NASA TECHNICAL NOTE

NASA TN D-4586
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TRENDS IN REPEATED LOADS ON TRANSPORT AIRPLANES

by Thomas L. Coleman

Langley Research Center
Langley Station, Hampton, Va.

NATIONAL AERONAUTICS AND SPACE ADMINISTRATION • WASHINGTON, D. C. • MAY 1968

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SUMMARY

Statistical loads data collected on piston- and turbine-powered transport airplanes during routine feeder-line, short-haul, and long-haul airline service from 1947 to 1965 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. It is shown that the distributions of repeated loads for various types of transports exhibit much less variation when expressed in terms of number of occurrences per flight rather than in terms of occurrence per flight mile.

INTRODUCTION

For over 30 years the National Aeronautics and Space Administration and its predecessor, the National Advisory Committee for Aeronautics, have collected statistical data on the normal-acceleration experience and the airspeed and altitude practices of commercial transport airplanes. This research was conducted in cooperation with the airplane manufacturers and airlines who bore the cost of installing and transporting the instrumentation. For each successive generation of airplanes, analyses of the data have provided 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 with the concepts used in design and for detecting unanticipated operational aspects, and also has provided a reservoir of data useful in the design of new types of airplanes.

In this paper, the statistical loads data collected on piston- and turbine-powered transports from 1947 to 1965 are summarized. The data presented pertain to the repeated loads resulting from atmospheric turbulence, maneuvers, airplane oscillatory motions, landing contact, and ground operations. Much of the basic data used in the analysis have been reported in references 1 to 4. For the most part, the data are presented as normalized cumulative frequency distributions of normal accelerations measured near the center of gravity of the airplanes. The data are analyzed to show the trends in the repeated loads spectra with the evolution of the transports. The effect of the normalization procedure on the results — whether in terms of flight miles or flights — is examined.

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 5 and 6, respectively. Consequently, only a brief description of the recorders and the type of 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 usually installed within 5 feet (1.52 m) of 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 (9.07 to 11.34 kg).

Figure 1.- NACA VGH recorder.   L-66-4085.1

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. When installed it weighs less than 5 pounds (2.27 kg) and is usually mounted within 5 feet (1.52 m) of the center of gravity of the airplane.
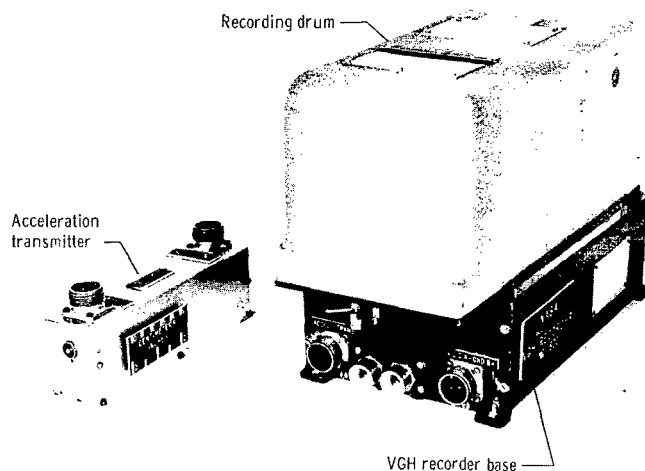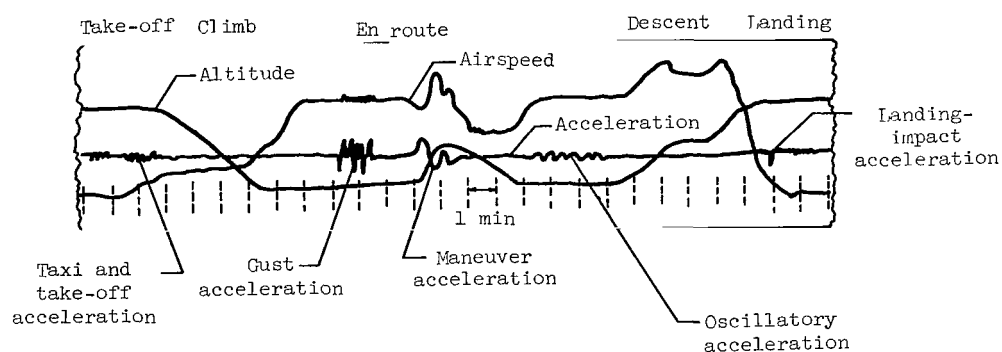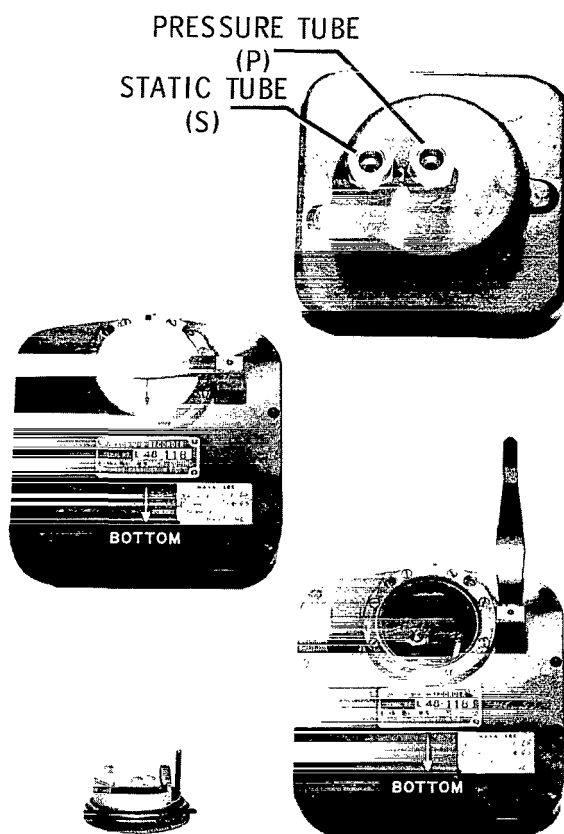
Figure 2.- Illustrative VGH record.

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Figure 3.- The NASA oil-damped VG recorder.

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 covered by the record (usually approximately 200 flight hours). In order to preclude the inclusion of accelerations caused by landing impact and ground operations in the in-flight data, the portion of the V-G record below the take-off and landing speeds is discarded.
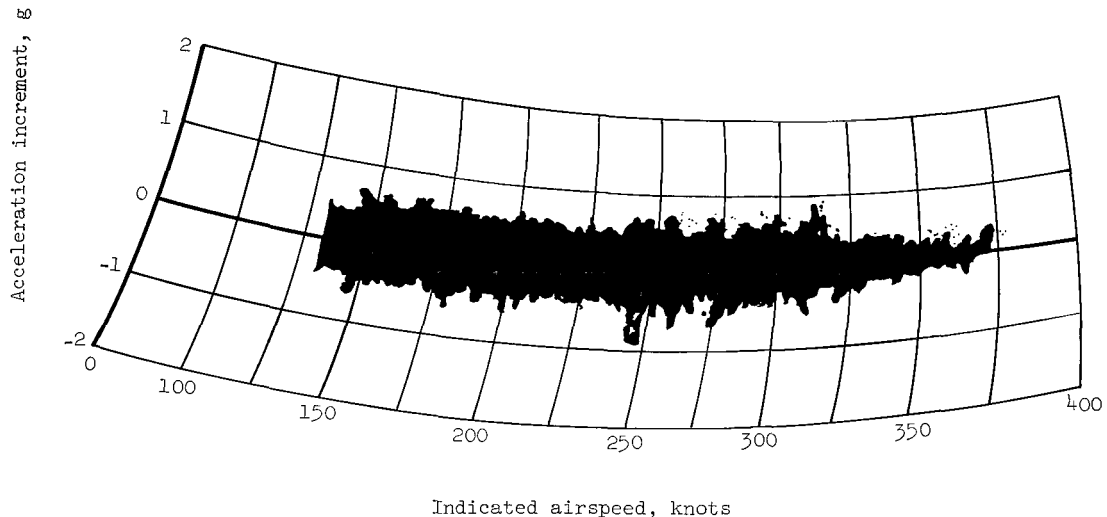
Figure 4.- Example of V-G record (200 flight hours).

