TRENDS IN REPEATED LOADS ON TRANSPORT AIRPLANES

By Thomas L. Coleman

NASA Langley Research Center
Langley Station, Hampton, Virginia, U.S.A.

Presented at the Symposium on Fatigue Design Procedures
Sponsored by the International Committee
on Aeronautical Fatigue

[redacted]

Munich, Germany
June 16-18, 1965

CONTENTS

TRENDS IN REPEATED LOADS ON TRANSPORT AIRPLANES

By Thomas L. Coleman

NASA Langley Research Center

SUMMARY

18375

Statistical loads data collected by NASA since 1947 on piston- and turbine-powered transport airplanes during routine feeder-line, short-haul, and long-haul airline service are summarized. The data presented pertain to the repeated loads resulting from atmospheric turbulence, maneuvers, airplane oscillatory motions, landing contact, and ground operations. The data for several categories of airplanes are compared to show the trends in the loads with the evolution of the transports. The data are presented in terms of the normal accelerations measured near the center of gravity of the airplanes.

Author

INTRODUCTION

For over 30 years, the NASA and its predecessor, the NACA, have collected statistical data on the normal accelerations experienced by, and the airspeed and altitude practices of, commercial transport airplanes. This research has been conducted with the cooperation of airplane manufacturers and airlines who have borne the cost of installing and transporting the instrumentation. Analyses of the data have provided, for each successive generation of airplanes, information on the magnitude and frequency of occurrence of accelerations (or loads) due to various sources, such as gusts and maneuvers, and on the effect of airplane characteristics and operating practices on the loads. This information has provided a continual basis for comparing actual airplane operations

L-4197

with the concepts used in design, for detecting unanticipated operational aspects, and constitutes a reservoir of data useful in the design of new types of airplanes.

In this paper, the statistical loads data collected since 1947 on piston- and turbine-powered transports are summarized. The data presented pertain to the repeated loads resulting from atmospheric turbulence, maneuvers, airplane oscillatory motions, landing contact, and ground operations. Where sufficient data are available, the loads for several categories of airplanes are compared to show the trends in the loads with the evolution of the transports. The data are presented in terms of the normal accelerations measured near the center of gravity of the airplane.

GENERAL BACKGROUND

Instrumentation

The data to be discussed were obtained primarily with NASA VGH and V-G recorders, which are described in detail in references 1 and 2, respectively. Consequently, only a brief description of the recorders and the type record obtained is given below.

VGH recorder.- A picture of the VGH recorder is shown in figure 1. The recorder consists of three major components: the recorder base, the attached film recording drum, and the acceleration transmitter. The transmitter is installed near (usually within 5 feet) the center of gravity of the airplane, whereas the recorder base may be mounted at any convenient location within the airplane. The installed weight of the VGH recorder is 20 to 25 pounds.

An illustrative VGH record is shown in figure 2. It is a time-history record of indicated airspeed, pressure altitude, and normal acceleration. From this record, it is possible to make detailed counts of the normal acceleration peaks caused by various sources such as gusts, maneuvers, and ground operations and to determine the associated airspeeds and altitudes.

V-G recorder.- A picture of the V-G recorder is shown in figure 3. It weighs less than 5 pounds installed and is usually mounted within 5 feet of the center of gravity of the airplane.

An illustrative V-G record is shown in figure 4. It is an envelope of the maximum positive and negative accelerations experienced throughout the airspeed range during the period (usually approximately 200 flight hours) covered by the record.

Record Evaluation

Detailed methods used for evaluating the VGH and V-G records are given in references 3 and 4. Consequently, only a brief explanation of the methods of evaluating the records are given in the following sections.

VGH records.- The sketch in the left of figure 5 illustrates the manner of evaluating the VGH records. The steady-flight position of the acceleration trace is used as a reference from which to read the incremental acceleration peaks which equal or exceed a selected threshold value. Only the maximum value of the acceleration is read for each crossing of the reference. The selected threshold values range from ±0.05g to ±0.30g, depending upon the airplane type and the source of the accelerations being evaluated. For each acceleration peak evaluated, the corresponding values of airspeed and altitude are also evaluated. In addition, the airspeed and altitude at 1-minute intervals are read to provide data on the airspeed operating practices and the altitudes flown. The acceleration data are sorted according to source (gusts, maneuvers), flight condition (climb, cruise, and descent), and by altitude.

V-G records.- The sketch in the right of figure 5 illustrates the manner of evaluating the V-G records. As indicated, only one maximum positive and one negative acceleration increment from the reference are evaluated from each record. Generally, it is not possible to determine the source (i.e., gusts or maneuvers) of the maximum accelerations on a V-G record. Consequently, the V-G acceleration data are not generally sorted according to source, but rather are given as combined data representing in-flight accelerations.

NOTE: For many of the early transport airplanes, the maximum accelerations on the V-G records were ascribed to gusts rather than maneuvers. Because of the relatively high response of these airplanes to gusts, the assumption was considered to be valid. For several types of current transports, however, detailed data from VGH records indicate that the assumption may not be valid since maneuver accelerations may be as high as gust accelerations.

Method of combining VGH and V-G data.- Because VGH data samples are generally small (approximately 1000 flight hours), they do not provide reliable estimates of the frequency of the large accelerations. They do, however, provide detailed information on the smaller accelerations and the sources of these accelerations. Conversely, the larger samples of V-G data do not provide detailed information on the sources of the accelerations, but do give reliable estimates of the frequency of the large accelerations. Consequently, the two types of data are complementary and may be combined to obtain an estimate of the total in-flight acceleration experience.

The method of combining the VGH and V-G data is illustrated in figure 6. The figure shows the cumulative frequency distributions per mile of flight of gust and maneuver accelerations as determined from the VGH data sample, the maximum accelerations from the V-G data, and the total in-flight acceleration distribution obtained by summing the ordinate values of the maneuver, gust, and V-G acceleration distributions.

For the combination of VGH and V-G data in figure 6, the cumulative frequency distributions of gust and maneuver acceleration from the VGH data were normalized by dividing by the flight miles represented by the VGH data sample. Correspondingly, the cumulative frequency distribution of the maximum accelerations from the V-G data was divided by the flight miles represented by the V-G data sample. Thus, each distribution gives the average frequency with which given values of acceleration (the abscissa) were equaled or exceeded per mile of flight. The reciprocal of the ordinate gives the average number of miles required to equal or exceed given values of acceleration.

Cumulative frequency distributions per mile of flight such as given in figure 6 will be used in subsequent sections of this paper.

Scope of Data

Types of airline operations.- The airlines from which the data were obtained were engaged in United States domestic and transoceanic operations. In addition, data from one foreign airline providing transoceanic service are included.

The individual airline operations covered by the data may be grouped according to one of the following broad categories of airline service: feeder line, short haul, or long haul. The average length of flight of the individual operations in each class of service were:

Feeder line - 80 to 90 nautical miles

Short haul - 170 to 470 nautical miles

Long haul - 700 to 1700 nautical miles

Types of airplanes.- For each of the three classes of airline service (feeder line, short haul, and long haul), data from both piston- and turbine-powered transports are included. Some of the characteristics of the airplanes are given in table I. As shown in the table, the airplane types for the feeder-line service were a two-engine piston airplane and a two-engine turboprop airplane. For the short-haul service, three types of two-engine piston airplanes and two types of four-engine turboprop airplanes are represented. For the long-haul service, six basic types of four-engine piston airplanes and three basic types of four-engine turbojet transports are included. In addition to the basic types of airplanes, data from several models of three of the airplane types were obtained as denoted by the dash-numbered suffix after the basic airplane designation. In total, 16 basic airplane types plus an additional five models (H-1, O-2, O-3, P-2, and P-3) are represented.

As shown in table I, the maximum gross weights of the airplane range from 25,200 pounds for one of the two-engine piston transport (type A) to 312,000 pounds for two models of one of the four-engine turbojet transports (O-2 and O-3). The maximum wing loadings ranged from approximately 25 to 112 pounds per square foot.

In order to show some of the operational features of the airplanes, the range of the average true airspeed (from take-off to landing) and the average cruise altitude of the piston and turbine airplanes for each class of service is shown in figure 7. For the feeder-line service, the average true airspeed was 145 knots for the piston airplane and 180 knots for the turboprop airplane. Both airplanes had an average cruise altitude of approximately 6000 feet. For the short-haul service, the average cruise altitudes for the piston airplanes ranged from 7000 to 11,000 feet and the average true airspeeds were approximately 180 knots. The short-haul turboprop airplanes had average cruise altitudes between 14,000 and 18,000 feet and average true airspeeds of 240 to 300 knots. The cruise altitudes for the long-haul piston airplanes ranged from approximately 10,000 to 20,000 feet and the average true airspeeds ranged from 180 to 280 knots. The long-haul turbojet airplanes had average cruise altitudes between 29,000 and 34,000 feet and average true airspeeds of 415 to 450 knots. As a matter of interest, it may be noted in figure 7 that, for the short-haul and long-haul operations, the increased airspeeds derived from the turbine transports have been accompanied by an increase in average cruise altitude. This increase in altitude has had an effect on the repeated gust loads as will be discussed in a later section.

Sample sizes.- The sizes of the data samples in terms of the number of airplanes instrumented, number of airlines represented, and the number of flight hours of VGH and V-G data are shown in table II. The VGH sample sizes for the various types of airplanes range from 673 flight hours for one of the two-engine piston transports (type C) to 7038 flight hours for one of the four-engine turboprop airplanes (type M). The sizes of the V-G data samples for the various airplanes range from approximately 10,000 flight hours to 90,000 flight hours.

In general, the data sampling program has been aimed at obtaining at least 1000 flight hours of VGH data and 10,000 flight hours of V-G data from each airline operation. (As used herein, an airline operation is defined as the operations of a given airplane type on a given airline.) To obtain data samples of these sizes, usually one or two airplanes on a given airline were instrumented with VGH recorders and several airplanes were instrumented with V-G recorders as is indicated in table II. The sampling period for each operation usually covered a period of 1 to 3 years in order to minimize bias of the data by possible seasonal effects.

In order to obtain information on the effect of route and type of operation on the loads, VGH data were obtained for several of the airplane types (types D and M, for example) during operations on two or three airlines. Likewise, the number of airlines from which V-G data were obtained for a given airplane type ranged up to seven. In total, the VGH data samples represent 42,188 flight hours covering 28 operations and the V-G data samples represent 506,643 flight hours covering 35 operations. Two- and four-engine piston and turboprop airplanes and four-engine turbojet airplanes used in feeder-line, short-haul, and long-haul operations are represented by the samples.

It may be noted that data from another important type of airplane, the two- and three-engine turbojet short-haul transports, are not included in table II. VGH programs have been initiated to obtain data on three models of this type of airplane but results are not yet available.

The data for all of the piston-engine airplanes listed in table II were collected between 1947 and 1948 and have been reported in reference 3. Data for two of the turboprop airplanes (types L and N) were collected between 1956 and 1961 and are reported in references 5 and 6. The data from the remaining turbine-powered airplanes were collected subsequent to 1958. Results from limited samples of these data are given in reference 4.

RESULTS AND DISCUSSION

Gust Accelerations

Information pertaining to the gust accelerations experienced by the piston- and turbine-powered airplanes in feeder-line, short-haul, and long-haul combining, with equal weight, the distributions for the individual operations associated with each type of airplane.

The results in figure 9 show that differences on the order of 100 to 1 exist among the average frequencies of occurrence of given values of gust accelerations for the various types of airplanes. The gust accelerations occurred most frequently on the two-engine turboprop and piston airplanes used in the feeder-line service and least frequently on the turbojet airplanes used in long-haul service. The acceleration frequency for the four-engine turboprop short-haul airplane is approximately one-fifth that for the two-engine piston short-haul airplane and is roughly the same as that for the four-engine piston long-haul airplane. For the long-haul turbojet airplane, the acceleration frequency is approximately one-fifth that of the four-engine piston airplanes. For both the piston- and turbine-powered classes of airplanes, the acceleration frequency is seen to decrease progressively in going from the feeder-line, to the short-haul, to the long-haul service.

The differences among the gust acceleration experiences for the various types of airplanes shown in figure 9 are significant and are due primarily to differences in the gust environment experienced by the airplanes and to differences in airplane response characteristics to turbulence. The effects of these two factors on the gust acceleration experience will be discussed in the following two sections.

<u>Effect of gust environment</u>.- A number of factors, such as route, flight profile (length of flight and cruise altitude), and airline practice relative to turbulence avoidance, influence the number of gusts actually encountered by an airplane. A typical model of a gust environment for transport airplanes has been reported in reference 7 and is reproduced in figure 10. The curves

operations is given in figure 8. The "hatched" regions denote the range of the cumulative frequency distributions of gust accelerations per mile of flight for the individual operations within each grouping of airplane types. Because only one sample of data was available for each of the two-engine piston and turboprop airplanes engaged in feeder-line operations, single curves are shown for the two airplanes rather than a range of data. Inasmuch as the positive and negative distributions of gust accelerations are essentially symmetrical, they have been combined for the presentation in figure 8.

Several points of interest may be observed from the results in figure 8. Firstly, the gust acceleration distributions for the various types of airplanes in the three classes of airline service have approximately the same general shape. (An exception to this is that the distribution for the two-engine piston airplane used in the feeder-line service does not show the characteristic curvature exhibited by the other distributions. This is attributed to the particular route on which the airplane was operated. This route was almost entirely confined to mountainous regions and precluded operations during weather conditions, such as thunderstorms, conducive to severe turbulence which produces the high values of accelerations.) Secondly, the results show orders of magnitude differences among the frequencies of occurrence of given values of accelerations for the various types of airplanes and types of service. Thirdly, for a given type of airplane, an order of magnitude variation in the acceleration frequencies exists in some cases.

In order to facilitate comparison of the gust acceleration distributions for the various types of airplanes and airline service, average distributions for each type are shown in figure 9. These average curves were obtained by show the cumulative frequency distributions of derived gust velocity per mile of flight within the indicated altitude intervals. (The term "derived gust velocity" is defined in ref. 8.) As shown in figure 10, there is a significant decrease in the gust velocity frequency with increasing altitude. The gust experience for a given airplane depends not only upon the cruising altitude, however, but also is strongly dependent upon the distance flown at the lower altitudes during the climb and descent phases of flight. Because of this effect, the gust velocity experience for an airplane is generally influenced more by the turbulence at the lower altitudes than at its cruise altitude.

As an indication of the amount of turbulence encountered by the various airplanes, figure 11 shows the average percent of the total flight time which was flown in rough air by the piston- and turbine-powered airplanes in feeder-line, short-haul, and long-haul service. For this presentation, rough air is defined as turbulent areas containing gust velocities higher than 2 or 3 fps, which is a low level of turbulence. The approximate cruise altitude for each airplane type is also shown in the figure.

The results in figure 11 show that the percent of time in rough air varied from about 20 percent for the feeder-line airplanes, to about 12 percent for the short-haul airplanes, and about 7 percent for the long-haul airplanes. It is noted that the short-haul turboprop and the long-haul turbojet airplanes experienced less rough air than did the piston airplanes used in the corresponding service. This is due primarily to the higher cruise altitudes of the turbine airplanes.

The differences shown in figure 11 in the amount of rough air encountered by the various airplane types account for approximately one-third of the 100 to 1 range in gust acceleration frequencies previously noted (fig. 9). (The intensity of the turbulence encountered can also be a factor influencing the gust accelerations. For the present airplane operations, however, the gust intensities did not appear to vary significantly between operations.)

