEED TIME HISTORIES OF ILS APPROACHES

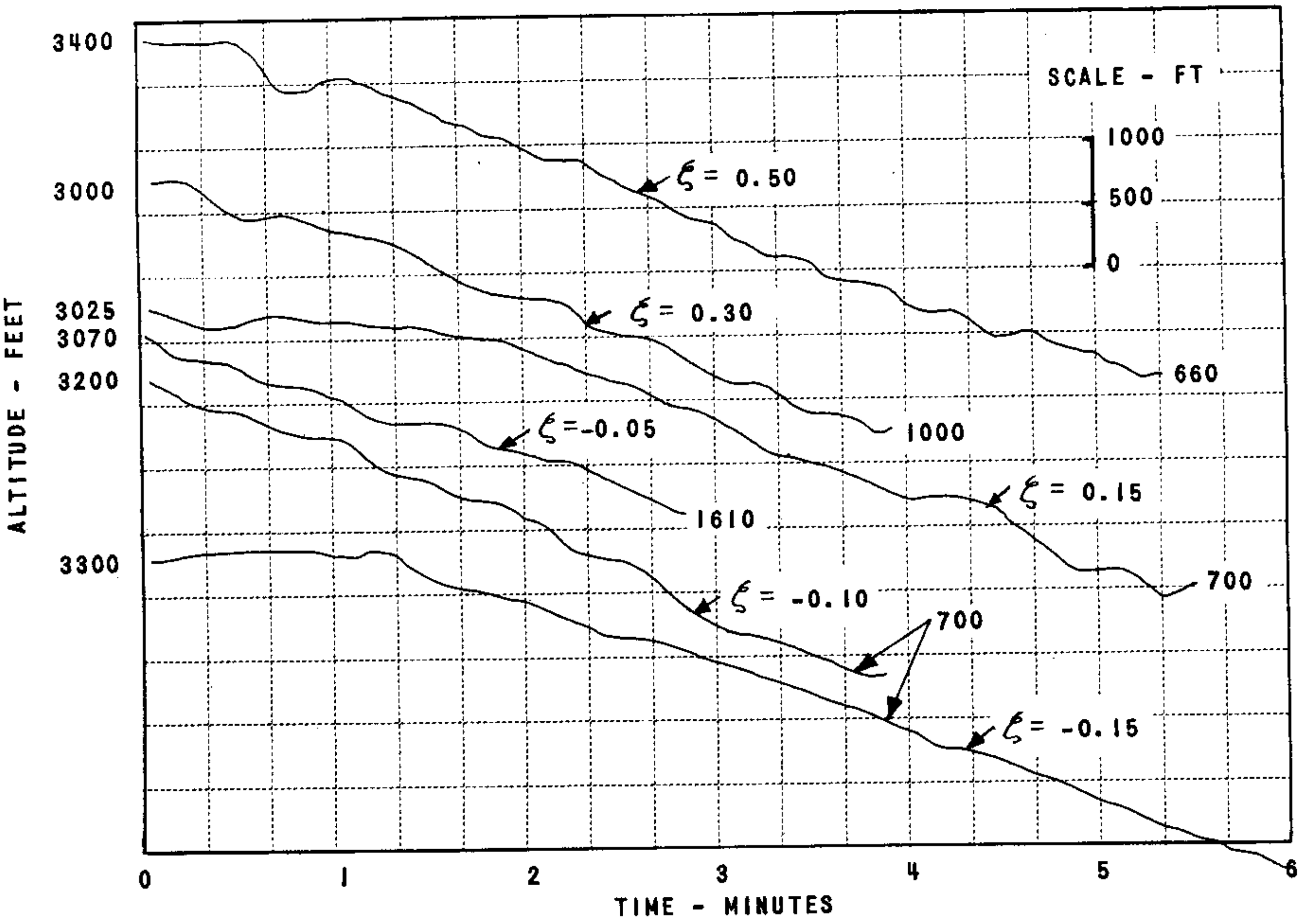


FIGURE 14 ALTITUDE TIME HISTORIES OF ILS APPROACHES

TABLE I

RESUME OF PILOT'S COMMENTS AND RATINGS

CONFIGURATION % CRITICAL DAMP	FLIGHT	ORDER	OVER-ALL RATING	ABILITY TO TRIM	ATTAINMENT OF ALT. & A.S. AFTER PROCEDURE TURN	EFFORT REQUIRED	SELF-RATING OF INSTRUMENT FLYING	IS IT A FRUSTRATING AIRPLANE TO FLY	CHANGE IN INSTRUMENT MONITORING FROM NORMAL METHOD	TURBULENCE
-23	131	4	AP to U				No Comments			
	133	3	U	Difficult to impossible	A little difficult	Fairly excessive	Poor	Yes	A little change to horizon	Smooth
	135	3	U	Difficult all time ±200 ft	Difficult	Extensive	Poor	Yes	Used horizon lot	
	138	2	U	Poor	Difficult	Excessive	Poor^{+}	Yes	Horizon more than rate of climb	Smooth
	142	1	U	Impossible	Difficult	Excessive	Poor	Yes		Smooth
-15	134	1	A	Impossible	A little difficult	Fairly extensive	Poor^{+}	Yes	(None)	Smooth
	136	2	AP^{-}	Quite good	Oscillations	Moderate	Poor^{+}	A little	No change	Light
	140	3	U	Poor	Difficult	Excessive	Poor	Yes	Horizon considerably	Smooth with 7 min. mod.
	144	1	A^{-}	Very nicely	Fairly easily	Normal	Normal	No	No change	Smooth
-5	131	1	A^{-}	Continually divergent		Moderate	Normal^{-}	A little		Lt. to mod. lt.
	132	1	A^{-}	Pretty good	Fairly easy to make	Moderate	Normal^{-}	A little bit due to alt. variations	No change	Smooth 80% of time
	135	2	AP^{+}	Not too good		Moderate	Normal^{-}	A little bit	No change	Slight
	139	3	AP^{-}	Not too well	Not too well	Moderate	Normal	A little	Slight change horizon	Smooth to moderate
	140	1	U^{+}	Not well	A little difficult	Excessive	Poor^{+}	A little	Horizon quite a bit	Smooth
	145	1	AP^{+}	Limits ±200 ft	Quite easily	Normal	Normal^{-}	A little	No change	Patches of light
+5	133	1	AP-AP^{+}	Poor to imp. ±100 to ±200 ft		Moderate	Fairly Poor	A little	No change	Smooth