Record Analysis

Detailed methods used for evaluating the VGH and V-G records are given in references 1 and 2. Consequently, only a brief explanation of the methods of evaluating the records is given in the following sections.

VGH records.- The sketch on the left-hand side of figure 5 illustrates the manner of evaluating the VGH records. The steady-flight position of the acceleration trace is

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

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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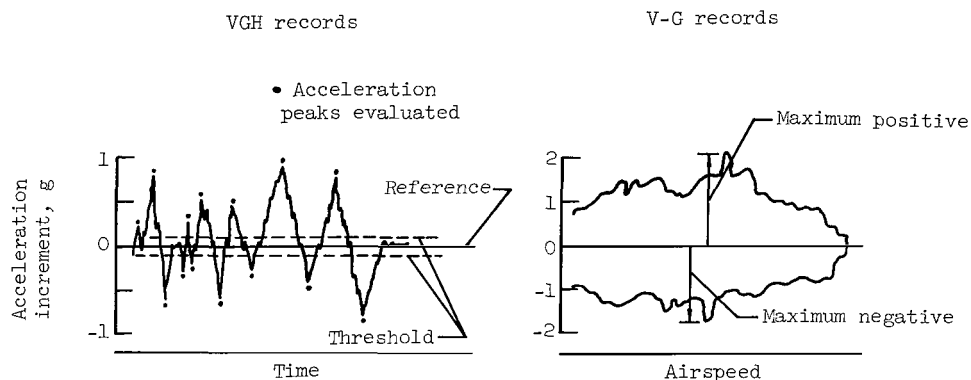 the acceleration is read for each crossing of the reference. (Other methods of evaluating accelerations from time-history records − such as counting each reversal of the trace as a peak − have been employed by some investigators. The method employed herein, however, has been used from the inception of the VGH program, is simple, and gives an adequate representation of the repeated loads for the purposes of this report.) 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 are read at 1-minute intervals 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 on the right-hand side of figure 5 illustrates the manner of evaluating the V-G records. Since the V-G record is an envelope of maximum acceleration values as a function of airspeed, it is not possible to determine the number of times the accelerations occurred within the envelope. Therefore, the procedure is to read only the maximum positive and the maximum negative acceleration increments from each record. These values are then treated as extreme values and are used to estimate the frequency of occurrence of high values of acceleration, as subsequently discussed. Generally, it is not possible to determine the source (that is, 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.

It should be noted that 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.- VGH data samples are generally too small (approximately 1000 flight hours) to provide reliable estimates of the frequency of the large accelerations which do not often occur. Being obtained from time-history records, however, the data do provide complete frequency counts of the small accelerations according to the source − gusts, maneuvers, landing impact, and ground operations. Conversely, the V-G data samples do not provide detailed information on the sources of the accelerations nor on the number of times the small accelerations occur. Since the V-G data samples are generally large (10 000 to 50 000 flight hours), they do provide

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 for gust and maneuver accelerations per mile of flight as determined fro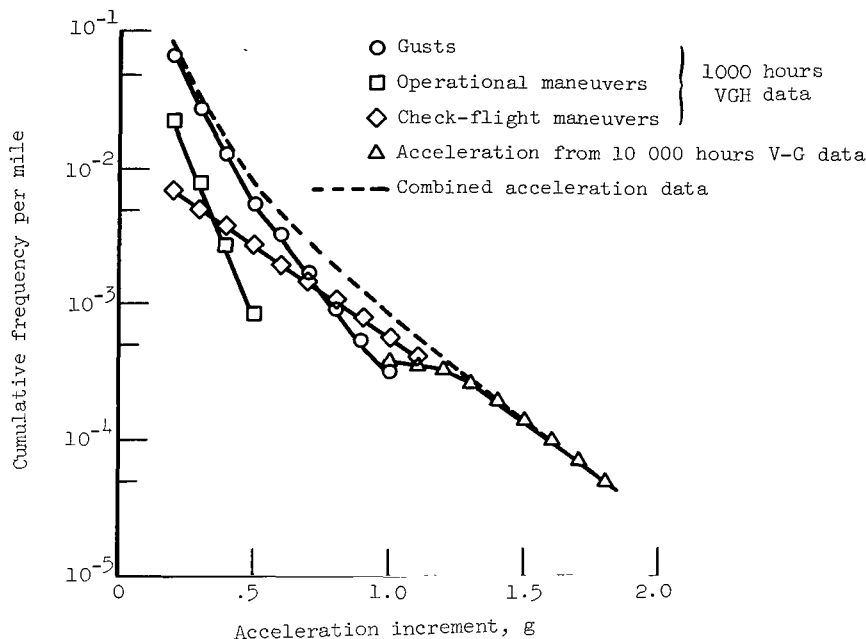m the VGH data sample, the maximum accelerations from the V-G data, and the total in-flight acceleration distribution, obtained by summing the ordinate values of the maneuver, gust, and V-G acceleration distributions.

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.

Figure 6.- VGH and V-G data.

Cumulative frequency distributions per mile of flight such as given in figure 6 are 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 around-the-world transoceanic service are included. Thus, in broad terms, all geographic areas in which U.S. commercial transports operate 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 flight lengths of the individual operations in each class of service were: feeder line, 80 to 90 nautical miles; short haul, 170 to 470 nautical miles; and 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.

TABLE I.- AIRPLANE CHARACTERISTICS

Airline service	Airplane type	Propulsion	Maximum gross weight		Wing area		Wing loading	
			lb	N	ft^2	m^2	lb/ft^2	N/m^2
Feeder	A	2-engine piston	25 200	112 095	987	9.17	25.4	1216.2
	L	2-engine turboprop	35 700	158 802	754	7.00	47.3	2264.7
Short haul	B	2-engine piston	39 900	177 484	864	8.03	46.1	2207.3
	C		40 500	180 153	817	7.59	49.5	2370.1
	D		47 000	209 066	920	8.55	51.0	2441.9
	M	4-engine turboprop	113 000	502 649	1300	12.08	86.9	4160.8
	N		63 000	280 238	963	8.95	65.4	3131.4
Long haul	E	4-engine piston	94 000	418 133	1650	15.33	57.0	2729.2
	F		107 000	475 960	1650	15.33	64.8	3102.6
	G		70 700	314 489	1461	13.57	48.4	2317.4
	H		89 900	399 895	1463	13.59	61.3	2935.1
	H-1		93 200	414 574	1463	13.59	61.3	2935.1
	J		122 000	542 683	1463	13.59	83.2	3983.6
	K		147 000	653 889	1720	15.98	85.4	4089.0
	O-1	4-engine turbojet	247 000	1 098 711	2433	22.60	101.5	4859.8
	[a]O-2		312 000	1 387 845	2892	26.87	107.9	5166.3
	[a]O-3		312 000	1 387 845	2892	26.87	107.9	5166.3
	P-1		273 000	1 214 364	2773	25.76	98.4	4711.4
	P-2		276 000	1 227 709	2773	25.76	99.5	4764.1
	P-3		310 000	1 378 949	2773	25.76	111.8	5353.0
	Q		184 000	818 473	2150	19.97	85.8	4108.1

[a]Types O-2 and O-3 differ only in the model of the engines.