Effect of airplane response characteristics.- For a given turbulence environment, the magnitude of the accelerations experienced by an airplane is determined by the airplane response characteristics to the turbulence. One method of describing the response characteristics is by use of the following gust equation which is given in reference 8:

$$\frac{a_n}{U_{de}} = \frac{\rho_o K_g V_e m}{2\ W/S}$$

where:

a_n	normal acceleration increment, g
U_{de}	derived gust velocity, ft/sec
ρ_o	air density at sea level, slugs/cu ft
K_g	gust factor
V_e	equivalent airspeed, ft/sec
m	slope of lift curve, per radian
S	wing area, sq ft
W	airplane weight, lb

The ratio a_n/U_{de} gives the acceleration per unit gust velocity and may be viewed as a gust sensitivity factor. This factor varies directly with the equivalent airspeed and lift-curve slope and inversely with wing loading.

Figure 12 shows the ranges of the gust sensitivity factor for the various airplane types used in the feeder-line, short-haul, and long-haul services.

The results shown in the figure are average values, based on considerations of the operational airspeeds and weights and are not directly comparable to the values used in the airplane design. It is seen that the gust sensitivity factors ranged from approximately 0.032 for the feeder-line airplanes to an average of about 0.02 for the long-haul airplanes.

The effect which the differences in the gust sensitivity factor (fig. 12) has on the gust acceleration experience is illustrated in figure 13. The plot in the left of the figure shows a cumulative frequency distribution of gust velocity per mile of flight. This gust velocity distribution is typical of the gust experience of the transport airplanes. (For individual operations, however, the gust distributions may be substantially above or below the curve shown and may also have a slightly different slope.)

The plot in the right of figure 13 shows the gust acceleration distributions for two airplanes: a feeder-line type with a gust sensitivity factor of 0.03g/fps and a long-haul type with a gust sensitivity factor of 0.02g/fps. Both airplanes are assumed to encounter the gust environment shown in the left of the figure.

The illustration in figure 13 shows the strong effect which the gust sensitivity factor has on the number of gust accelerations experienced. For example, a gust velocity of 20 fps results in an acceleration increment of 0.4g on the long-haul airplane and 0.6g on the short-haul airplane. In terms of frequency of occurrence of given values of acceleration, it is seen that an order of magnitude difference exists between the two airplane types. In this illustration, for example, acceleration increments greater than 0.5g are about 15 times more frequent for the feeder-line airplane than for the long-haul airplane.

The strong effect of the gust sensitivity factor on the number of gust accelerations (as illustrated in fig. 13) is the main reason for the large variations among the gust acceleration experience previously shown in figures 8 and 9 for the different airplane types. Approximately two-thirds of the 100 to 1 variation in the gust acceleration frequencies (fig. 9) is attributable to the differences among the gust sensitivity factors for the various airplane types. Thus, the differences among the gust acceleration frequencies due to the gust sensitivity factors are roughly twice those due to differences in the amount of rough air encountered by the various airplane types.

Maneuver Accelerations

Pilot-imposed maneuver accelerations may be classified as being operational maneuvers or check-flight maneuvers. Operational maneuvers are those performed during routine passenger-carrying operations for the purpose of maintaining the desired flight path. Check-flight maneuvers are those performed during pilot training or airplane check-out flights. Both classes of maneuver accelerations are discussed in the following two sections.

Operational maneuvers.- The average cumulative frequency distribution of operational maneuver accelerations per mile of flight for each type of airplane is given in figure 14. (A distribution for the two-engine piston airplane for the feeder-line service is not given inasmuch as operational maneuvers were not evaluated for this operation.) Because the positive and negative distributions were essentially symmetrical, they were combined for the present discussion.

The results in figure 14 show that the shapes of the distributions of operational maneuver accelerations for the various types of airplanes are very similar. The variations among the acceleration frequencies for the piston- and turbine-powered airplanes used in the short-haul and long-haul operations are less than a factor of about 3. The acceleration frequencies for the two-engine turboprop airplane used in the feeder-line service are approximately five times higher than for the other airplanes. It is thought that the short flights (approximately 80 nautical miles) in combination with the good performance of the two-engine turboprop airplane resulted in the comparatively high maneuver acceleration frequency for the feeder-line operation. With this exception, the results in figure 14 do not show significant differences among the operational maneuver acceleration experiences for the various airplane types.

Check-flight maneuvers.- The average cumulative frequency distributions per mile of flight of check-flight maneuver accelerations are given in figure 15 for each of the airplane types. Although the positive and negative distributions are not symmetrical (as will be indicated in a later section), they have been combined for present purposes. The ordinate values in figure 15 are in terms of the total flight miles, rather than the flight miles in check flights. This permits a more direct comparison and facilitates subsequent combination of the check-flight maneuvers with the results for the gust and operational maneuver accelerations. Also shown in figure 15 are the upper and lower bounds of the distributions for the individual operations which were used to obtain the average curves for each airplane type.

The results in figure 15 show that differences of approximately 10 to 1 exist among the average frequencies of occurrence of check-flight maneuver accelerations for the various airplane types. Of more significance, however, are the extremely large variations (up to 1000 to 1) indicated by the upper and lower bounds for the individual operations. In this regard, recorded differences on the order of 100 to 1 among the check-flight maneuver experiences of airplanes of a given type operated by different airlines are not unusual.

Likewise, differences on the order of 10 to 1 between like airplanes operated by a single airline have been observed. It is thought that there are two main reasons for the large differences among the check-flight maneuver experiences. Firstly, there are apparently significant differences between airlines in regard to the amount of check-flight flying required and in the number and types of maneuvers performed. Secondly, the percent of the total flight time which is spent in check flights varies by an order of magnitude between individual airplanes. For the operations reported herein, the percent of total flight time which was spent in check flights ranged from approximately 0.1 percent to 10 percent. On the basis of the available data, average values for the amount of check-flight flying, in percent of total flight time, are: 1 percent for the piston airplanes, 3 percent for the turboprop airplanes, and 5 percent for the turbojet airplanes. It is not known, however, whether these values are applicable on a fleetwide basis or are peculiar to the particular airplanes sampled. From the foregoing discussion, it is evident that significant and, for the most part, unpredictable differences exist among the check-flight maneuver experiences of individual airplanes.

Comparison of Gust and Maneuver Accelerations

A comparison of the frequency of occurrence of gust, operational maneuver, and check-flight maneuver accelerations for each airplane type is given in figures 16 to 18. For this comparison, the average cumulative frequency distributions of the positive and negative accelerations per mile of flight are shown separately for the piston and turbine airplanes used in each of the three classes of airline service: feeder line, short haul, and long haul.

The results in figure 16 for the feeder-line operations and in figure 17 for the short-haul operations show that, for both the piston and turbine airplanes, gust accelerations generally occurred much more frequently than operational and check-flight maneuver accelerations. For accelerations larger than approximately +1.0g, however, accelerations due to check-flight maneuvers occurred with a frequency approaching, or equaling, that of the gust accelerations.

The results in figure 18 for the long-haul operations show that, for the piston airplanes, gust accelerations occurred more frequently than maneuver accelerations for acceleration levels below 0.8g. Check-flight maneuvers produced accelerations larger than about +0.8g more frequently than did gusts.

For the turbojet airplanes, the results in figure 18 show that, for negative values of acceleration, maneuver accelerations occurred only slightly less frequently than gust accelerations. For positive values of accelerations, operational maneuver accelerations occurred with approximately the same frequency as gust accelerations. Over most of the positive acceleration range, check-flight maneuver accelerations occurred more frequently than did gust accelerations. That the check-flight maneuver accelerations are high relative to the gust accelerations is due less to an increase in the check-flight experience than to the low gust acceleration experience of the turbojet airplanes.

Oscillatory Accelerations

From the VGH time-history records, it has been observed that certain airplanes on occasion oscillate in the longitudinal or the longitudinal-lateral stability mode. These oscillations are a source of repeated loads as will be discussed in the following paragraphs.

A typical example of the oscillatory accelerations is shown in figure 19, which is a reproduction of a section of a VGH record from a turbine-powered airplane. The oscillations produce the varying load as indicated by the sinusoidal-like variations of the acceleration trace. In this example, the amplitude of the incremental accelerations is approximately ±0.2g and the period is about 15 seconds. Large variations in the waveforms of the accelerations and in the periods of the oscillations have been observed. The maximum amplitude of the continuous-type oscillations generally has been less than ±0.3g although values up to ±0.6g have been recorded.

Oscillations of the general type shown in figure 19 have been observed on each of the turbine-powered airplanes on which VGH data have been collected. (In contrast, they were rarely, if ever, observed on the piston transport airplanes.) The percent of the total flight time that the oscillations occurred ranged for less than 1 percent to 27 percent for individual airplanes. The frequency of occurrence of the oscillations appears to be associated with individual airplanes rather than with airplane types or airlines. For the most part, the oscillations are thought to be associated with the flight control systems - both automatic and manual. A detailed discussion of the characteristics and causes of the oscillatory accelerations is given in reference 4.

The cumulative frequency distributions of oscillatory accelerations per mile of flight are shown in figure 20 for a number of individual airplanes. For comparison, the range of the operational maneuver acceleration distributions from figure 14 is also shown in the figure. The results show that the frequencies of occurrence of given values of oscillatory acceleration for the different airplanes vary by as much as 1000 to 1. The oscillatory acceleration experience for several of the airplanes is partly within the range of the operational maneuver acceleration experience. The results in figure 20 suggest that the oscillatory accelerations are not a major source of fatigue loads for most airplanes, but that on certain airplanes the oscillatory accelerations may cause approximately as many repeated loads as are caused by operational maneuvers.

Total In-Flight Acceleration Experiences

Frequency per flight mile.- As was discussed earlier in this paper, the VGH data samples usually are not large enough to define the frequency of occurrence of the large values of acceleration. Consequently, estimates of the total acceleration experiences are obtained by combining the VGH data with the more extensive samples of V-G data (see fig. 6). This method was used to obtain estimates of the total acceleration histories for each airplane type. The results are shown in figure 21 in terms of the average cumulative frequency distribution of positive and negative accelerations per mile of flight. In this presentation, no distinction is made as to the sources (i.e., gusts or maneuvers) of the accelerations. In general, however, it may be said that gusts are the predominant factor in defining the curves, especially for values of acceleration less than 0.5g.

The results in figure 21 show that differences among the total in-flight acceleration frequencies for the various types of airplanes range up to a factor of approximately 50 to 1. In general, the total acceleration distributions are in approximately the same order as was previously shown for the gust accelerations (fig. 9). The reason that the range (50 to 1) of the total in-flight acceleration frequencies is reduced from that (100 to 1) for the gust accelerations alone is due mainly to the contribution of the maneuver accelerations to the total accelerations for the turbojet long-haul airplanes.

The various airplanes represented by the data in figure 21 are designed to different load factors, depending upon the particular airplane characteristics.

Consequently, the relative severity of the acceleration histories shown in figure 21 is in no way indicative of the load experiences relative to design values. The results are, however, thought to be the best available estimates of the in-flight acceleration histories for the various airplane types.

Frequency per flight.- Up to this point in the paper, the acceleration data (such as given in fig. 21) have been presented, compared, and discussed in terms of the cumulative frequency of occurrence per mile of flight - a basis which is widely used in the aviation community. It is of interest, however, to examine the results on another basis - the cumulative frequency of occurrence per flight. For this purpose, the distributions of total in-flight acceleration from figure 21 are replotted in figure 22 in terms of the cumulative frequency per flight. For this figure, the average flight distance of the operations for each of the airplane types was used to convert the data given in figure 21 to the per-flight basis.

The results in figure 22 show that, on the per-flight basis, the differences among the average acceleration experiences for the various airplane types are less than 5 to 1 over most of the acceleration range. This is in sharp contrast to the 50-to-1 variation previously shown on a per-flight-mile comparison basis in figure 21. Thus, the large variations in the in-flight repeated loads which are customarily associated with different types of airplanes, are significantly reduced merely by expressing the repeated loads in terms of "per flight" rather than "per flight mile."

In view of the consistency obtained above between the in-flight acceleration experiences of different types of airplanes, the question arises as to whether the "per-flight basis" of comparison also will reduce the variations among the in-flight acceleration experiences of several different airline operations involving a given type of airplane. Information pertinent to this question is given in table III. The first three columns in the table list each individual airplane type for which VGH data were available from two or more airline operations, the number of operations involved, and the range of average flight lengths for the individual operations. The last two columns give the factor by which the cumulative frequency of occurrence of in-flight acceleration increments larger than 0.4g varied among the operations of each airplane type. This variation factor is given on both a "per-flight-mile" basis and a "per-flight" basis.

Comparison of the factors in the last two columns in table III shows that the maximum variations among the acceleration frequencies for different operations of a given airplane type was 6.0 to 1 on a "flight-mile" basis and 2.6 to 1 on a "flight" basis. For all of the airplanes, except airplane K, the variation in the acceleration frequencies was approximately the same expressed in either "flight miles" or "flights." For airplane K, however, the variation in acceleration frequencies is only 1.5 to 1 when expressed on the "per-flight" basis in contrast to the 6.0-to-1 variation on the "per-flight-mile" basis.

The reason that the basis for expressing the acceleration frequency made a significant difference for airplane K and not for the other airplanes is associated with the average flight lengths of the operations. It is noted in table III that the average flight length for the individual operations of airplane K ranged from 390 to 1430 miles, whereas the average flight lengths for each of the other airplanes covered a much smaller range. The flight length is an important consideration because the majority of the repeated loads occur during the climb and descent phases of flight rather than during cruise. Consequently, the variation among the acceleration frequencies for different operations of a given airplane type generally will be less when expressed in terms of "flights" rather than "flight miles." If the individual operations have approximately the same average flight length, the variations among the acceleration frequencies will be about the same on either basis.

Implications.- The foregoing discussions of the in-flight acceleration experiences have indicated that:

1. The in-flight maneuver and gust acceleration experiences of various types of airplanes can be more consistently expressed in terms of frequency per flight than in terms of frequency per flight mile. In terms of frequency per flight, the spread in the acceleration frequencies for the various types of airplanes is about 5 to 1 as compared to 50 to 1 on a per-flight-mile basis.

2. The in-flight acceleration experiences of different airline operations of a given airplane type also tend to be more consistent in terms of flight rather than flight miles. This appears to be especially the case when the airplane type is used in different airline operations having large (factor of 3 or 4) differences in the average flight lengths.

These results imply that the frequency per flight may be a more consistent and appropriate basis for assessing in-flight fatigue loadings than the frequency-per-flight-mile basis. This implication appears to be particularly significant when taken together with recognition that other repeated loads (pressurization cycles, landing impact, ground operations, and the ground-air-ground cycle) are more nearly a function of the number of flights rather than the number of flight miles. Although additional study is required to further assess the "per-flight" and "per-flight-mile" basis for evaluating fatigue loadings, the frequency-per-flight basis at this time appears to offer the following advantages:

1. Provides a better accounting of the load variations among different airline operations of a given airplane type.

2. Provides a better accounting of the load experience of an airplane during its life which, generally, includes the airplane being relegated to shorter flights as it ages. (For example, many long-haul airplanes of yesteryear are used today for short-haul operations.)