	134	2	A^{-}	Within ±100 ft	Easily	Normal	Normal	Not particularly	No change	Smooth
	138	3	A^{-}	A little difficult	Quite easily	Normal	Normal	Not particularly	No change	Smooth
	143	1	A^{-}	Fairly good no groove ±200 ft	Fairly well	Normal	Normal	A little	No change	Smooth
+15	131	2	A	Quite good		Normal	Normal	Not particularly		Lt. to slight mod.
	132	2	A^{+}	Good	Good	Normal	Normal	No	Very little	Smooth
	136	1	A	Quite good		Normal	Normal	Not particularly	No change	Patches of lt. mostly smooth
	139	2	A	Quite well	Quite well	Moderate	Normal	No	No change	Smooth
	142	3	AG^{-} smooth A^{+} rough	Good	Fairly easily	Normal	Normal			½ mod. ½ smooth
	145	2	A	Very well	A little difficult	Normal	Normal	No	No change	Half & half
+30	133	2	AG^{-}	Quite good	Good	Normal	Normal	Not particularly	(None)	Smooth
	135	1	A	Pretty fair	Easily	Normal	Normal	Not particularly	No change	Smooth
	136	3	A	Fair	Quite easily	Moderate	Normal	Not particularly	No big change	Lt. to mod. lt.
	142	2	AP	Poor	Quite well	Moderate	Fairly poor	Yes		Lt. to mod. heavy
	143	3 u-out	AG	Well		Normal	Normal		No change	Lt. to mod.
	144	2 u-out	A^{+}	Good	Fairly easily	Less than normal	A little better than normal	No	No change	Smooth
+50	131	3	A^{-}				No comments			
	132	3	AG	Very well	Very well	Normal	Normal $^{+}$	No	(None)	80% of time quite heavy
	134	3	A^{+}					No	(None)	
	138	1	AG^{-}	Very well	A little difficult	Normal	Normal	No	(None)	Smooth
	139	1	AG	Very well	Quickly and good	A little	Excellent	No	(None)	Smooth
	140	2	A^{+}	Well	Stabilize quickly	Normal	Normal	No	(None)	Smooth
	143	2 u-out	A^{+}	Quite well	Quite easily	Normal	Normal	No	(None)	Lt. to mod.
	144	3 u-out	A^{+}	Good	Fairly easily	Very moderate	Normal	No	(None)	Smooth
	145	3 u-out	AG^{-}	Good (groove)	Tend to overcontrol	Normal	Normal	No	(None)	Mod. to light