As shown in table I, the maximum gross weights of the airplanes ranged from 25 200 pounds (11 431 kg) for one of the two-engine piston transports (type A) to 312 000 pounds (141 521 kg) 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 (1216.4 to 5353.0 N/m^2).

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. The figure shows that the average true airspeeds for the various classes of service ranged from about 145 knots to about 430 knots and the average cruise altitudes ranged from about 6000 ft (1.83 km) to 34 000 feet (10.36 km). 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 were accompanied by an increase in average cruise altitude. This increase in altitude had an effect on the repeated gust loads, a fact which is discussed in a later section.
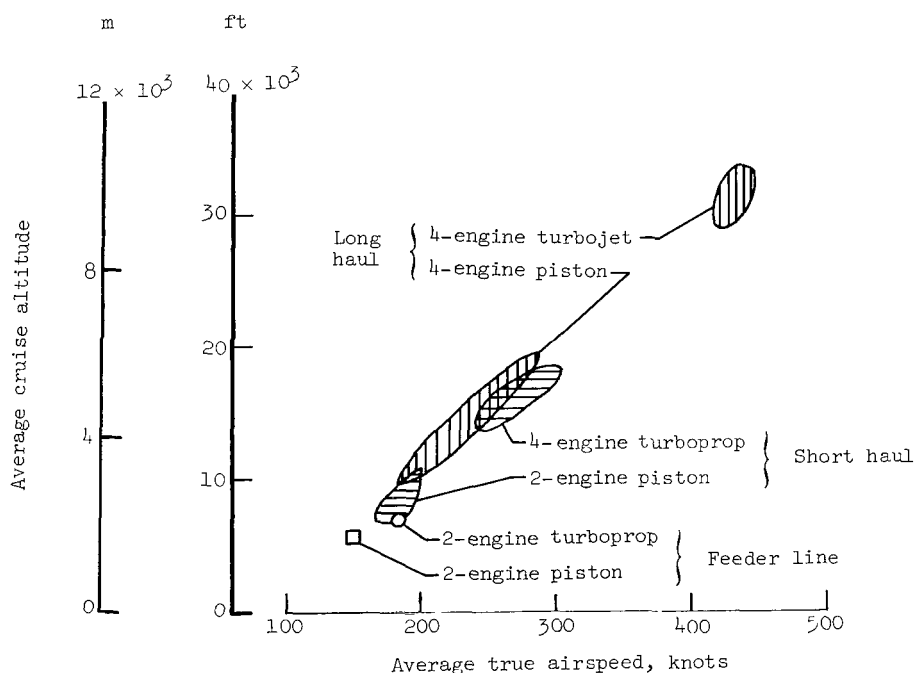

Figure 7.- Airspeeds and altitudes for transport airplanes.

Sample sizes.- The sizes of the data samples in terms of the number of airplanes instrumented, the 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

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

Airline service	Airplane type	Propulsion	VGH data Number of – Airplanes	VGH data Number of – Airlines	VGH data Flight hours	V-G data Number of – Airplanes	V-G data Number of – Airlines	V-G data Flight hours
Feeder	A	2-engine piston	1	1	1 278	27	7	91 089
	L	2-engine turboprop	2	1	2 100	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	2 418	3	1	13 327
	M	4-engine turboprop	3	3	7 038	8	2	38 138
	N		1	1	1 834	--	-	-----
Long haul	E	4-engine piston	-	-	----	10	1	48 187
	F		1	1	1 038	--	-	-----
	G		1	1	673	24	5	69 757
	H		2	2	2 555	6	2	23 148
	H-1		1	1	1 062	5	1	14 953
	J		4	2	4 666	--	-	-----
	K		3	3	3 908	4	1	15 387
	O-1		2	2	2 410	8	3	51 264
	O-2		2	2	2 822	3	2	19 330
	O-3		2	1	1 539	--	-	-----
	P-1	4-engine turbojet	-	-	----	2	1	13 571
	P-2		2	1	2 464	5	2	24 478
	P-3		1	1	1 651	4	1	13 750
	Q		1	1	1 222	4	1	10 103
Total					42 188			506 643

airplanes range from 673 flight hours for one of the four-engine piston transports (type G) 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. The V-G and VGH data samples were collected on commercial transports between 1947 and 1965.

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 consists of a given airplane type in service on a given airline. Thus, the data for a given operation reflect the combined effects of the operating procedures of the particular airlines, the airplane characteristics, and any influences of the airline routes on the repeated loads.) To obtain data samples of these sizes, one or two airplanes on a given airline were instrumented with VGH recorders, and several airplanes were instrumented with V-G recorders. (See table II.) In order to minimize bias due to possible seasonal effects, the sampling period for each operation usually covered a period of 1 to 3 years.

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To obtain information on the combined effects of route and airline practices 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, there were up to seven airlines from which V-G data were obtained for a given airplane type. 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.

The data for all the piston-engine airplanes listed in table II were collected between 1947 and 1958 and have been reported in reference 1, whereas data for two of the turboprop airplanes (types L and N) were collected between 1957 and 1961 and are reported in references 3 and 4. The data from the remaining turbine-powered airplanes were collected between 1958 and 1965. Results from limited samples of these data are given in reference 2.

RESULTS AND DISCUSSION

Gust Accelerations

Information obtained from the VGH data on the gust accelerations experienced by each type of aircraft is given in figure 8. The "hatched" regions denote the range of the cumulative frequency distributions of gust accelerations per mile of flight for all operations within each grouping of airplane types. Because only one sample of data was
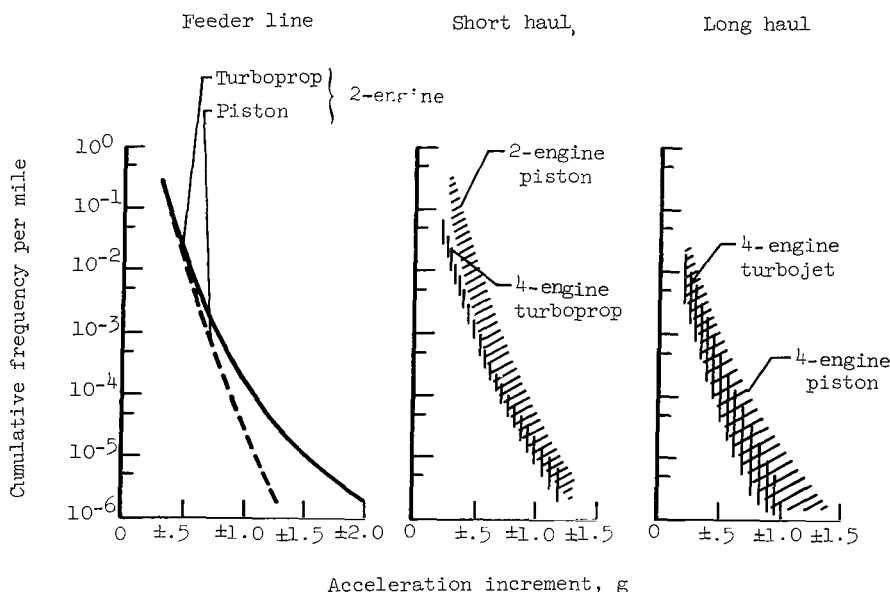
Figure 8.- Cumulative frequency distributions of gust accelerations for various types of transport airplanes.

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 about 1g, they have been combined for presentation in figure 8.