3. May possibly provide a simple and convenient basis for deriving a limited number of loading spectra for generalized fatigue analysis and tests.

Landing Impact Accelerations

Information pertaining to the landing impact accelerations experienced by the piston- and turbine-powered transports is given in figure 23. The ordinate is the probability per flight that a given value of the abscissa, the maximum positive acceleration increment due to initial landing impact, will be exceeded. Two ranges of probability curves are shown: one for piston airplanes and the other for turbine airplanes. The band for the piston airplanes covers data from a total of 3211 landings by three types of four-engine and one type of two-engine piston airplanes. The band for the turbine airplane encompasses landings by one type of two-engine turboprop airplane, two types of four-engine turboprop airplanes, and three types of four-engine turbojet airplanes. The average probability distributions for the piston- and turbine-powered airplanes are also shown in the figure.

The results in figure 23 indicate that the landing impact accelerations generally are higher for the turbine airplanes than for the piston airplanes. At a probability of 0.01, or for one landing in a hundred, for example, the turbine airplanes would, on the average, experience a landing impact acceleration equal to or greater than 0.72g as compared to a value of 0.48g for the piston airplanes.

The reasons for the significantly higher landing impact accelerations for the turbine airplanes as compared to the piston airplanes are not fully known. It is, in part at least, a reflection of higher vertical velocities experienced at landing contact by certain types of turbine airplanes. (This aspect has been discussed in detail in ref. 4.) Differences in landing-gear characteristics for the piston and turbine airplanes may also exist which could have a bearing on the landing impact accelerations.

The ranges shown in figure 23 for the probability distributions indicate rather large variations in landing impact acceleration experience for the different types of piston and turbine airplanes. For the turbine airplanes, the probability distributions for individual operations of both the turboprop and the turbojet airplanes spread over most of the range indicated in the figure. Thus, it is thought that the airplane operator may be a major factor influencing the landing impact acceleration experience.

Accelerations During Ground Operations

Extensive data samples pertaining to the accelerations during taxiing, take-off, and landing of the various types of transport airplanes are not available. Consequently, no attempt is made to compare the ground-induced accelerations for the various types of airplanes. Rather, two recently obtained data samples will be presented to indicate some of the general characteristics of the ground-induced accelerations.

Figure 24 shows the cumulative frequency distributions of accelerations per flight experienced by a two-engine turboprop airplane and a four-engine turbojet airplane. Three distributions are shown for each airplane and represent the accelerations experienced during taxiing operations, the take-off roll, and the landing roll-out. For each airplane type, the results indicate that the landing roll-out is the predominant source of the ground accelerations and that the taxiing and take-off rolls produce roughly (within a factor of 2) the same number of accelerations. It is also noted that the results for the two types of airplanes are similar as regards the magnitude and frequency of occurrence of the accelerations during the three phases of the ground operations. Additional ground accelerations for several types of airplanes are currently being obtained and evaluated by NASA. These data should provide an improved description of the acceleration experience during ground operations.

CONCLUDING REMARKS

A review of repeated loads data collected by NASA on piston- and turbine-powered commercial transport airplanes since 1947 has been made. This review has served to summarize the available data on repeated loads caused by gusts, operational maneuvers, check-flight maneuvers, landing impact, and ground operations according to airplane type (two- and four-engine piston, two- and four-engine turboprop, and four-engine turbojet) and airline service (feeder line, short haul, and long haul). The following trends in the repeated loads were indicated by the review:

1. For both the piston- and turbine-powered classes of airplanes, the frequency of gust accelerations per mile of flight decreased significantly and in a progressive order from the feeder-line, to the short-haul, to the long-haul airplanes. These decreases resulted primarily because the beneficial effect of higher wing loading and the less severe gust environment associated with the

higher cruise altitudes more than offset the detrimental effect of increased speeds on the accelerations.

2. The frequency of accelerations caused by operational maneuvers during passenger-carrying flights has remained relatively constant for the various types of airplanes and types of airline service. The turboprop and turbojet transports are used in pilot training airplane check flights a larger percentage of the total flight time than were the piston transport airplanes. However, no particular trend in the frequency of the check-flight maneuver accelerations is evident.

3. In general, the landing impact accelerations for the turbine-powered airplanes are higher than for the piston transports.

4. The acceleration experiences due to landing impact and check-flight maneuvers appear to be influenced significantly by the airline. Consequently, it is not expected that substantial refinement will be attained in the estimation of the loads from these two sources.

5. For the wide range of airplanes and operations covered by the review, the in-flight acceleration histories have remained unexpectedly consistent when viewed on a flight rather than a flight-mile basis. This is due to the fact that the majority of the repeated loads occur in the climb and descent phases of flight rather than during cruise. The consistency of the acceleration histories on the flight basis is interesting and appears to warrant further analysis to determine if it has significant implications relative to airplane fatigue.

REFERENCES

1. Richardson, Norman R.: NACA VGH Recorder. NACA TN 2265, 1951.
2. Taback, Israel: The NACA Oil-Damped V-G Recorder. NACA TN 2194, 1950.
3. Walker, Walter G., and Copp, Martin R.: Summary of VGH and V-G Data Obtained From Piston-Engine Transport Airplanes From 1947 to 1958. NASA TN D-29, 1959.
4. Staff of Langley Airworthiness Branch: Operational Experiences of Turbine-Powered Commercial Transport Airplanes. NASA TN D-1392, 1962.
5. Copp, Martin R., and Fetner, Mary W.: Analysis of Acceleration, Airspeed, and Gust-Velocity Data From a Four-Engine Turboprop Transport Operating Over the Eastern United States. NASA TN D-36, 1959.
6. Hunter, Paul A., and Walker, Walter G.: An Analysis of V-G and VGH Operations Data From a Twin-Engine Turboprop Transport Airplane. NASA TN D-1925, July 1963.
7. Coleman, Thomas L., and Stickle, Joseph W.: Turbulence Environment for Supersonic Transports. Proceedings Symposium on Supersonic Transports. Soc. Exp. Test Pilots, Sept. 1961, pp. 144-160.
8. Pratt, Kermit G., and Walker, Walter G.: A Revised Gust-Load Formula and a Re-Evaluation of V-G Data Taken on Civil Transport Airplanes From 1933 to 1950. NACA Report 1206, 1954. (Supersedes NACA TN 2964 by Kermit G. Pratt and TN 3041 by Walter G. Walker.)

TABLE I.- AIRPLANE CHARACTERISTICS

Airline service	Airplane type	Propulsion	Maximum gross weight, lb	Wing area, sq ft	Wing loading, lb/sq ft
Feeder	A	2-engine piston	25,200	987	25.4
	L	2-engine turboprop	35,700	754	47.3
Short haul	B	2-engine piston	39,900	864	46.1
	C		40,500	817	49.5
	D		47,000	920	51.0
	M	4-engine turboprop	113,000	1300	86.9
	N		63,000	963	65.4
Long haul	E	4-engine piston	94,000	1650	57.0
	F		107,000	1650	64.8
	G		70,700	1461	48.4
	H		89,900	1463	61.3
	H-1		93,200	1463	61.3
	J		122,000	1463	83.2
	K		147,000	1720	85.4
	O-1	4-engine turbojet	247,000	2433	101.5
	[a]O-2		312,000	2892	107.9
	[a]O-3		312,000	2892	107.9
	P-1		273,000	2773	98.4
	P-2		276,000	2773	99.5
	P-3		310,000	2773	111.8
	Q		184,000	2150	85.8

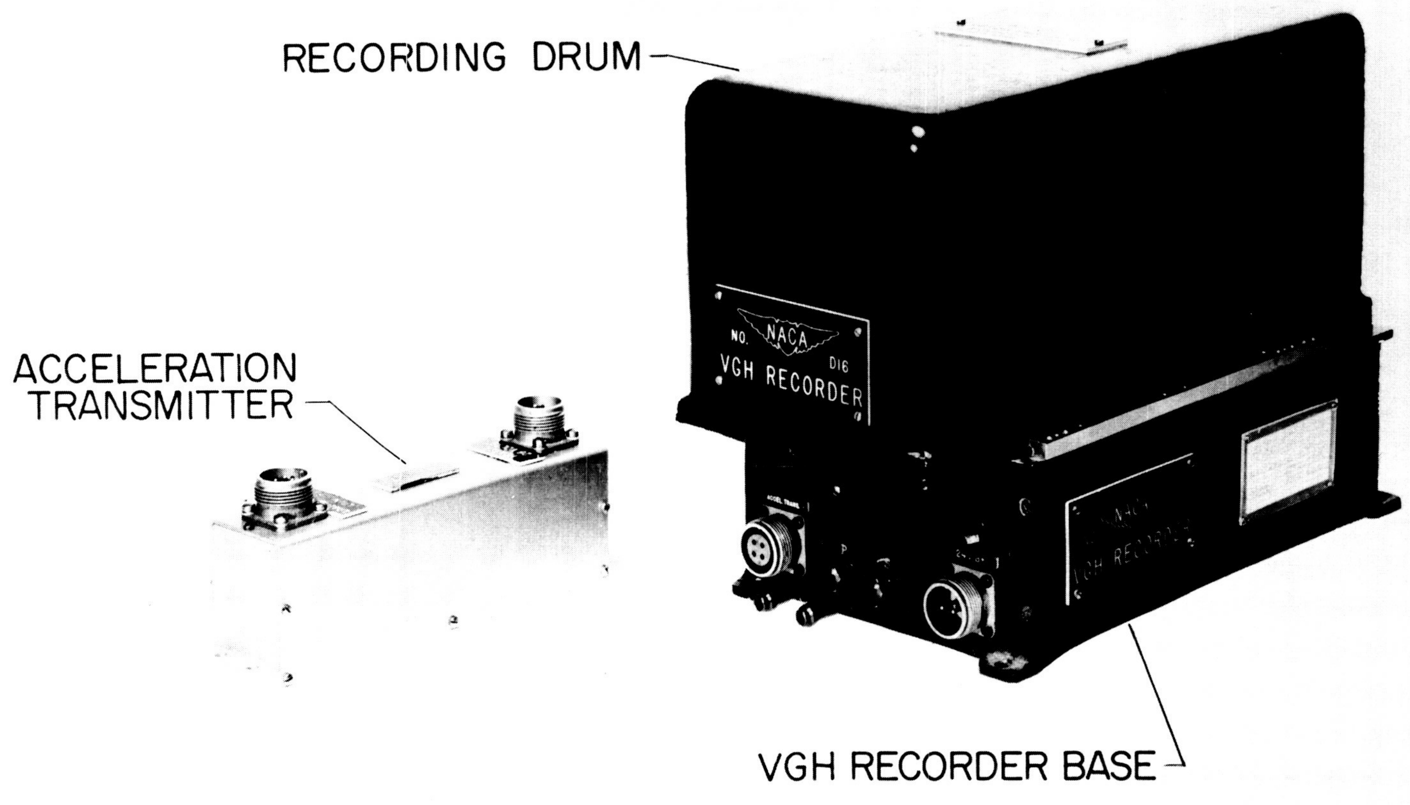
[a]Types O-1 and O-2 differ only in the model of the engines.

TABLE II.- SCOPE AND SIZES OF VGH AND V-G DATA SAMPLES

Airline service	Airplane type	Propulsion	VGH data			V-G data		
			Number of:			Number of:		
			Airplanes	Airlines	Flight hours	Airplanes	Airlines	Flight hours
Feeder	A	2-engine piston	1	1	1278	27	7	91,089
	L	2-engine turboprop	2	1	2100	2	1	10,368
Short haul	B	2-engine piston	1	1	834	24	1	38,578
	C		1	1	676	7	3	11,215
	D		2	2	2418	3	1	13,327
	M	4-engine turboprop	3	3	7038	8	2	38,138
	N		1	1	1834	--	--	------
Long haul	E	4-engine piston	-	-	------	10	1	48,187
	F		1	1	1038	--	-	------
	G		1	1	673	24	5	69,757
	H		2	2	2555	6	2	23,148
	H-1		1	1	1062	5	1	14,953
	J		4	2	4666	--	-	------
	K		3	3	3908	4	1	15,387
	O-1	4-engine turbojet	2	2	2410	8	3	51,264
	O-2		2	2	2822	3	2	19,330
	O-3		2	1	1539	--	-	------
	P-1		-	-	----	2	1	13,571
	P-2		2	1	2464	5	2	24,478
	P-3		1	1	1651	4	1	13,750
	Q		1	1	1222	4	1	10,103
Total					42,188			506,643

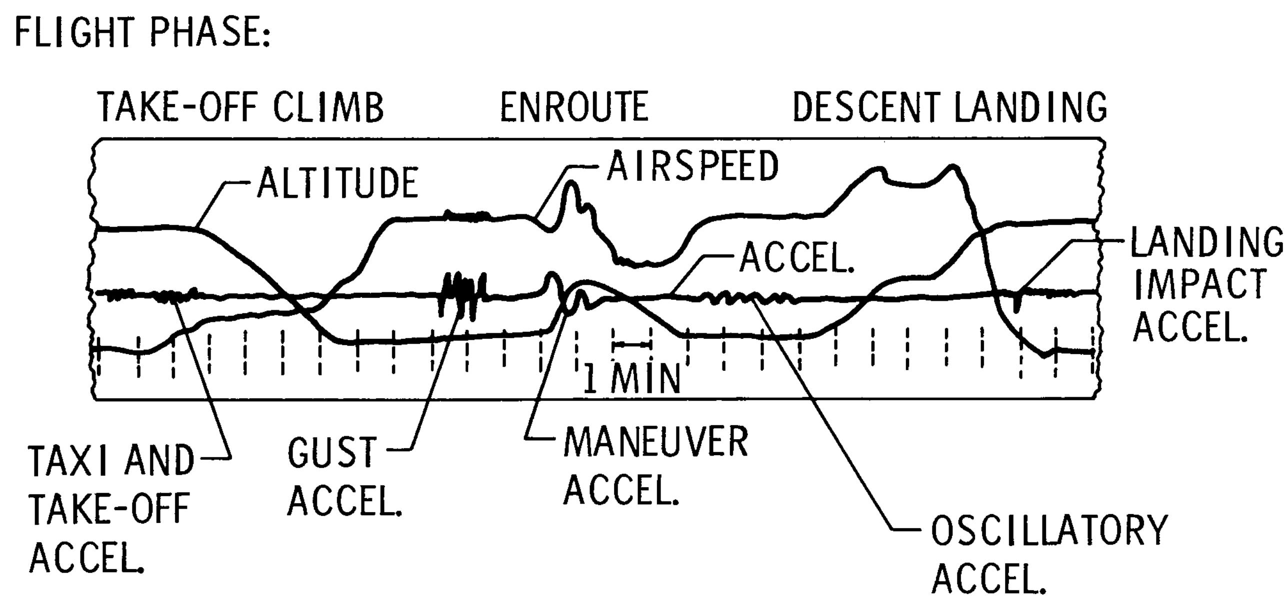
TABLE III.- VARIATIONS AMONG ACCELERATION FREQUENCIES FOR INDIVIDUAL OPERATIONS OF GIVEN AIRPLANE TYPES

Airplane type (table I)	Number of operations (table II)	Range of average flight lengths, nautical miles	Variation in acceleration frequency per:	
			Flight mile	Flight
D	2	165 to 170	2.2:1	2.1:1
H	3	350 to 405	2.9:1	2.6:1
J	2	385 to 525	1.7:1	1.4:1
K	3	390 to 1430	6.0:1	1.5:1
M	3	290 to 470	1.6:1	1.3:1
0-1	2	990 to 1430	1.2:1	1.2:1
0-2	2	1500 to 1680	1.2:1	1.1:1