NOTE: (None) - NOT COMMENTED UPON

TABLE II

ALTITUDE DEVIATION DATA

FLIGHT	CONFIGURATION	NORMAL PLOT ALTITUDE σ (FT)	PILOT'S RATING	PILOT'S COMMENTS IN SPECIFIC CASES	4σ (FT)	6σ (FT)	DATA RANGE (FT)	FROM RATING DEFINITION (FT)
133	+ 5%	± 60	AP+	±100 to ±200 ft	240	360	490	±200 to > ±200
	+30%	± 66	AG-		264	396	445	±100 to ±200
	-23%	±116	UN		464	696	745	> ±200
134	*-15%	± 89	A		356	534	555	±200
	+ 5%	± 58	A-	±100 ft	232	348	440	±200 to > ±200
	+50%	± 68	A+		272	408	500	±100 to ±200
135	+30%	± 50	A		200	300	295	±200
	- 5%	± 50	AP+		200	300	340	±200 to > ±200
	-23%	± 87	UN	±200 ft all the time	348	522	655	> ±200
136	+15%	± 58	A		232	348	365	±200
	-15%	± 69	AP-		276	414	480	>±200
	+30%	± 75	A		300	450	480	±200
138	+50%	± 40	AG-		160	240	290	±100 to ±200
	-23%	± 85	UN		340	510	650	> ± 200
	+ 5%	± 70	A-		280	420	480	±200 to > ±200
139	+50%	± 34	AG		136	204	205	±100
	-23%	± 56	A		224	336	355	±200
	+ 5%	± 85	AP-		340	510	560	> ±200
140	- 5%	± 70	UN+		280	420	455	> ±200
	+50%	± 49	A+	±100 ft hands off	196	294	310	±100 to ±200
	-15%	± 80	UN		320	480	485	> ±200
142	-23%	± 82	UN		328	492	520	> ±200
	**+30%	±103	AP		412	618	970	> ±200
	+15%	± 67	A+ AG-		248	412	470	±100 to ±200
143	+ 5%	± 70	A-	±200 ft	280	420	395	±200 to > ±200
	+50%u-out	± 60	A+		240	360	395	±100 to ±200
	+30%u-out	± 50	AG		200	300	335	±100
144	-15%	±114	A-		456	684	730	±200 to > ±200
	+30%u-out	± 90	A+		360	540	630	±100 to ±200
	+50%u-out	± 92	A+		368	552	650	±100 to ±200
145	- 5%	± 94	AP+		376	564	610	±200 to > ±200
	+15%u-out	± 80	A		320	480	620	±200
	+50%u-out	± 70	AG-		280	420	570	±100 to ±200

* *Actual distribution exceedingly skewed*

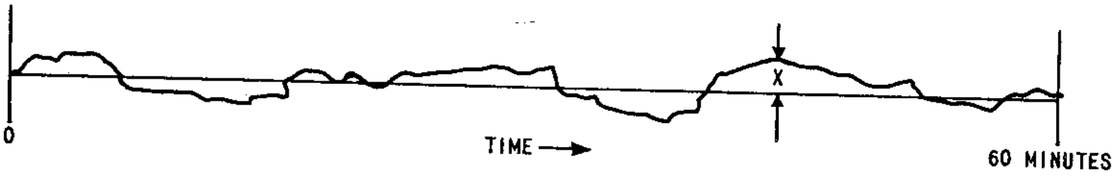
** *Distinctly two separate distributions*