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

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 combining, with equal weight, the distribution 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
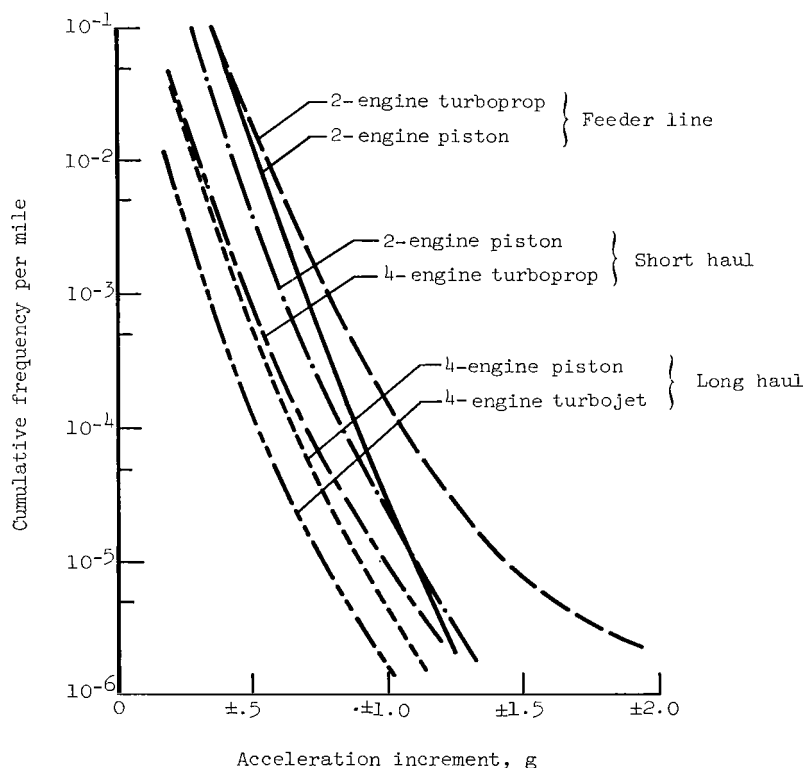

Figure 9.- Average cumulative frequency distributions of gust accelerations for various types of transport airplanes.

the two-engine turboprop and piston airplanes used in feeder-line 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 are discussed in the following two sections.

Effect of gust environment.- The number of gusts actually encountered by an airplane is influenced by several factors, such as route, flight profile (length of flight and
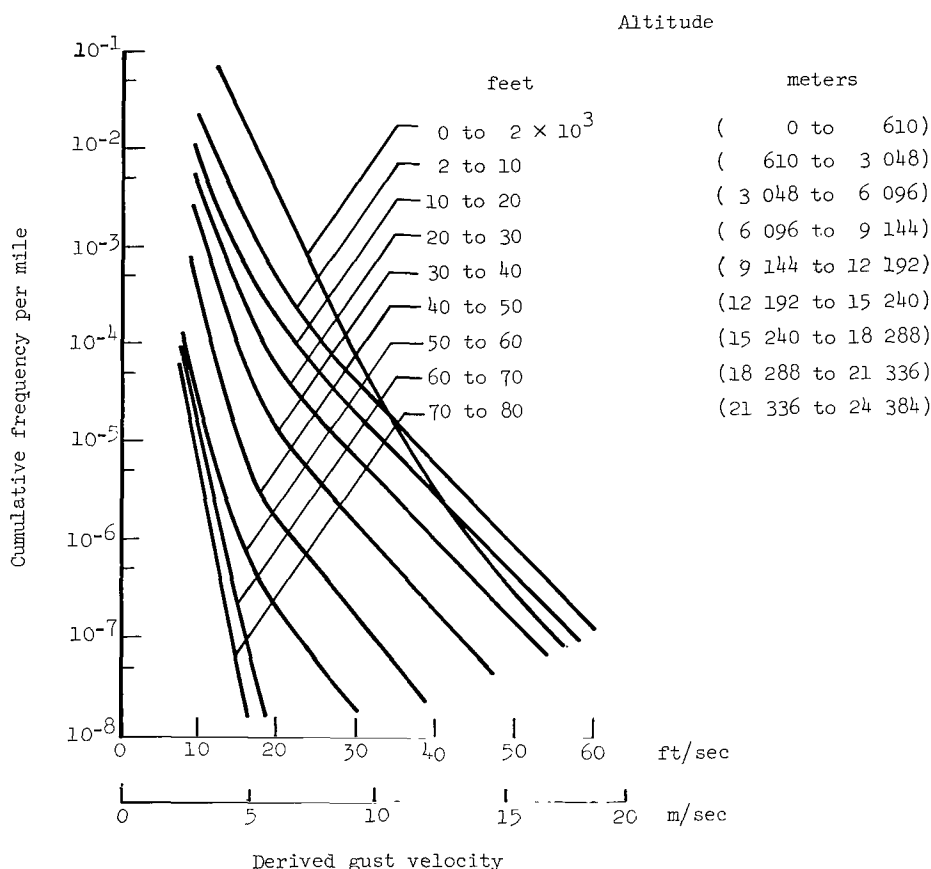
Figure 10.- Estimated gust environment for transport airplanes (from ref. 7).

cruise altitude), and airline practices relative to turbulence avoidance. A typical model of a gust environment for transport airplanes has been reported in reference 7 and is reproduced in figure 10. The curves 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 ft/sec (0.610 m/s). The approximate cruise altitude for each airplane type is also shown in the figure.
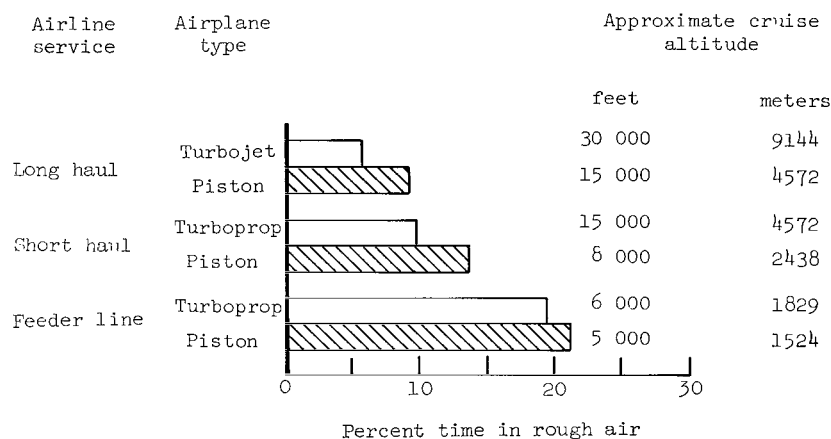

Figure 11.- Percent of total flight time in rough air.

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 to about 7 percent for the long-haul airplanes. The short-haul turboprop and the long-haul turbojet airplanes experienced less rough air than did the piston airplanes used in the corresponding service because of the higher cruise altitudes of the turbine airplanes.

The differences in the amount of rough air encountered by the various airplane types shown in figure 11 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 an influencing factor on 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 response characteristics of the airplane. Many methods of describing the responses of an airplane to turbulence are available and range in complexity from the discrete gust method (ref. 8) to the continuous turbulence method given in reference 9. For present purposes, the simple discrete method which uses the following gust equation taken from reference 8 is adequate:

$$\frac{a_n}{U_{de}} = \frac{\rho_0 K_g V_e m}{2W/S}$$

where

a_n normal acceleration increment, g

U_{de} derived gust velocity, ft/sec (m/s)

ρ_0 air density at sea level, slugs/cu ft (kg/m^3)

K_g gust factor

V_e equivalent airspeed, ft/sec (m/s)

m slope of lift curve per radian

S wing area, sq ft (m^2)

W airplane weight, lb (N)