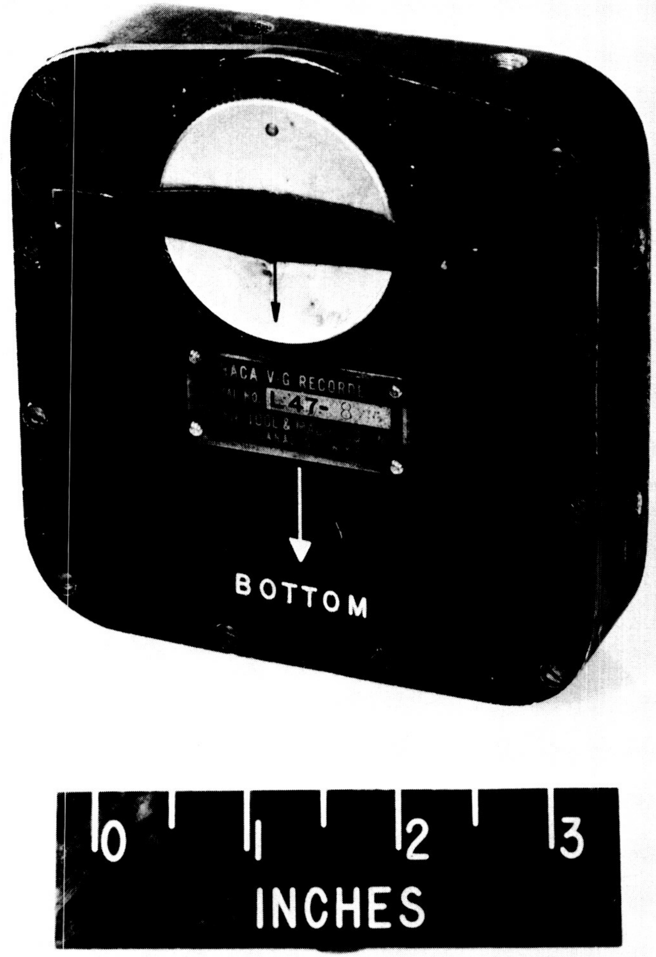
NASA

Figure 1.- NACA VGH recorder.



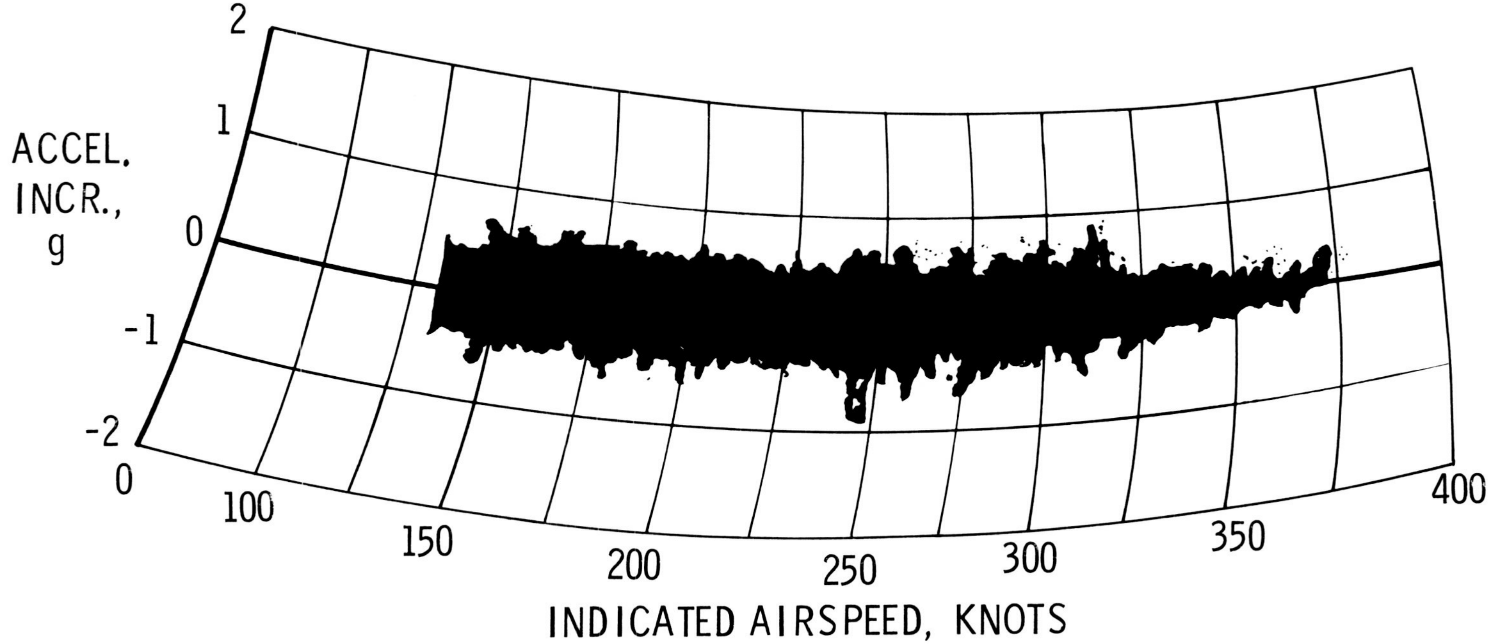
NASA

Figure 2.- Illustrative VGH record.



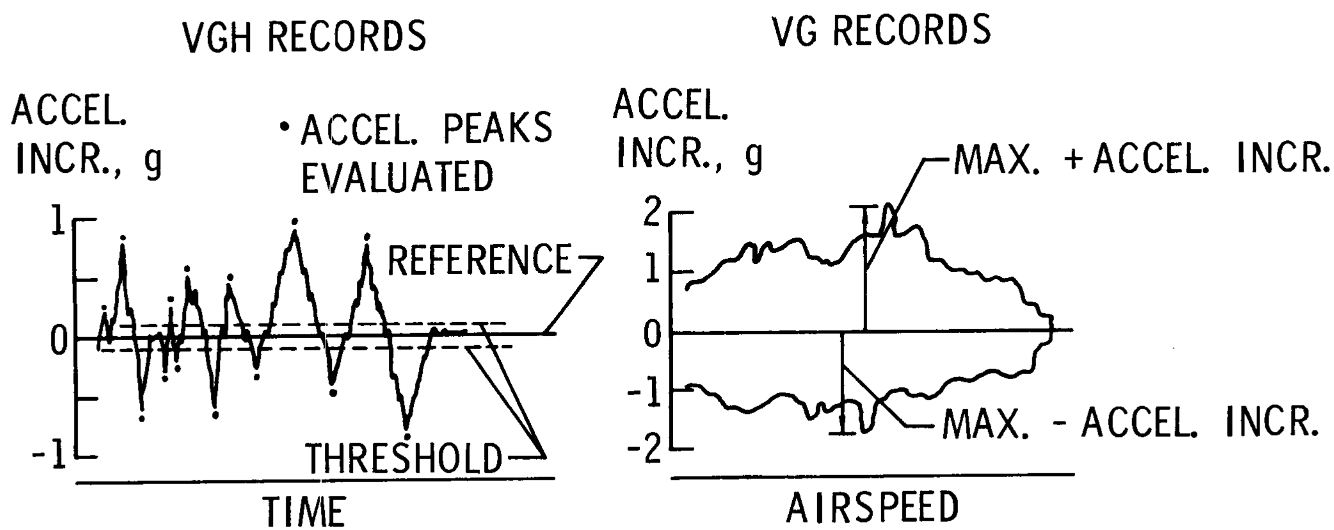
NASA

Figure 3.- V-G recorder.



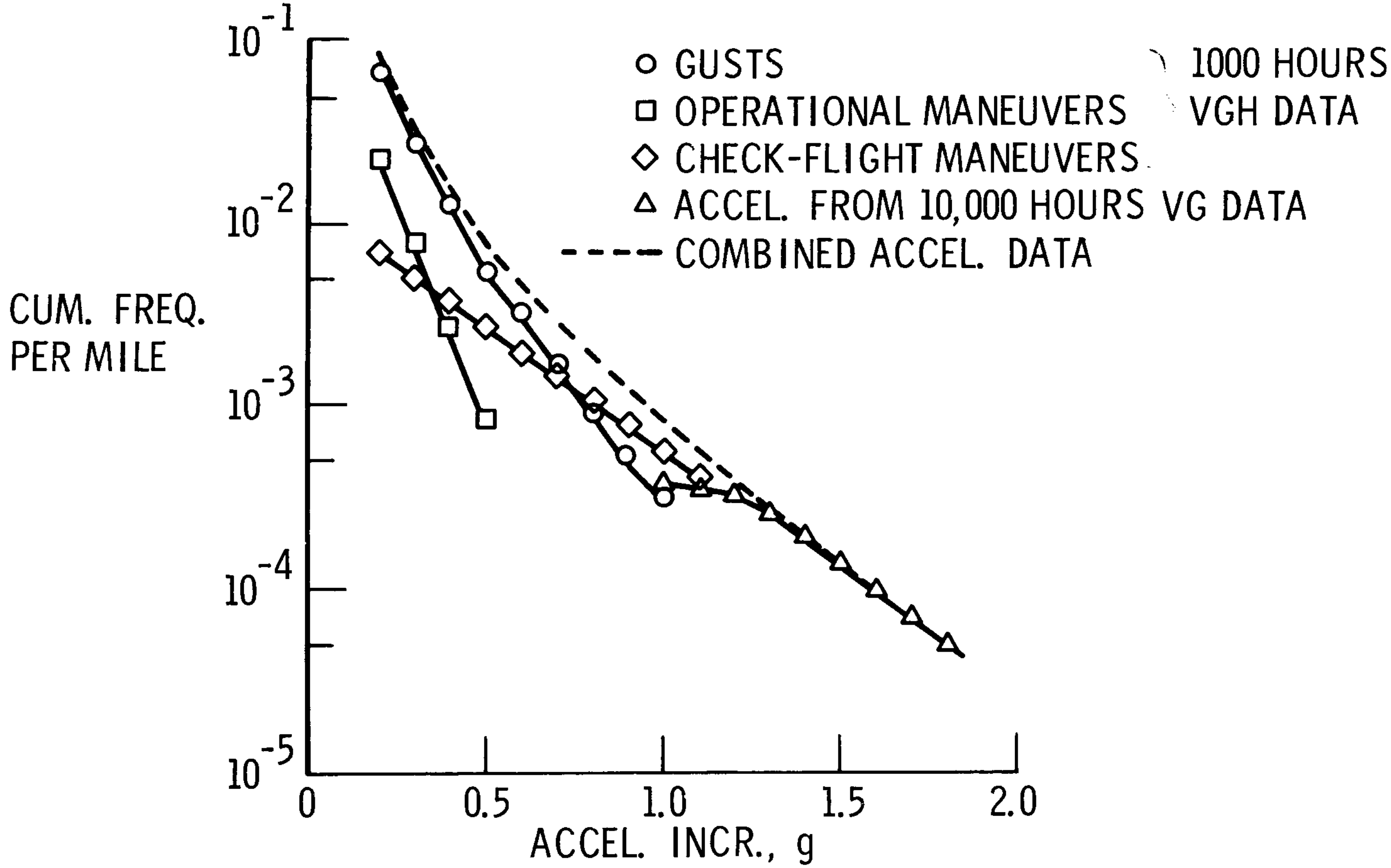
NASA

Figure 4.- Example of V-G record (200 flight hours).



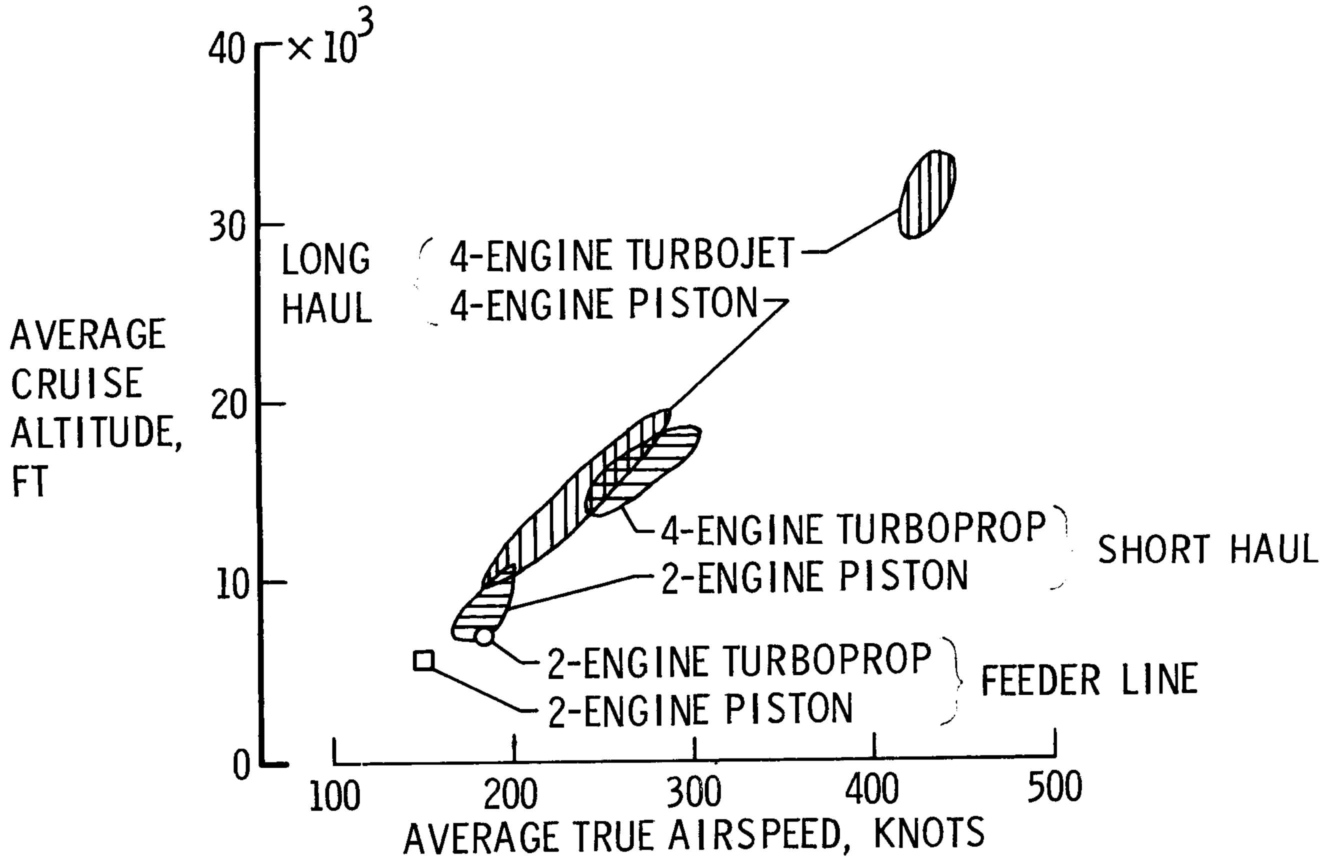
NASA

Figure 5.- Method of evaluating accelerations from VGH and V-G records.