TABLE III

DEVIATION DEFINITIONS

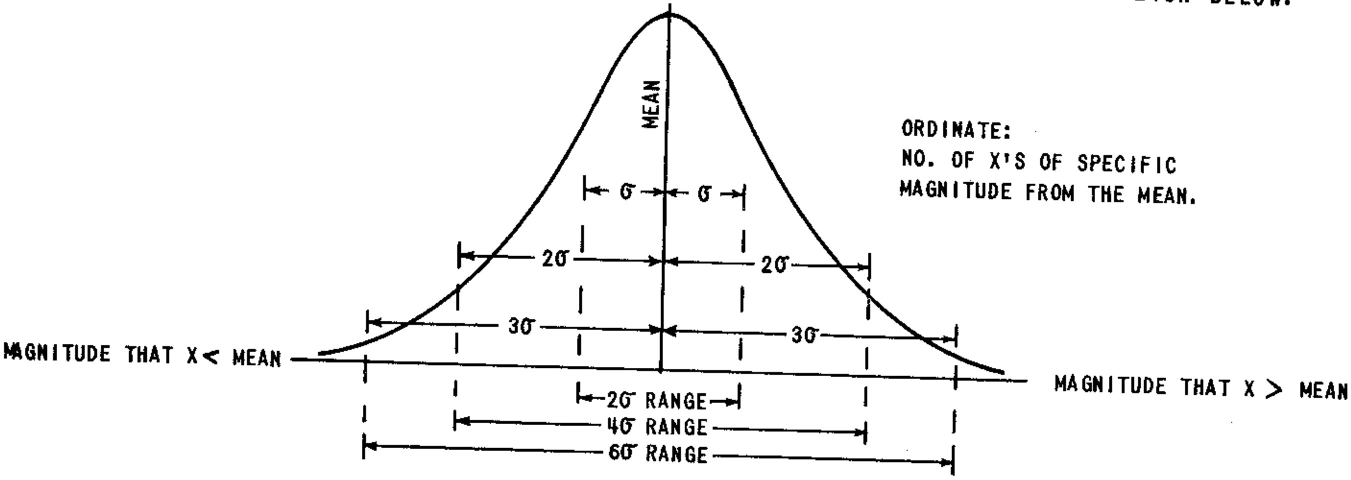
TABLE II IS BASED ON THE FOLLOWING DEFINITIONS

1) RECORDED TIME HISTORY; X MEASURED EVERY SIX SECONDS



2) FREQUENCY DISTRIBUTION; NORMAL OR MODERATELY SKEWED.

THE DISTANCE EQUAL TO ONE STANDARD DEVIATION (σ) MEASURED ON THE X AXIS ON BOTH SIDES OF THE ARITHMETIC MEAN DEFINES LIMITS WHICH INCLUDE APPROXIMATELY 68% OF THE DATA. THIS IS DEFINED AS A ONE σ DEVIATION. LIKEWISE, A 2 σ DEVIATION DEFINES LIMITS (2 σ MEASURED ON BOTH SIDES OF THE ARITHMETIC MEAN) WHICH INCLUDE APPROXIMATELY 95% OF THE DATA, AND A 3 σ DEVIATION INCLUDES APPROXIMATELY 99% OF THE DATA. SEE SKETCH BELOW.



IT MAY BE NOTED THAT σ MEASURED ON ONE SIDE OF THE MEAN MAY BE CONSIDERED POSITIVE WHILE THAT MEASURED ON THE OTHER SIDE MAY BE CONSIDERED NEGATIVE. THEREFORE, THE TOTAL "RANGE" (FROM + to −) OF A 1 σ DEVIATION IS TWICE THE ABSOLUTE MAGNITUDE OF σ ; LIKEWISE, THE TOTAL RANGE OF A 2 σ DEVIATION IS 4 σ (±2 σ), AND THE RANGE OF A 3 σ DEVIATION IS 6 σ (±3 σ).