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. The results shown in the figure are average values, based on considerations of the operational airspeeds and weights. They are not directly comparable to the values used in the airplane design. The gust sensitivity factors ranged from approximately 0.032 g/ft/sec (0.0098 g/m/s) for the feeder-line airplanes to an average of about 0.02 g/ft/sec (0.0061 g/m/s) for the long-haul airplanes.
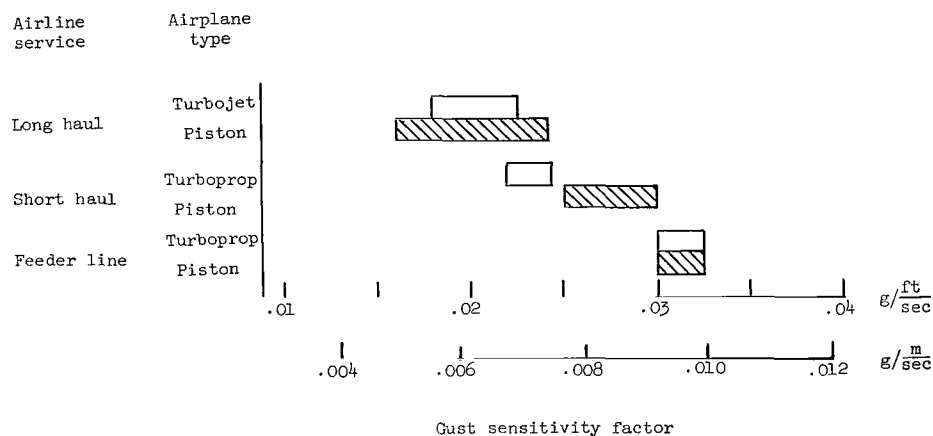
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Figure 12.- Airplane acceleration response sensitivity to turbulence.

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 on the left-hand side of figure 13 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 on the right-hand side of figure 13 shows the gust acceleration distributions for two airplanes: a typical feeder-line type with a gust sensitivity factor of 0.03 g/ft/sec (0.0091 g/m/s) and a typical long-haul type with a gust sensitivity factor
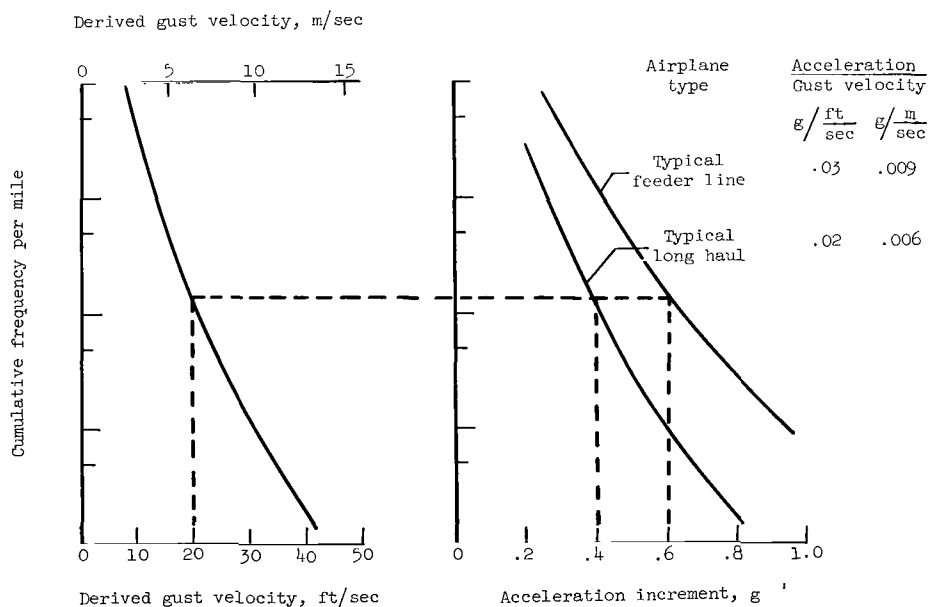

Figure 13.- Effect of airplane response characteristics on gust accelerations.

of 0.02 g/ft/sec (0.0061 g/m/s). Both airplanes are assumed to encounter the gust environment shown on the left-hand side of the figure.

The illustration in figure 13 shows the strong effect which the gust sensitivity factor has on the magnitude of gust accelerations experienced. For example, a gust velocity of 20 ft/sec (6.1 m/s) 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 for given values of acceleration, 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 typical feeder-line airplane than for the typical long-haul airplane.

The strong effect of the gust sensitivity factor on the magnitude of the gust accelerations (fig. 13) is the main reason for the large variations among the gust acceleration experiences for the different airplane types previously shown in references 8 and 9. 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

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 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 those for the other airplanes. Presumably, the short flights (approximately 80 nautical miles) combined with the good performance of the two-engine turboprop airplane resulted in the comparatively high
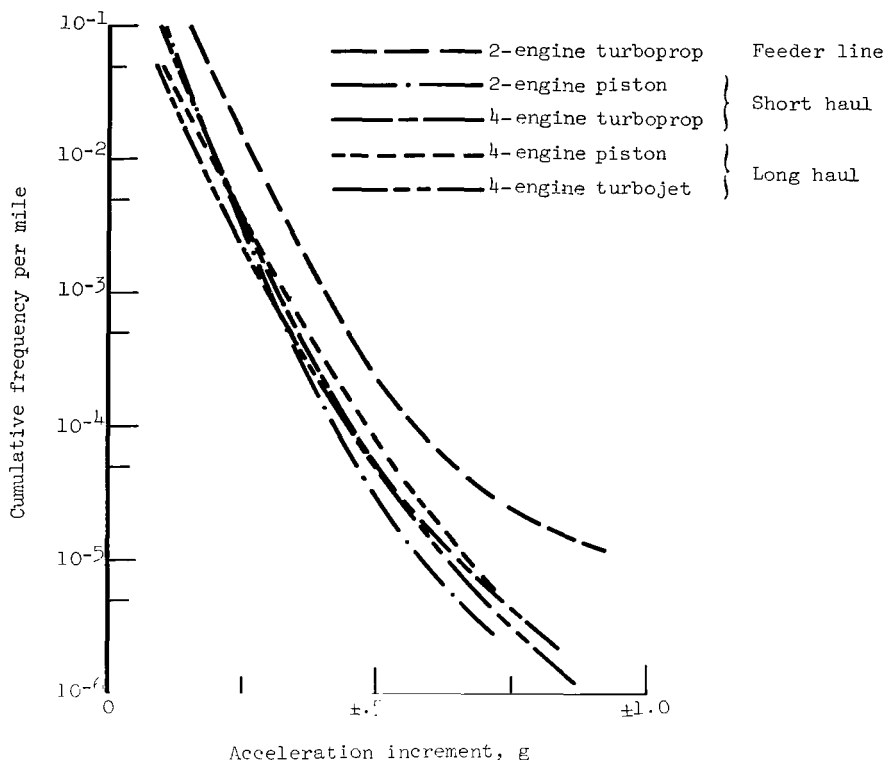
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Figure 14.- Average cumulative frequency distributions of operational maneuver accelerations for various types of transport airplanes.

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 for each of the airplane types are given in figure 15. 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 based on the total flight miles rather than on the flight miles in check flights. This basis 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 all the 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
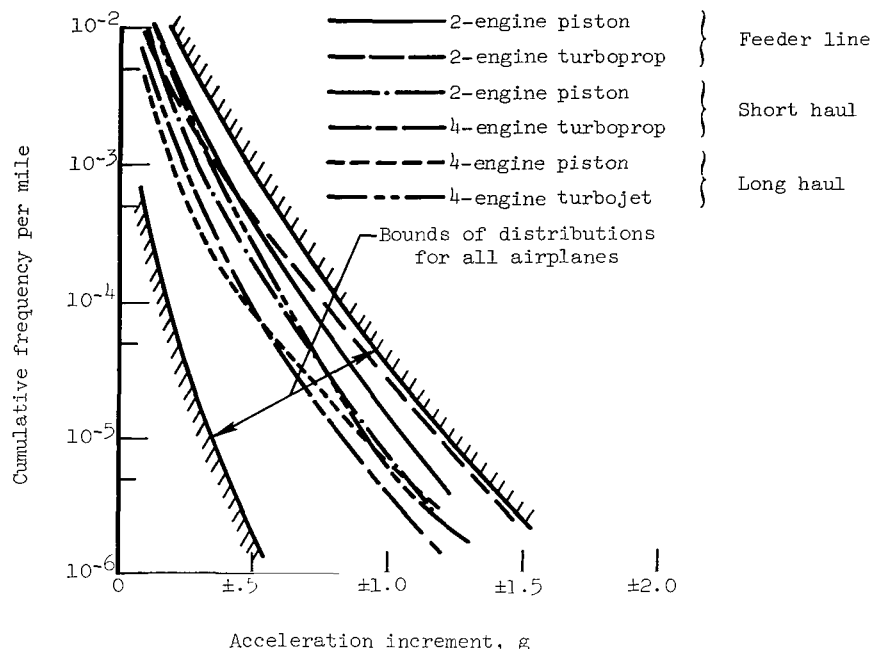
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Figure 15.- Average cumulative frequency distribution of check-flight maneuver accelerations for various types of transport airplanes.