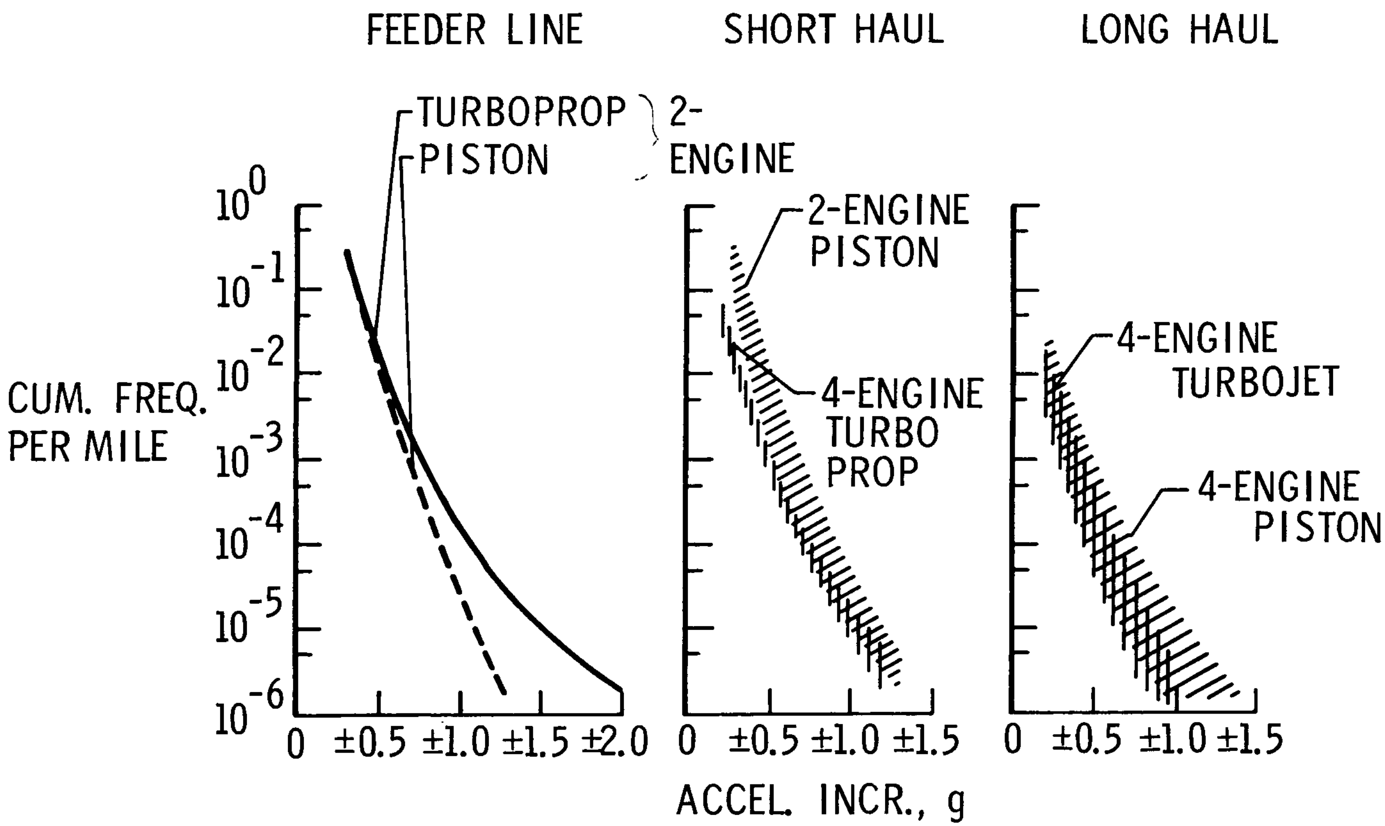
NASA

Figure 6.- Method of combining VGH and V-G data.



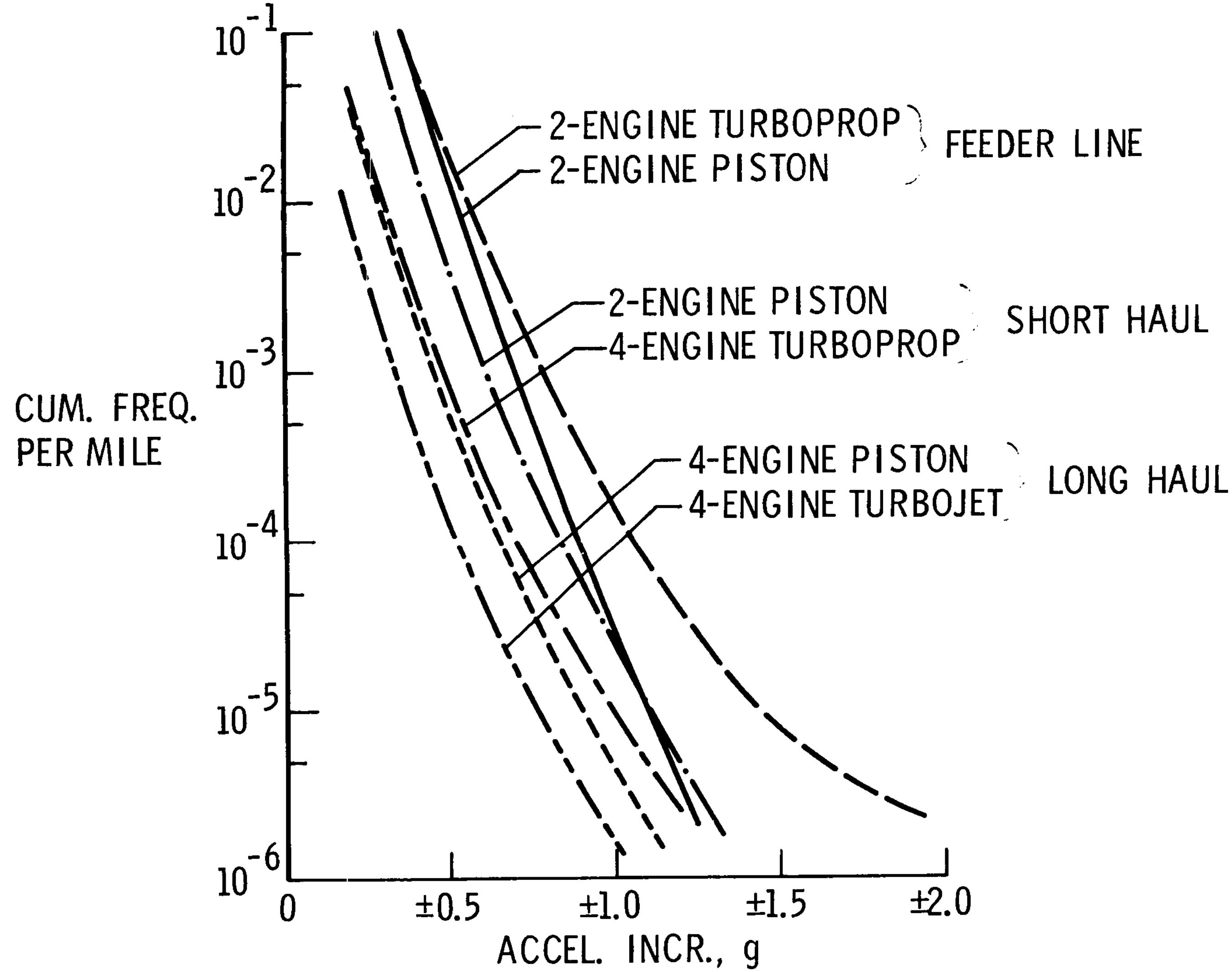
NASA

Figure 7.- Airspeeds and altitudes for transport airplanes.



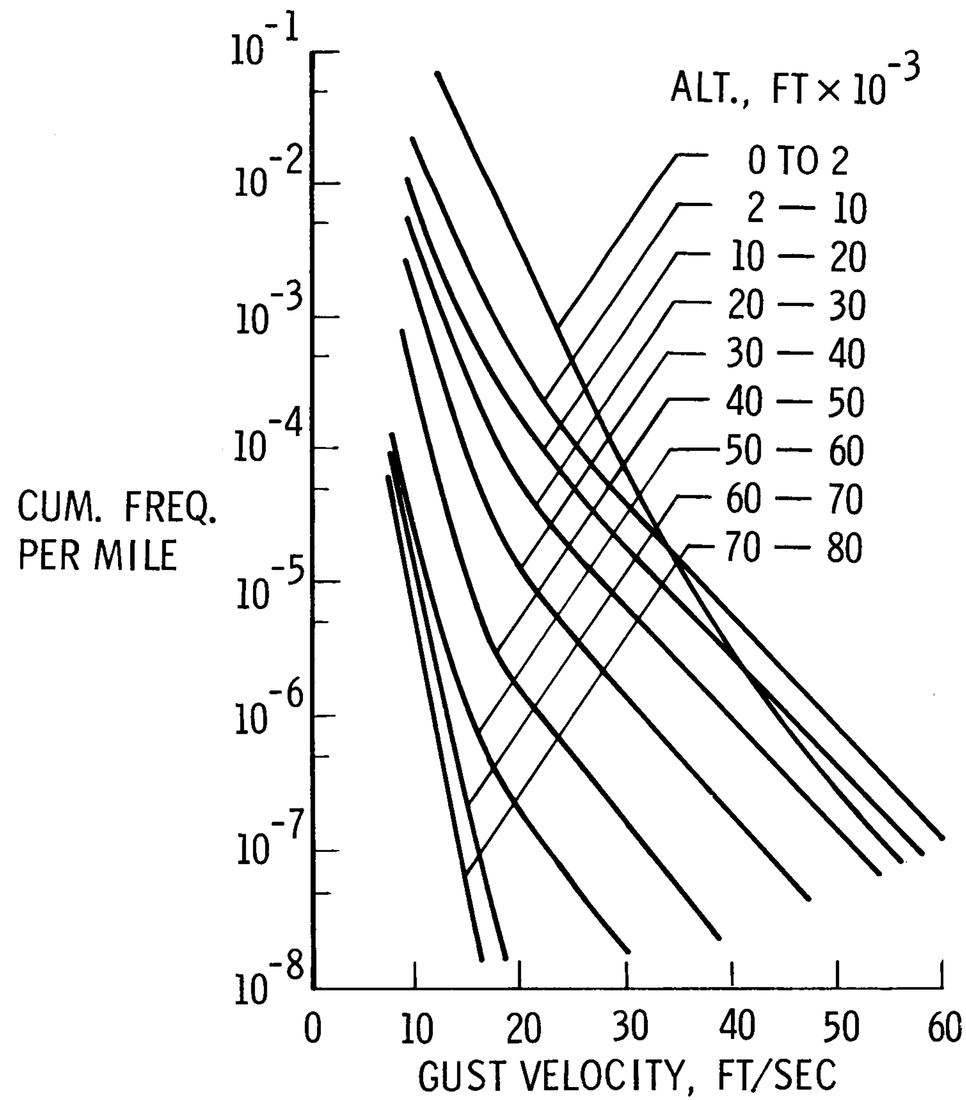
NASA

Figure 8.- Distributions of gust accelerations.



NASA

Figure 9.- Gust accelerations.



NASA

Figure 10.- Estimated gust environment for transport airplanes (from ref. 7).

