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AN ANALYSIS OF VGH DATA COLLECTED FROM ONE TYPE OF FOUR-ENGINE TURBOJET TRANSPORT AIRPLANE

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16. Abstract

Data are presented on incremental normal accelerations due to gusts, maneuvers, oscillations, landing impacts, and ground operations; on derived gust velocities; and on airspeed operating practices. These data were obtained from NASA VGH recorders installed on two identical four-engine turbojet transport airplanes flown by a single airline. The airline route structure consisted primarily of routes covering the eastern half of the United States, although a few flights were also made to the west coast and to northern South America.

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SUMMARY

An analysis of VGH records collected on two identical four-engine turbojet transport airplanes during routine commercial operations of a single airline has provided information on incremental normal accelerations and turbulence experienced and on airspeed operating practices. The data cover operations on routes which extended over the eastern half of the United States, with a few additional flights being made to the west coast and to northern South America.

No significant differences were seen in the results for the two individual airplanes operated by the same airline. Comparison of the present results with those for another type of four-engine turbojet transport also showed a high degree of similarity. At lower levels of acceleration, turbulence produced the most frequent loads whereas at the higher acceleration levels, check-flight maneuver accelerations were the most frequent source of loads. The airplanes were operated at speeds close to the placard limit, particularly at the higher altitudes where the airplane was Mach limited. The observance of speed reduction for turbulence was apparent from the data when higher levels of turbulence were considered. The frequency of given levels of normal acceleration for landing impact and ground operations of the present results were of the same order of magnitude as for other types of four-engine turbojet transports.

INTRODUCTION

In a continuation of a project begun by the National Advisory Committee for Aeronautics in 1946, the National Aeronautics and Space Administration collects data on incremental normal acceleration, airspeed, and altitude during routine airline operations for most new airplane types. These measurements are being utilized to provide statistical data on a number of operational aspects of the turbine-powered aircraft, such as accelerations due to gusts, maneuvers, and oscillations; operating practices; and landing-impact and other ground-induced accelerations. In the past, information obtained from the data-collection program has proved useful for comparison of the operational experiences of airplanes with the concepts to which they were designed, for detection of new or unanticipated aspects of the operations, and as background information for application in the design of new airplanes. Typical results obtained for several types of airplanes are given in references 1 to 7.

This paper presents an analysis of the acceleration and gust velocity experience and the operating airspeeds and altitudes of one type of four-engine turbojet transport during commerical operation. Some of the preliminary data from this operation have been reported in references 3 and 5 but are included herein to provide a complete description of the operation. The present results are compared with those from another type of four-engine turbojet transport flown over the same general geographic area.

SYMBOLS

The measurements of this investigation are given in both U.S. Customary Units and the International System of Units (SI). Factors relating the two systems are given in reference 8.

a_n	incremental normal acceleration, g units
c	wing chord, feet (meters)
g	acceleration due to gravity, 32.2 feet/second^2 (9.81 meters/second^2)
K_g	gust factor, $\frac{0.88\mu_g}{5.3 + \mu_g}$
m	lift-curve slope, per radian
M_{NE}	never-exceed Mach number
M_{NO}	normal-operating-limit Mach number
S	wing area, feet^2 (meters^2)
U_{de}	derived gust velocity, feet/second (meters/second)
V_A	maneuvering speed, knots indicated
V_B	gust penetration speed, knots indicated
V_e	equivalent airspeed, feet/second (meters/second)

V_{NE} never-exceed speed, knots indicated

V_{NO} normal-operating-limit airspeed, knots indicated

W airplane weight, pounds force (newtons)

μ_g airplane mass ratio, $\frac{2W}{m\rho cgS}$

ρ atmospheric density, slugs/foot^3 $\left(\text{kilograms/meter}^3\right)$

ρ_o atmospheric density at sea level, slugs/foot^3 $\left(\text{kilograms/meter}^3\right)$

DATA

Instrumentation and Scope

The data were collected with NASA VGH recorders, which provide continuous time-history records of indicated airspeed, normal acceleration, and pressure altitude. A detailed description of the VGH recorder is given in reference 9. The normal accelerations were sensed by an accelerometer mounted in the lower fuselage at a location corresponding to 24 percent of the mean aerodynamic chord. The recorder was connected to the autopilot static-pressure source and to the copilot's pitot tube.