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. There are probably two main reasons for the large differences among the check-flight maneuver experiences. First, there are apparently significant differences between airlines in regard to the amount of check-flight flying required and to the number and types of maneuvers performed. Second, 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. Whether these values are applicable on a fleetwide basis or are peculiar to the particular airplane samples is not known. The foregoing discussion indicates 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.

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. (Operational maneuvers were not obtained for the two-engine piston airplane.) 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 at
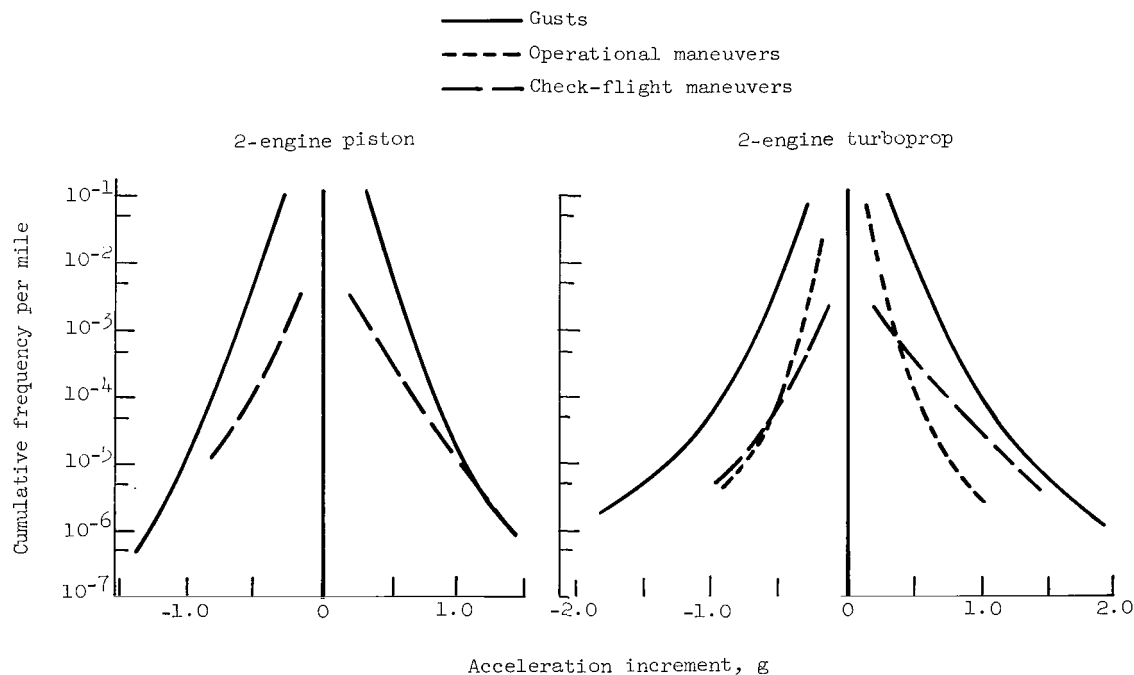

Figure 16.- Average cumulative frequency distribution of gust and maneuver accelerations for feeder-line airplanes.
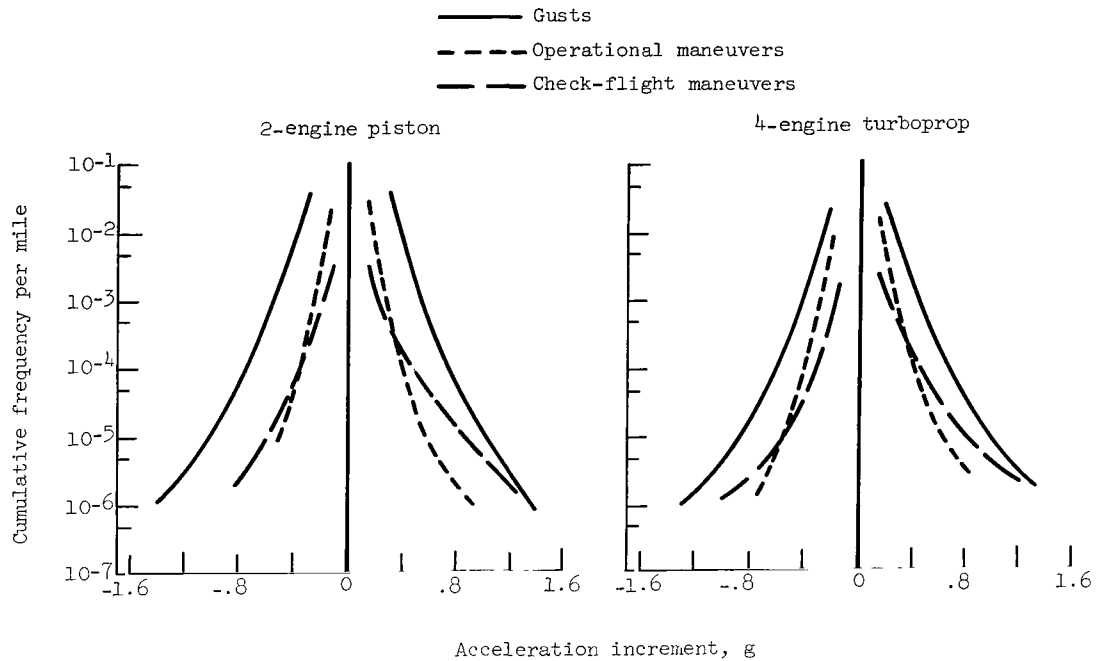
2-engine piston

4-engine turboprop

Cumulative frequency per mile

Acceleration increment, g

Figure 17.- Average cumulative frequency distribution of gust and maneuver accelerations for short-haul airplanes.