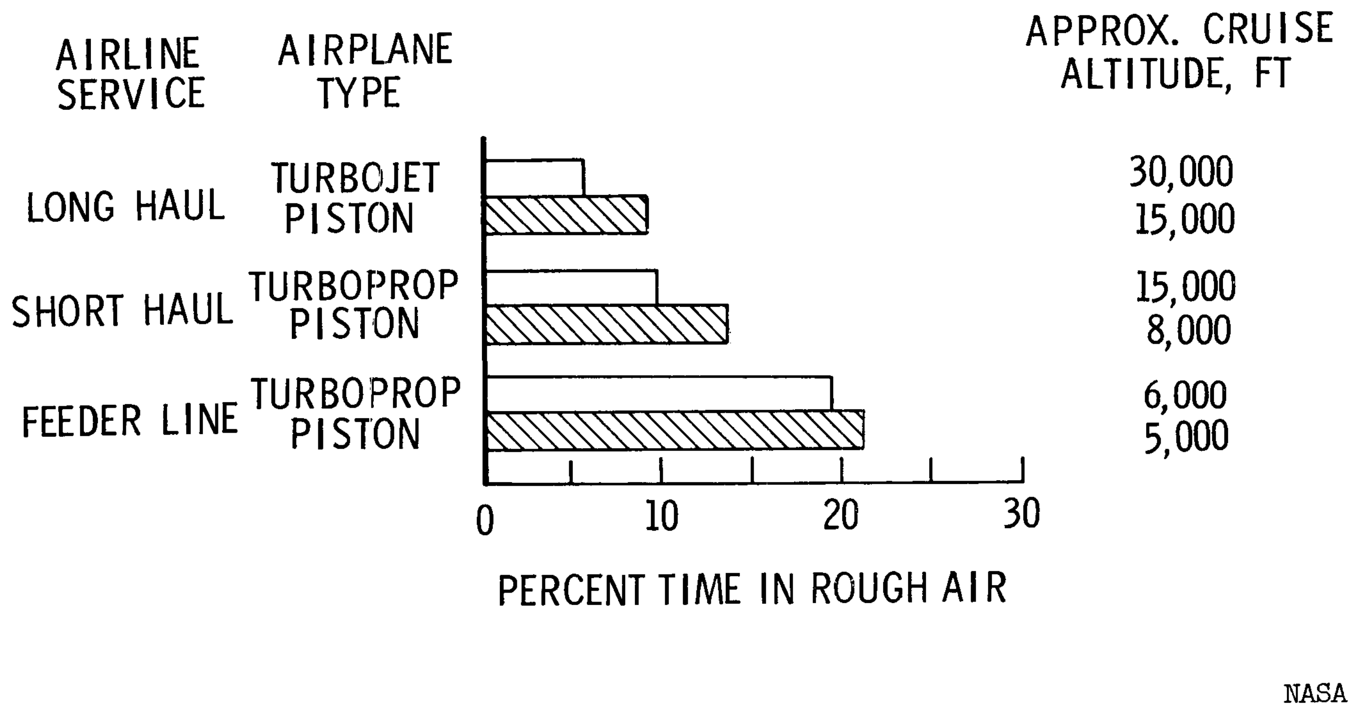
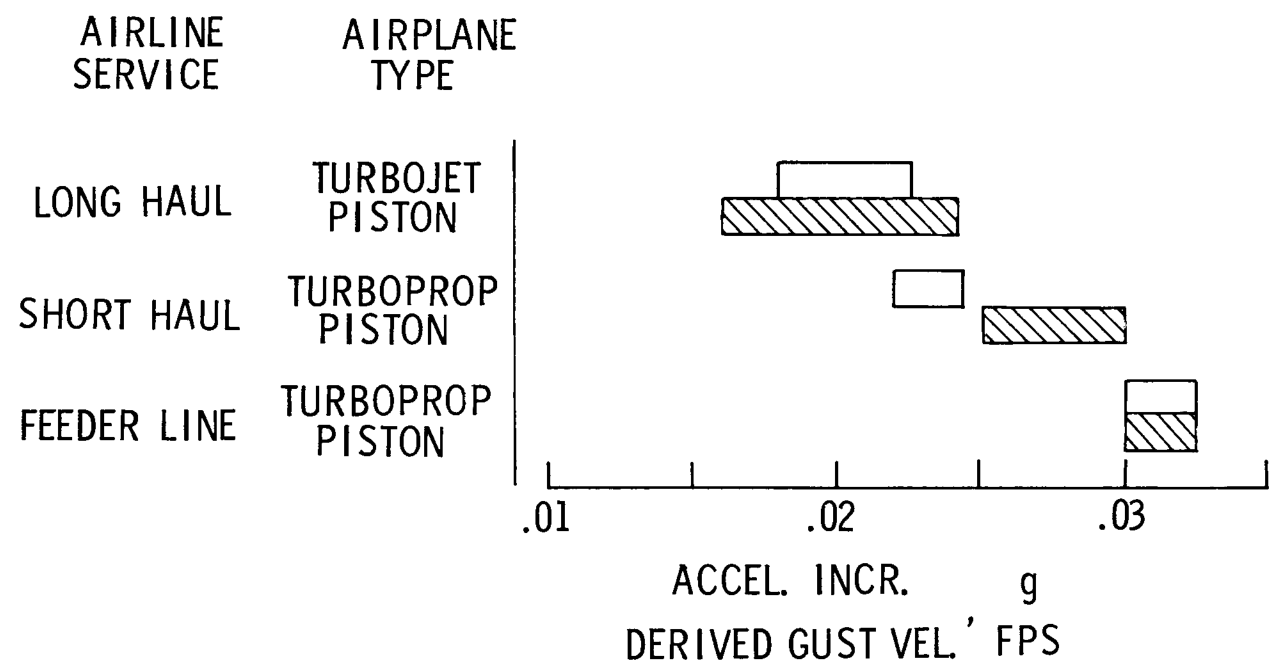
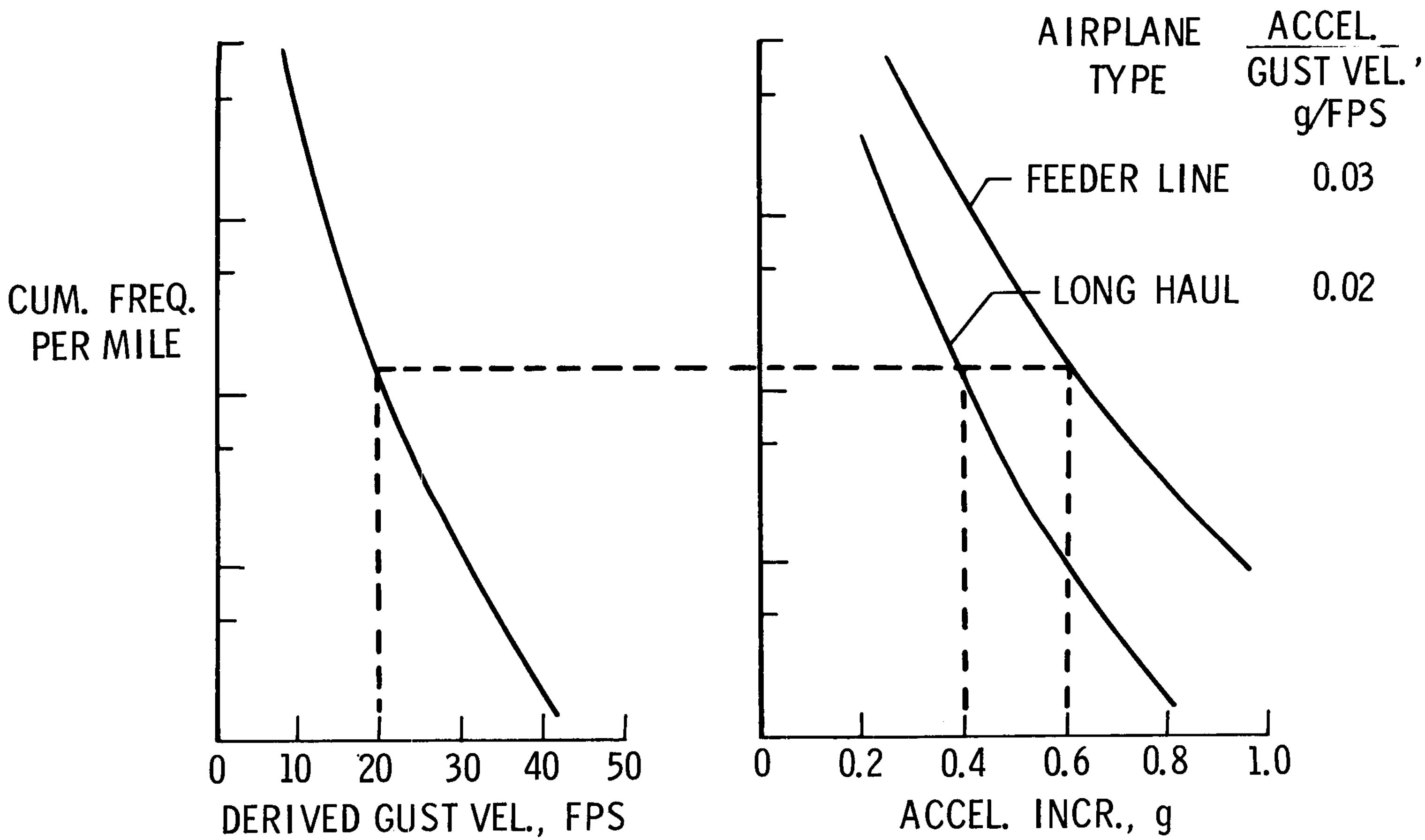


Figure 11.- Percent of total flight time in rough air.



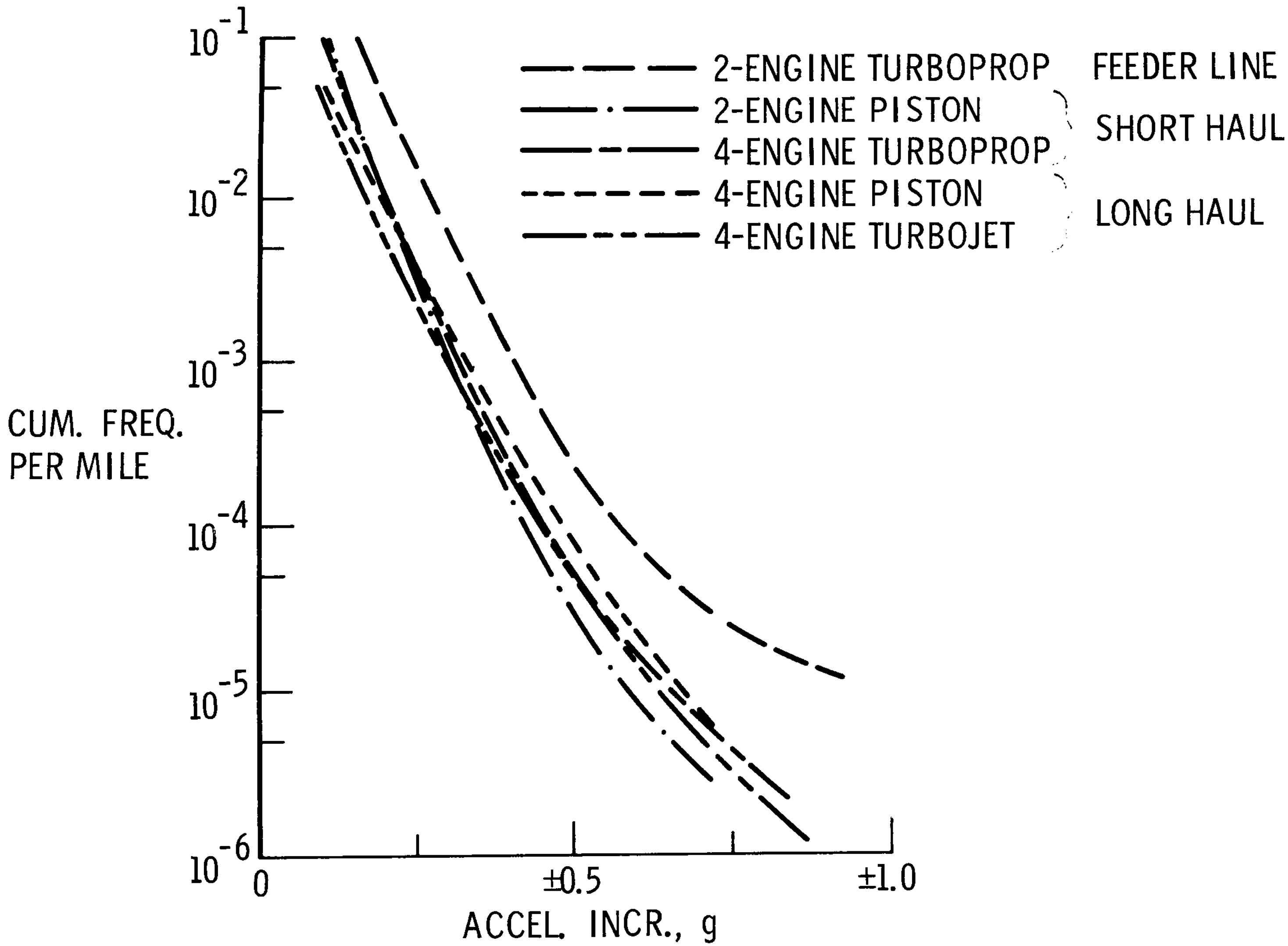
NASA

Figure 12.- Airplane acceleration response sensitivity to turbulence.



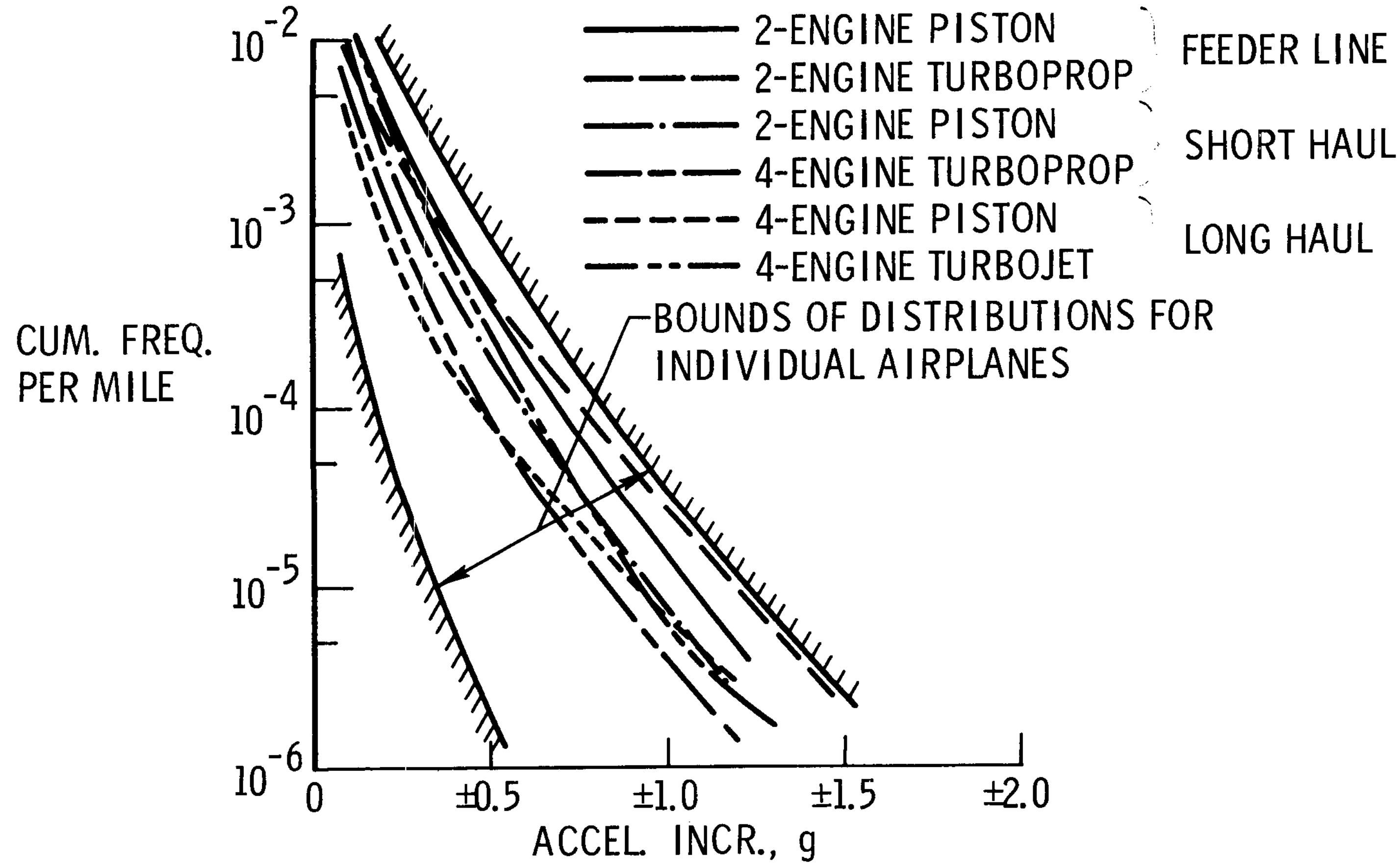
NASA

Figure 13.- Effect of airplane response characteristics on gust accelerations.



NASA

Figure 14.- Operational maneuver accelerations.



NASA

Figure 15.- Check-flight maneuver accelerations.