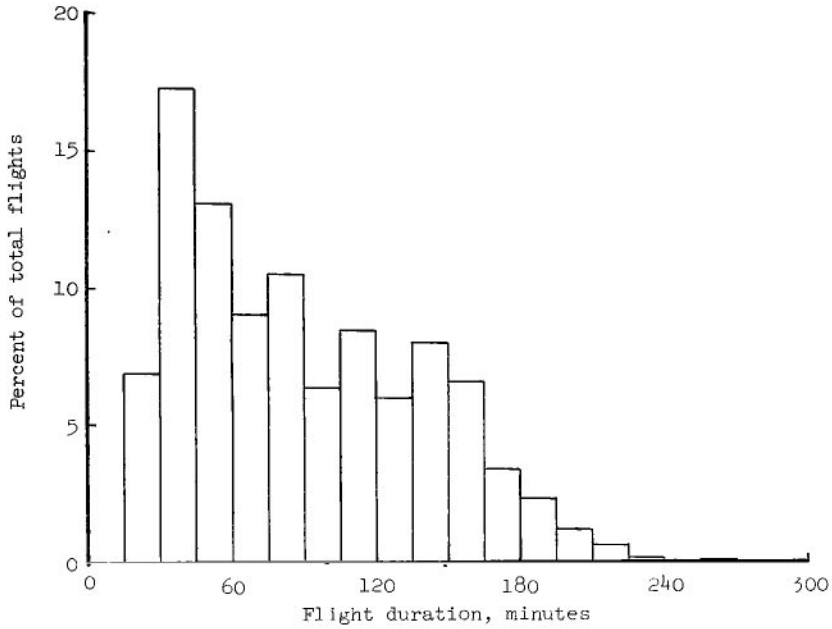
The two airplanes were operated on routes covering the eastern half of the United States, with a few additional flights being made to the west coast of the United States and to northern South America.

The scope of the data samples for the two airplanes is summarized in table I. As shown in the table, the sizes of the data samples were reasonably similar (2082 hours and 1904 hours) although airplane 1 spent a larger percent of time in check flights (6.38 percent) than did airplane 2 (4.56 percent). The data-collection period covered almost 2 years, and except for one period of about $1\frac{1}{2}$ months for airplane 2, the recording periods noted in table I were covered almost continuously. Histograms of flight duration and of pressure altitude are shown in figure 1 to define the operation further. Characteristics of the airplane pertinent to the evaluation of the data are as follows:

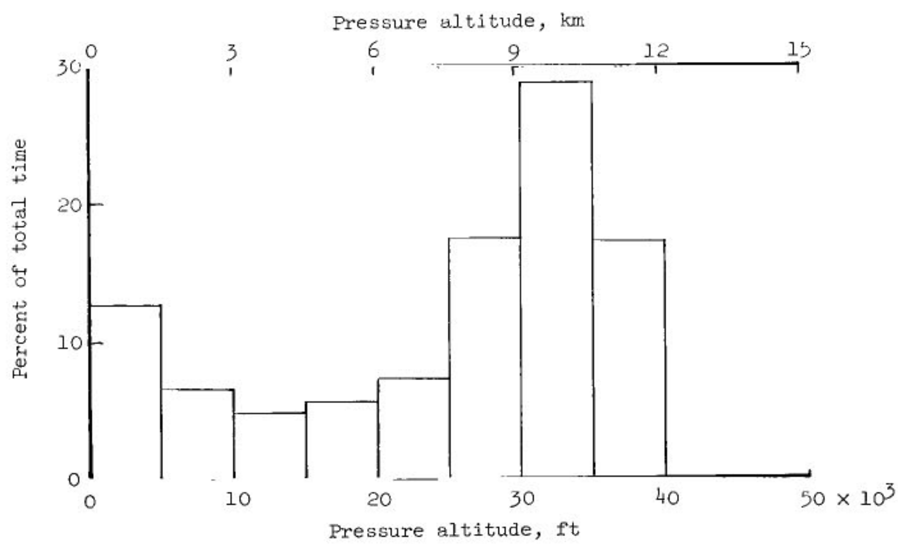
Span, ft (m)	120 (36.58)
Aspect ratio	7.0
Mean aerodynamic chord, ft (m)	18.94 (5.77)
Wing area, ft^2 (m^2)	2000 (185.8)
Maximum take-off weight, lb (N)	184 500 (820 697)
Maximum landing weight, lb (N)	132 800 (590 724)
Wing loading based on maximum take-off weight, lb/ft^2 (N/m^2)	92.25 (4417)
Wing sweep at 25 percent chord, deg	35