——————— Gusts

━ ━ ━ ━Operational maneuvers

━ ━ Check-flight maneuvers

4-engine piston

4-engine turbojet

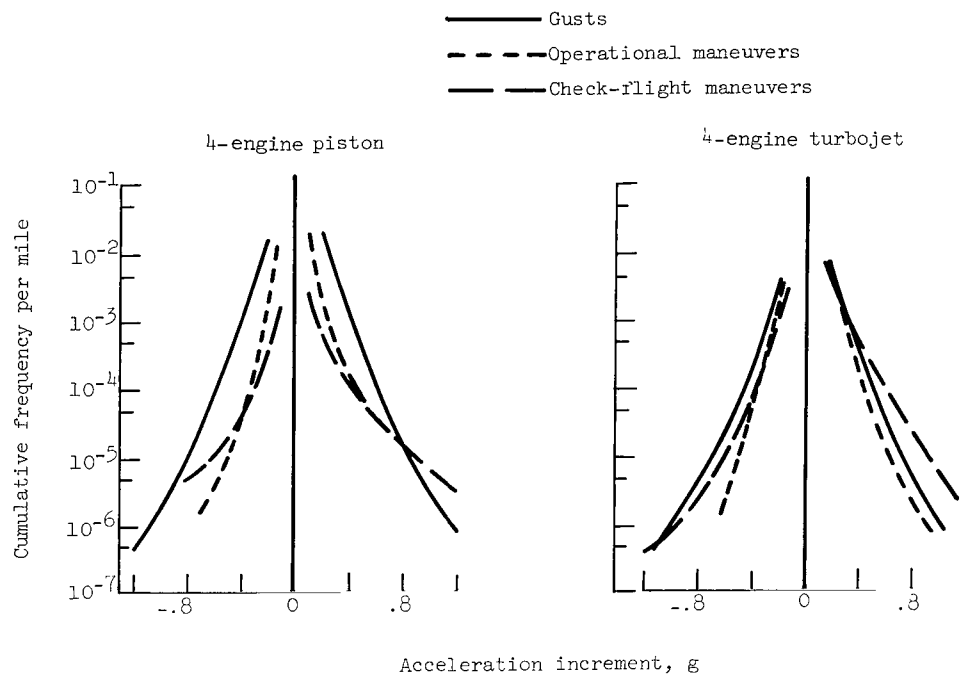Cumulative frequency per mile

Acceleration increment, g

Figure 18.- Average cumulative frequency distribution of gust and maneuver accelerations for long-haul airplanes.

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. This result is due primarily to the low gust acceleration experience of the turbojet airplanes.

Oscillatory Accelerations

From the VGH time-history records, it has been observed that on occasion certain airplanes 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.

An 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. In this example, the amplitude of the incremental accelerations is approximately ±0.2g and the period is about 10 seconds. Large variations in the wave forms 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.
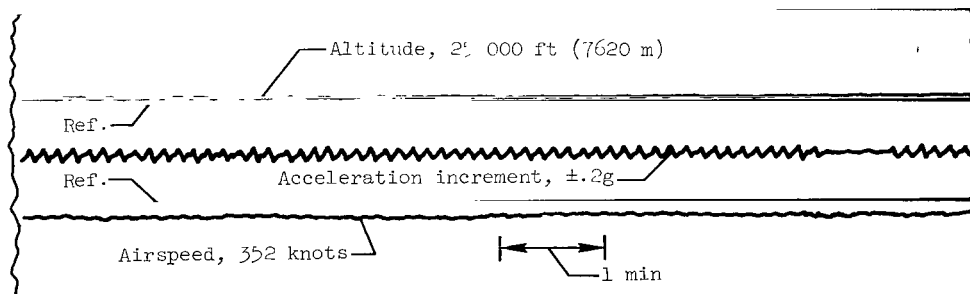

Figure 19.- Example of oscillatory accelerations.

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 from 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 character-istics and causes of the oscillatory accelerations is given in reference 2.

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
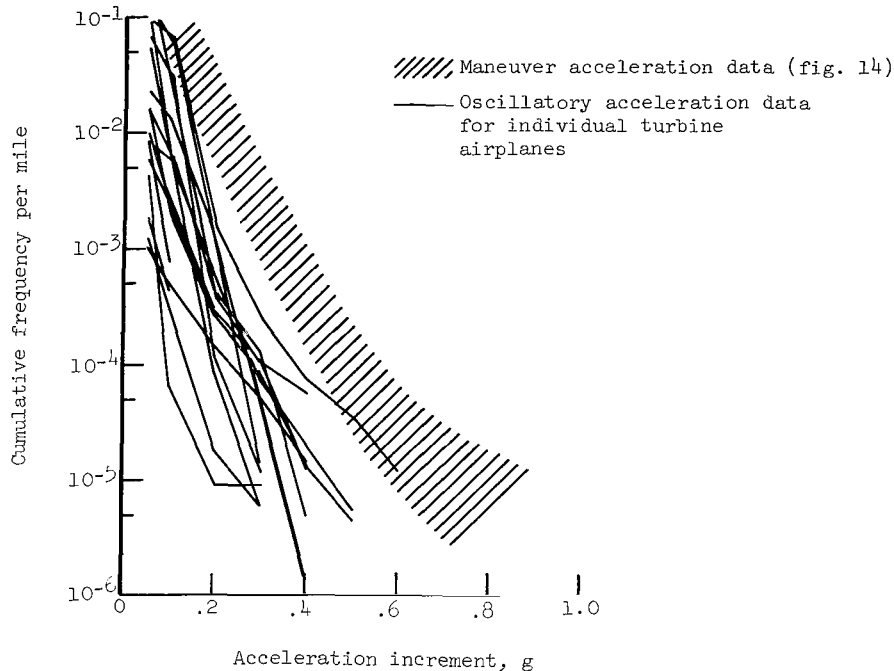

Figure 20.- Oscillatory accelerations for turbine airplanes.

range of the operational maneuver acceleration distributions from figure 14 is also shown in the figure. The results indicate 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 primary 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 discussed earlier, the VGH data samples usually are not large enough to define the frequency of occurrence of the large values of accel-eration. 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 source (that is, gusts or maneuvers) of the accelerations. In general, however, gust acceleration is 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
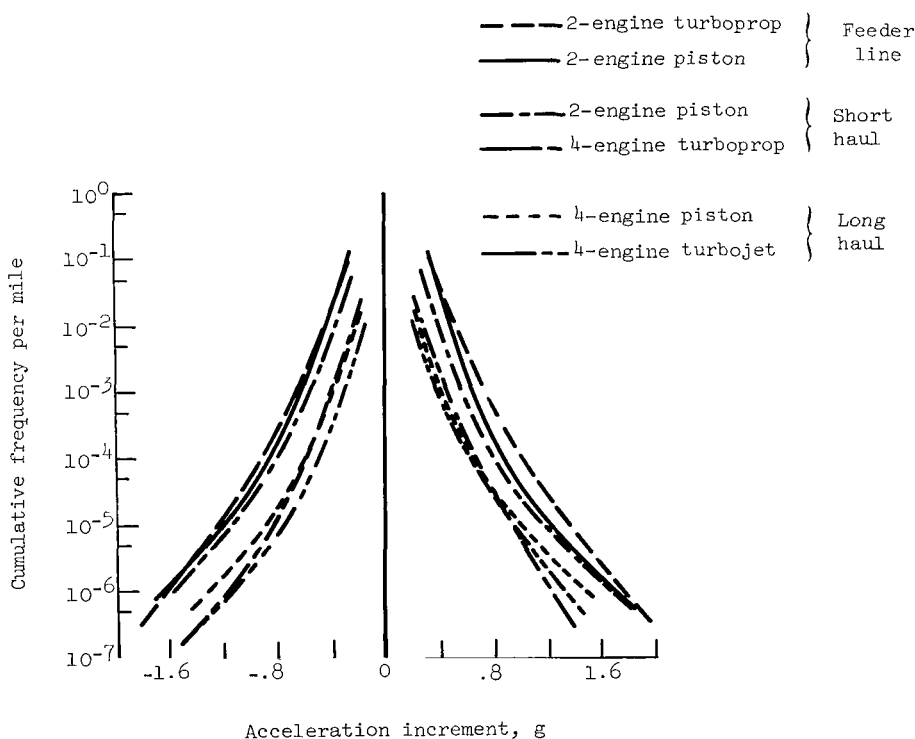

Figure 21.- Total in-flight acceleration distributions.