APPENDIX

DATA REDUCTION

INTRODUCTION

This section describes the procedures required for reduction of the data obtained to the form shown in the latter part of the report. Reduction to power spectral density data is primarily discussed as a mechanical function as performed on the IBM machine computers. For theory and detailed application, the reader is referred to Reference 5.

POWER SPECTRAL DENSITY DATA

The following steps apply to the altitude and elevator data as recorded on film:

1. Compute the mean and subtract from the original data as read every 6 sec from the film.
2. "Smooth" the data using the following formula*:

$$y_n = (1-\alpha)\, y_{n-1} + \left(1 - \frac{\alpha}{2}\right)(x_n - x_{n-1})$$

where for

$$\Delta t = 6 \text{ sec}, \qquad \alpha = .31$$

The above takes data x_n with a power spectrum, $\phi(\omega)$ and converts it to data y_n with a power spectrum $|Y(\omega)|^2 \phi(\omega)$

where $$|Y(\omega)|^2 = \frac{\left(1-\frac{\alpha}{2}\right)^2}{1-\alpha} \; \frac{1}{1 + \dfrac{\alpha^2}{4(1-\alpha)\sin^2 \pi f \Delta t}}$$

$$\omega = 2\pi f$$

$$f = \text{frequency in cps} = \frac{h}{\Delta t p}$$

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* *This step is desired to eliminate the distortion effects of the zero frequency power on the power near the phugoid frequency. The described numerical filter was used.*

h = power point number

p = lag number

Note: After the power spectrum of y_n is computed, it should be divided by $|Y(\omega)|^2$ to get the power spectrum of x_n

3. Compute autocorrelation on y_n

$$R_p = \sum_{i=0}^{i=n} \frac{y_i \, y_i + p}{h - p}$$

where p goes from 0 to 40

4. Compute R'_p = autocorrelation x weighting factor

weighting factor = $\frac{(1-\lambda^2)(1+\cos \pi \lambda)}{2}$

where

$$\lambda = \frac{p}{p_0}$$

p_0 = total number of lags (40 in this case)

5. Compute power spectrum of y_n

$$Q(h)_{y_n} = C \sum_{p=0}^{p=40} R'_p \cos \frac{\pi p h}{40}$$

where C = constant = $2\Delta t$

6. Compute power spectrum of x_n

$$Q(h)_{x_n} = \frac{Q(h)_{y_n}}{|Y(\omega)|^2}$$

The following functions were performed by the Datatron Digital Computer.

1. Computation of mean and subtraction from data.
2. Smoothing of data.
3. Computation of autocorrelation.

The following functions were performed by the IBM Card Programmed Calculator:

1. Computation of autocovariance times weighting factor
2. Computation of power spectra

Frequency Response

The amplitude portion of the frequency response of $\left(\frac{h_p}{\delta_e}\right)$, ft/deg, may be obtained from the power spectra of altitude and elevator in a simple fashion. The units of altitude power are ft^2/cps and elevator deflection, deg^2/cps. Therefore, for a given frequency,

$$\frac{h_p}{\delta_e}(ft/deg) = \sqrt{\frac{\text{Value of Altitude Power}\left(\frac{h_p^2}{cps}\right)}{\text{Value of Elevator Power}\left(\frac{\delta_e^2}{cps}\right)}}$$

A frequency response obtained in the above manner is discussed in a later section as compared with that obtained from an in-flight elevator pulse (both normal airplane damping). The latter was reduced from the altitude and elevator time histories using a Rolling Sphere Harmonic Analyser.

Altitude Total Variance

The altitude total variance (deviation from the mean) and root mean square value (the square root of the total variance) for each run were obtained by hand calculation based on the following statistical procedure.

A distribution curve was determined for each case by noting the number of occurrences within each of approximately thirteen class intervals. When plotted on probability paper, the curve obtained will be a straight line if the distribution is normal. From this plot, the rms (standard deviation) and other properties may be determined.