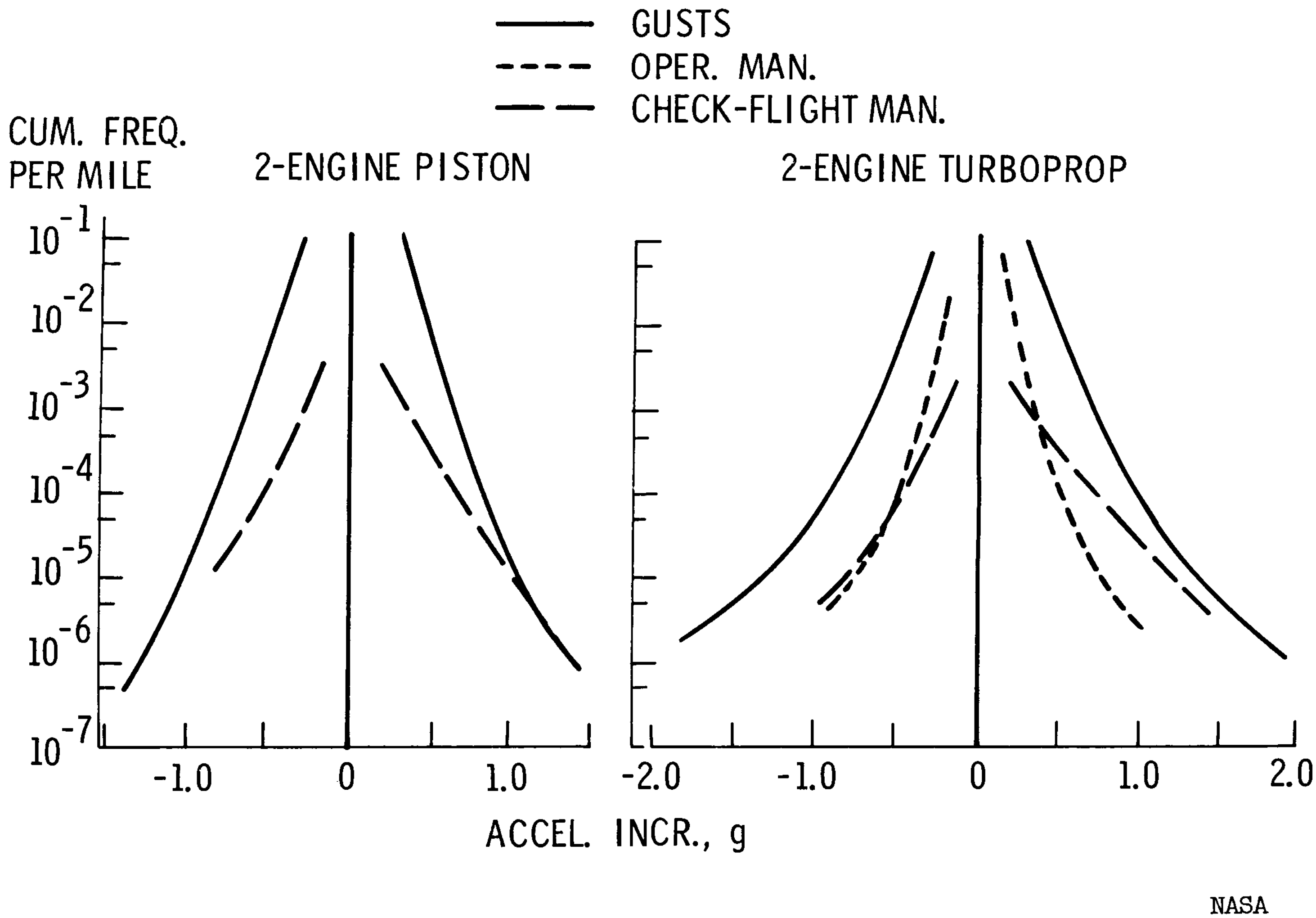
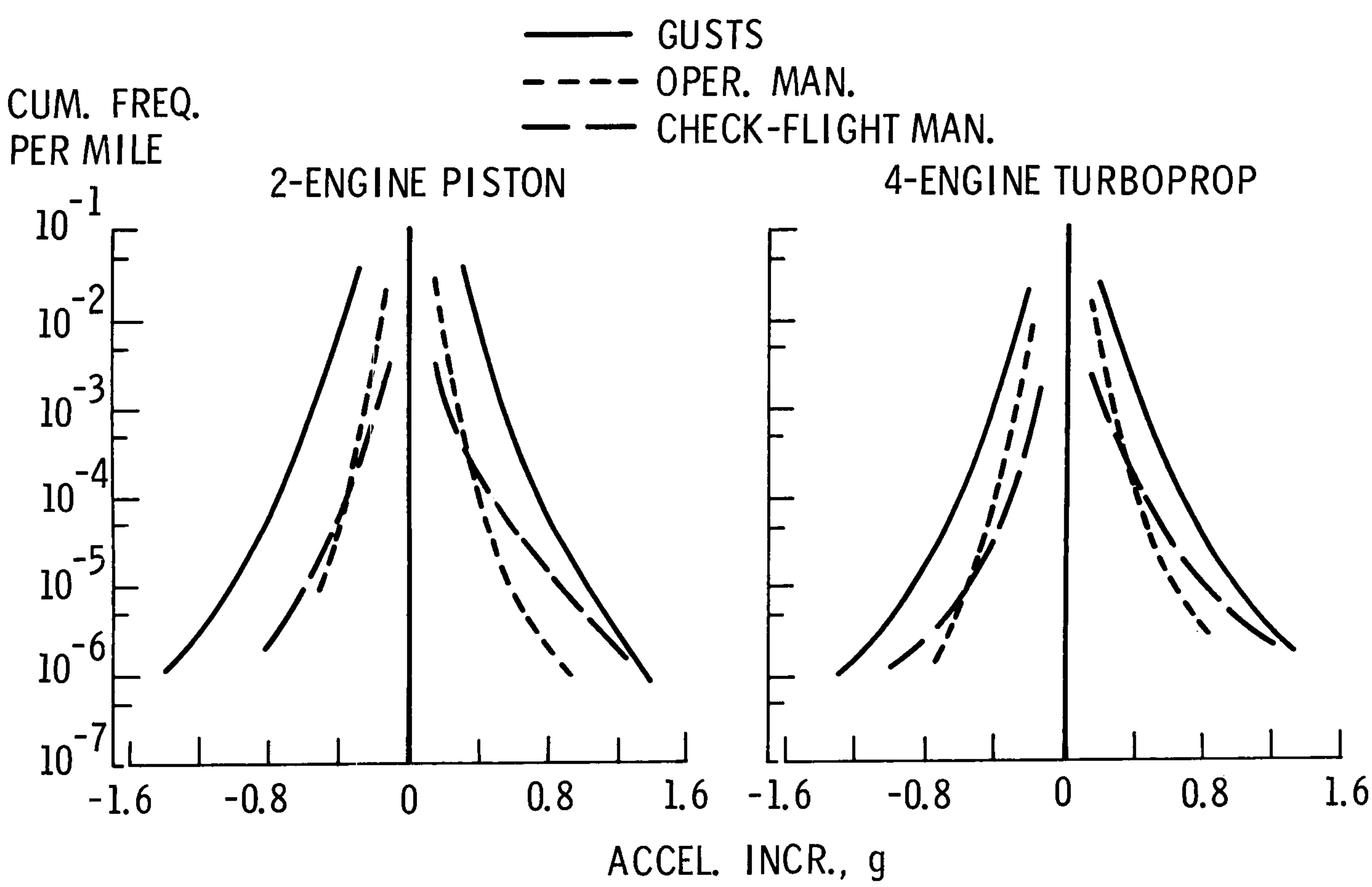


Figure 16.- Gust and maneuver accelerations for feeder-line airplanes.



NASA

Figure 17.- Gust and maneuver accelerations for short-haul airplanes.

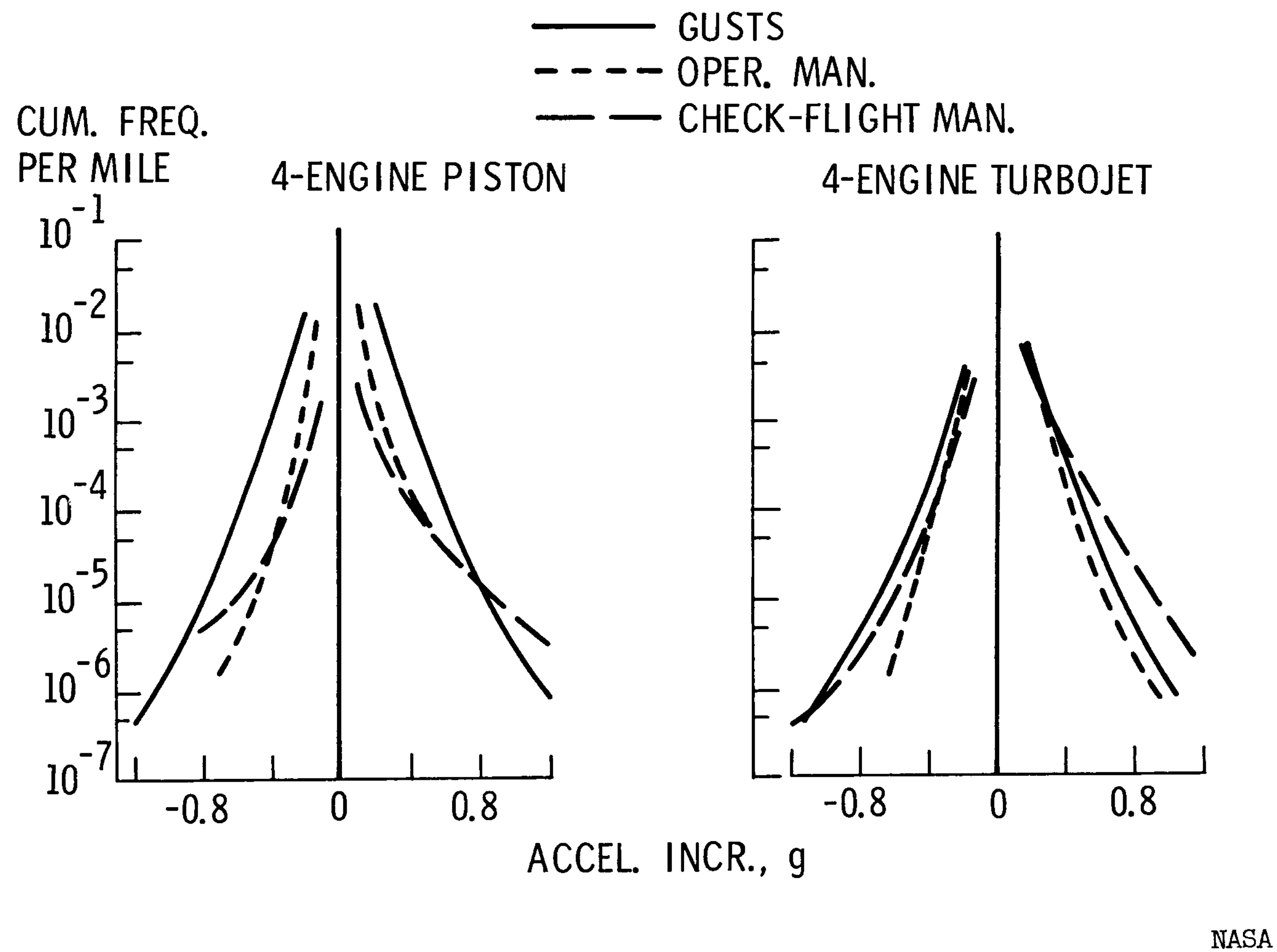
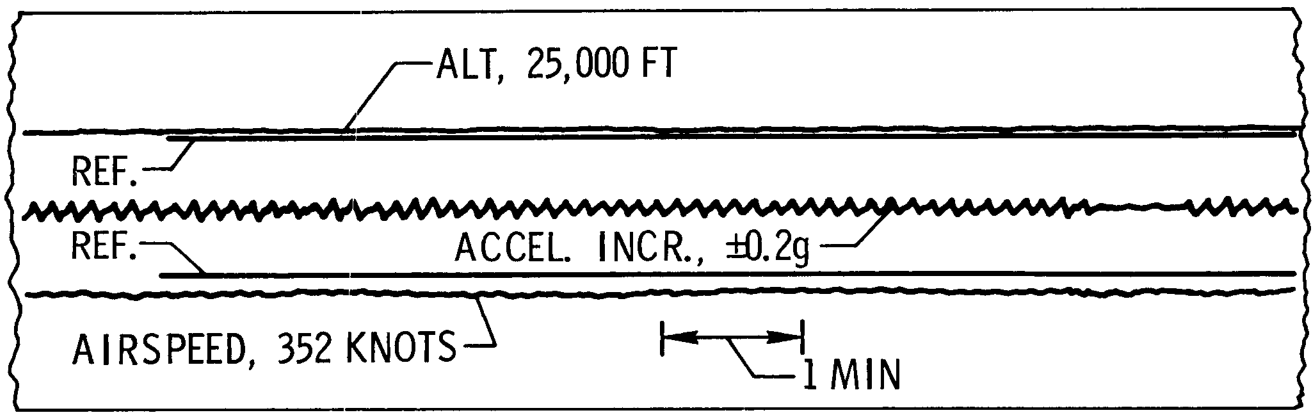
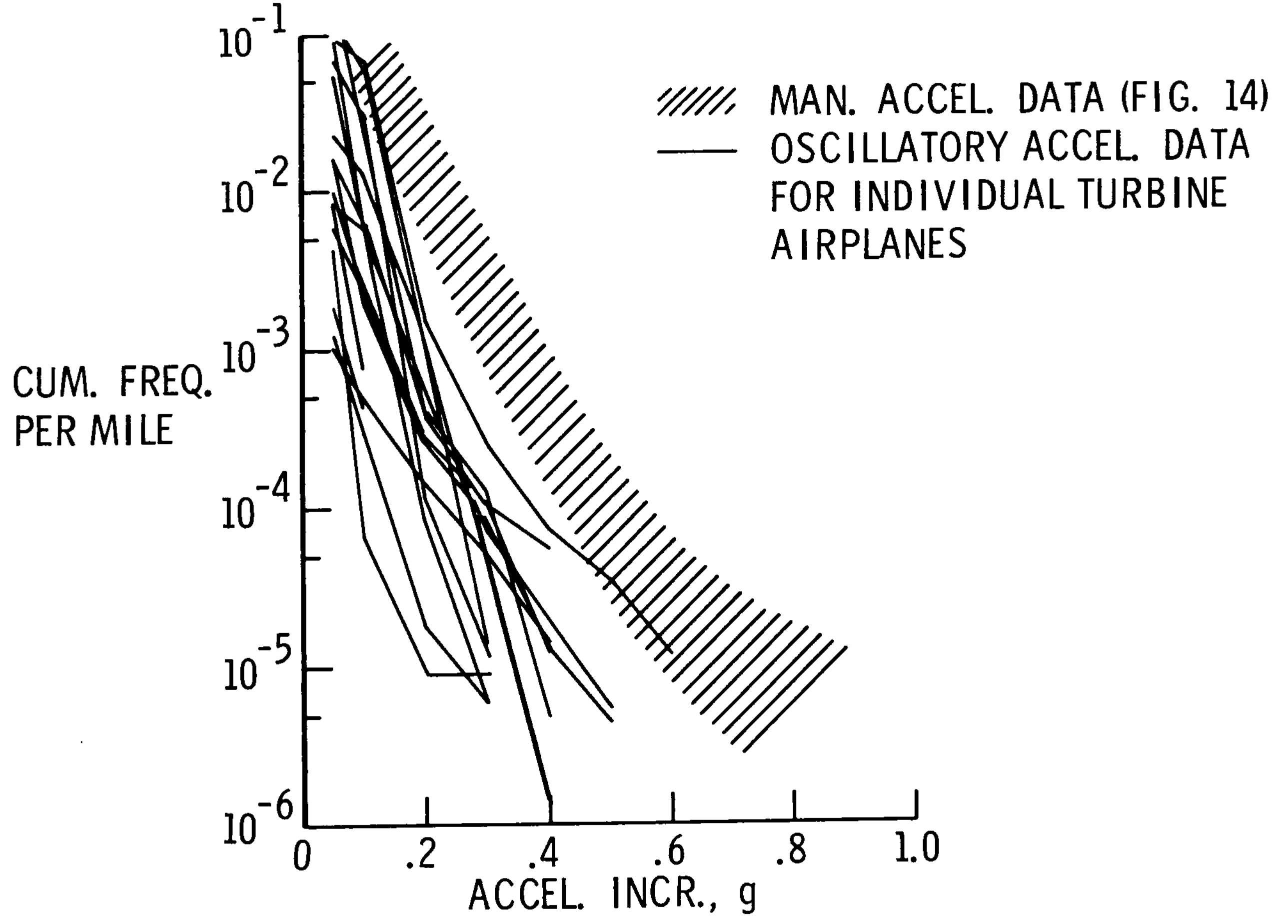


Figure 18.- Gust and maneuver accelerations for long-haul airplanes.