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 (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.
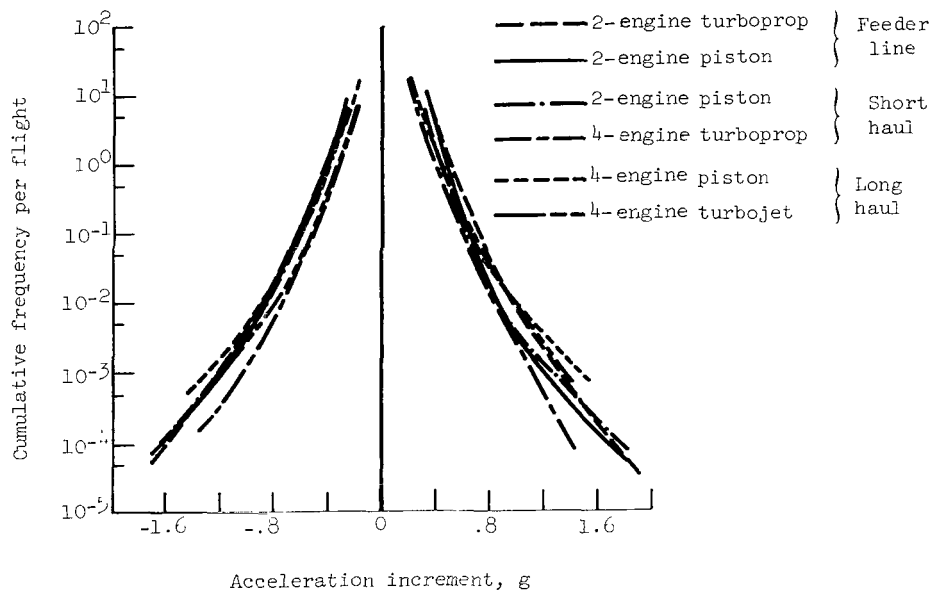

Figure 22.- Total in-flight accelerations (per flight).

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 result 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 among 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 were 6.0 to 1 on a flight-mile basis and 2.6 to 1 on a flight basis. For all 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 regarding frequency of acceleration because most of the repeated loads

TABLE III.- VARIATIONS AMONG ACCELERATION FREQUENCIES FOR

INDIVIDUAL OPERATIONS OF GIVEN AIRPLANE TYPES

Airplane type	Number of operations	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

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 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 with 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 flights rather than in terms of flight miles. This condition appears to be especially the case when the airplane type is used in the 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 it is recognized 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 assess further the per-flight and per-flight-mile bases for evaluating fatigue loadings, the frequency-per-flight basis at this time appears to offer the following advantages:

(1) Reduces the indicated load variations among different airline operations of a given airplane type

(2) Provides a better index 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, 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 are generally 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 with a value of 0.55g for the piston airplanes.

The reasons for the significantly higher landing-impact accelerations for the turbine airplanes as compared with the piston airplanes are not fully known; however, in
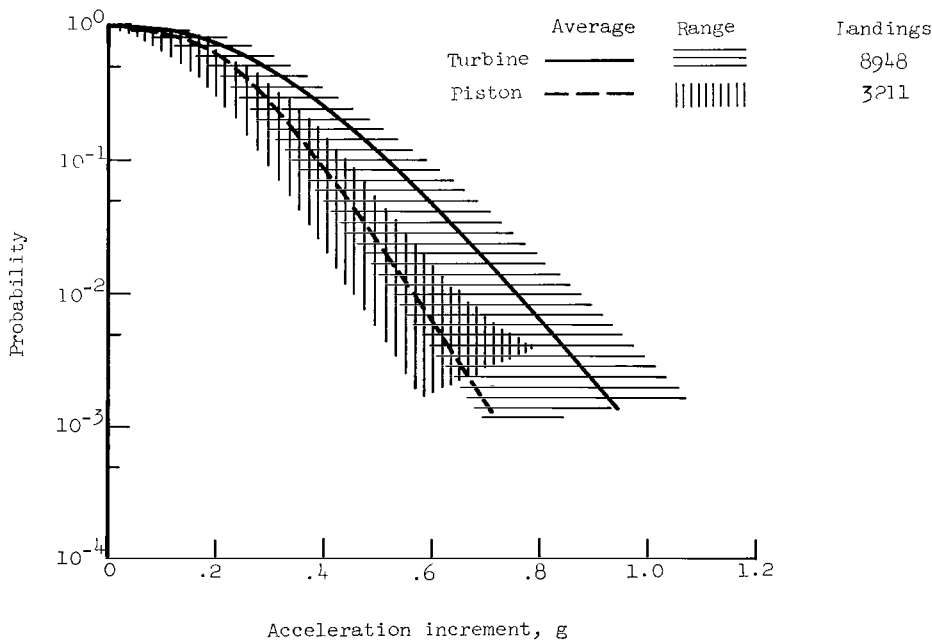

Figure 23.- Landing impact accelerations.

part at least, it is 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. 2.) 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, the airplane operator may be a major factor influencing the landing-impact acceleration experience.

Acceleration 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. Instead, two recently obtained data samples are presented to indicate some of the general characteristics of the ground-induced accelerations.

Figure 24 shows the cumulative frequency distributions of accelerations per flight due to ground operations experienced by a two-engine turboprop airplane and a four-engine turbojet airplane. Three distributions are shown for each airplane and represent
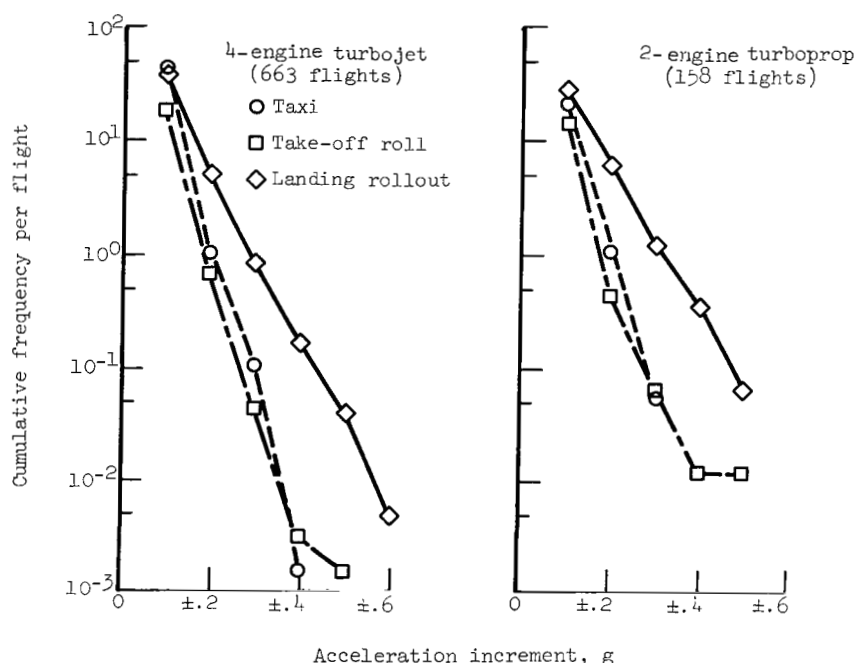

Figure 24.- Accelerations due to ground operations.

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. Furthermore, the results for the two types of airplanes are similar regarding the magnitude and frequency of occurrence of the accelerations during the three phases of the ground operations.

CONCLUDING REMARKS

A review of repeated loads data collected by the National Aeronautics and Space Administration on piston- and turbine-powered commercial transport airplanes from 1947 to 1965 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 effects of higher wing loading and 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 and 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 those 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, substantial refinement is not expected to 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 per-flight rather than on a per-mile basis. This consistency exists because most of the repeated loads occur in the climb and descent phases of flight rather than during cruise. The greater consistency of the acceleration histories on the flight basis suggests that per-flight may be a better basis for fatigue assessment than the conventional per-mile basis.

Langley Research Center,
  National Aeronautics and Space Administration,
    Langley Station, Hampton, Va., December 4, 1967,
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