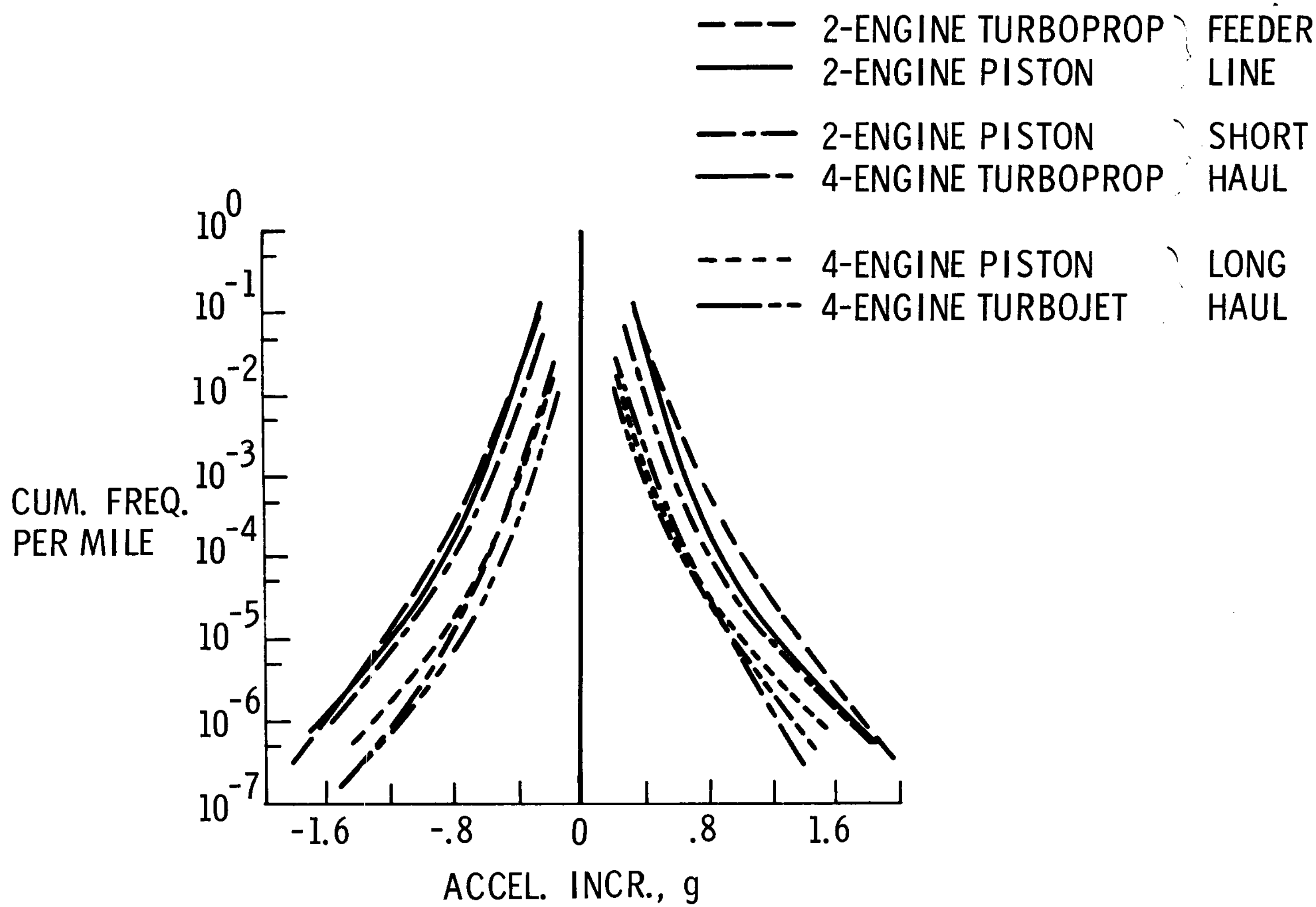
NASA

Figure 19.- Example of oscillatory accelerations.



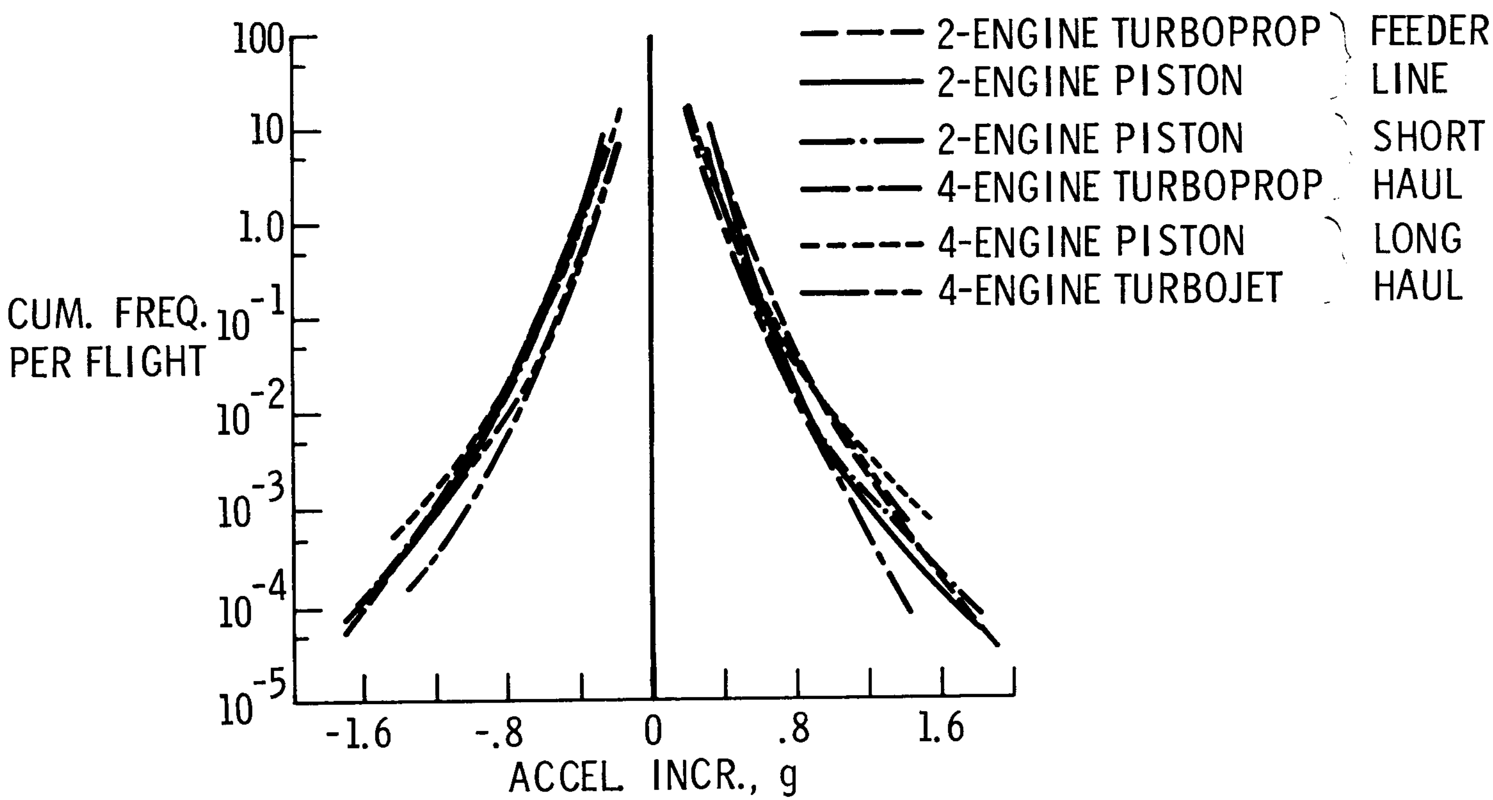
NASA

Figure 20.- Oscillatory accelerations for turbine airplanes.



NASA

Figure 21.- Total in-flight acceleration distributions.



NASA

Figure 22.- Total in-flight accelerations (per flight).

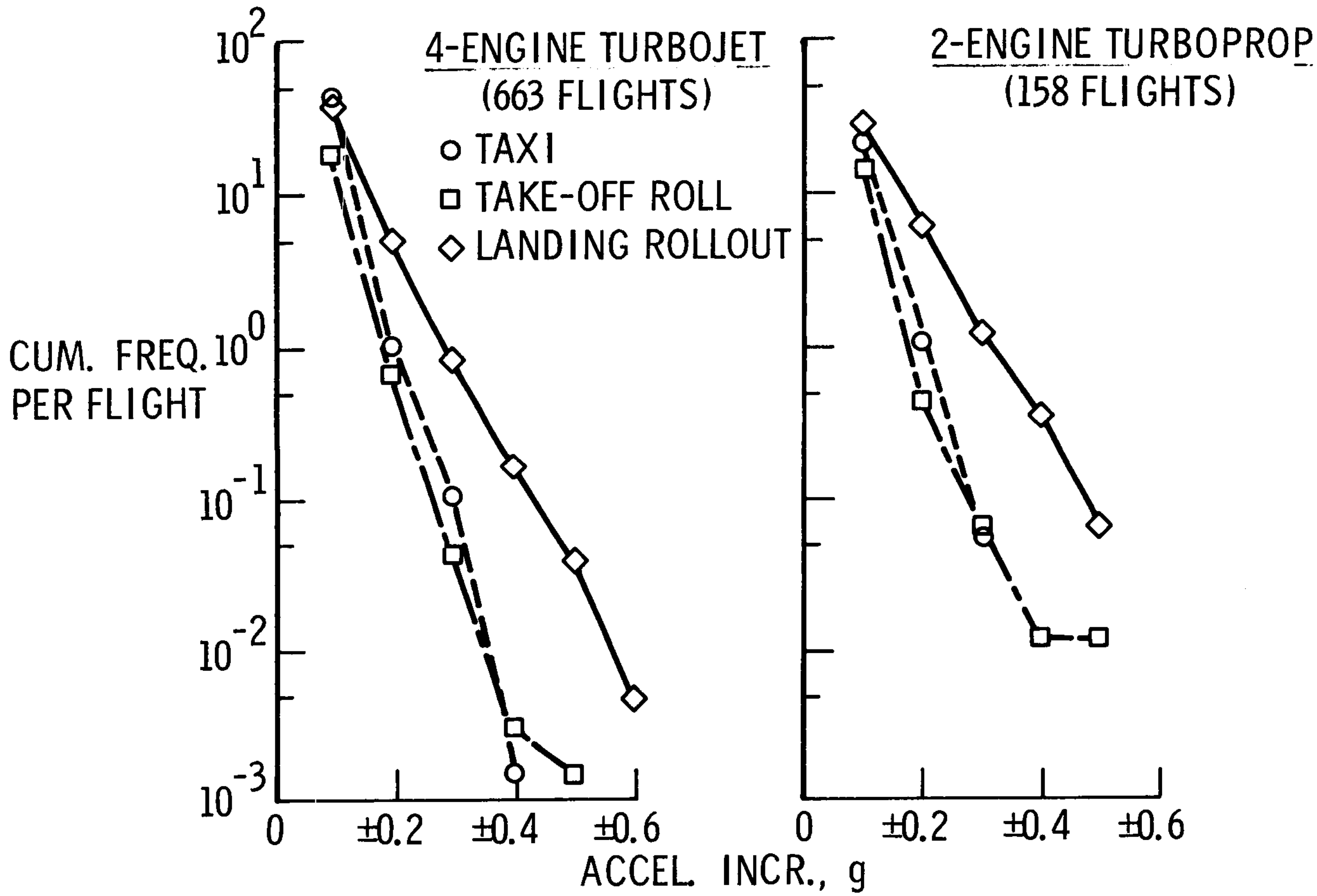
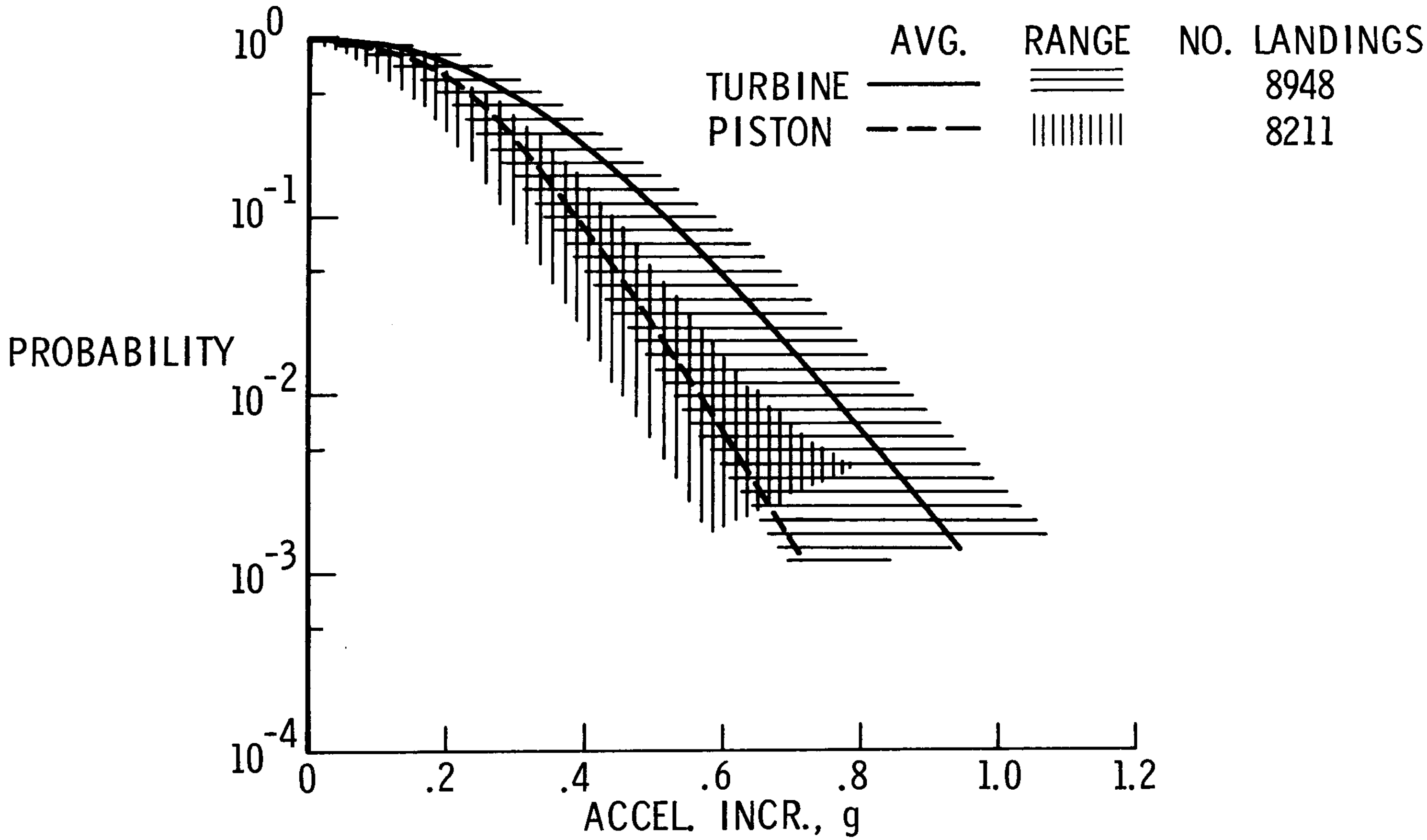


Figure 24.- Accelerations due to ground operations.

NASA-Langley, 1965



NASA

Figure 23.- Landing impact accelerations.