TABLE I.- SCOPE OF DATA

	Airplane 1	Airplane 2	Combined sample
Total hours	2081.9	1903.8	3985.7
Total nautical miles	9.11×10^5	8.30×10^5	1.74×10^6
Operational flights:			
Hours	1949.0	1817.0	3766.0
Number	1288	1211	2499
Average duration, min	90.8	90.0	90.4
Average altitude, ft (km)	24 493 (7.47)	24 362 (7.43)	24 430 (7.45)
Average indicated airspeed, knots	302.9	302.7	302.8
Nautical miles	8.53×10^5	7.92×10^5	1.65×10^6
Climb condition:			
Hours	350.7	319.7	670.4
Average indicated airspeed, knots	317.4	318.8	318.0
Nautical miles	1.41×10^5	1.29×10^5	2.71×10^5
Cruise condition:			
Hours	1114.9	1044.6	2159.5
Average altitude, ft (km)	31 889 (9.72)	31 856 (9.71)	31 873 (9.71)
Average indicated airspeed, knots	306.8	306.0	306.4
Nautical miles	5.47×10^5	5.10×10^5	1.06×10^6
Descent condition:			
Hours	483.4	452.7	936.1
Average indicated airspeed, knots	283.4	284.0	283.6
Nautical miles	1.65×10^5	1.53×10^5	3.18×10^5
Check flights:			
Hours	132.9	86.8	219.7
Number	239	140	379
Percent total time	6.38	4.56	5.51
Recording period	May 1960 to April 1962	July 1960 to April 1962	



(a) Histogram of flight duration.



(b) Histogram of altitude.

Figure 1.- Description of operation.

Evaluation

General. - Each flight on the VGH records was classified as being either a routine passenger-carrying operational flight or a check flight for pilot training or airplane testing. Check flights are distinguished from operational flights by the higher amplitude and frequency of occurrence of maneuver accelerations and by larger and more irregular variations in airspeed and altitude.

The operational flights were divided into three segments representing climb, cruise, and descent conditions. Both climb and descent occasionally included short periods of level flight as a result of operational or air traffic control procedures. The cruise condition occasionally included periods when the airplane was climbing or descending to a different cruise altitude. Operational flights were also divided into segments representing flight in rough or smooth air. The airplane was considered to be in rough air during the traverse of any continuously turbulent area which produced at least one incremental normal acceleration corresponding to a gust velocity of about 2 fps (0.6 m/sec) or higher. Turbulent areas were determined by the appearance of the acceleration and airspeed traces as described in the next section.

The average operating weights during each 30-minute interval of flight were coded on the records for subsequent correlation with the gust accelerations. These weights were based on weight data obtained from the airlines and on average fuel-consumption rates of the airplanes.

Accelerations. - The evaluation of accelerations consisted of reading positive and negative incremental acceleration peaks above a specified threshold by using the 1g position of the acceleration trace as a reference. Only the maximum peak for each crossing of the reference and threshold was read. For each gust and maneuver acceleration peak read, the corresponding airspeed and altitude were also read. In the event that a gust acceleration was superimposed on a maneuver acceleration, the maneuver acceleration rather than the 1g trace position was used as the reference. The criterion used to distinguish gust accelerations from maneuver accelerations was that gust accelerations have a much higher frequency content and are accompanied by high-frequency low-intensity fluctuations of the airspeed trace. Oscillatory accelerations appeared on the record as symmetrical acceleration excursions whose period was longer than for gusts and whose symmetry distinguished them from maneuvers. The duration of each occurrence of oscillation was noted and used to calculate the percent of flight time spent in oscillations. Incremental normal accelerations experienced during ground operations were classified as occurring during preflight taxi, take-off, landing roll-out, and postflight taxi. In addition, take-off and landing roll-out data were classified by airspeed intervals of 0 to 80 knots, 80 to 120 knots, and 120 to 140 knots. These data were obtained for only one of the two airplanes during a separate investigation after the collection of in-flight data.

The initial positive landing impacts were omitted in reading these data, since these were evaluated independently. The threshold values were ±0.2g for accelerations due to gusts and for those due to ground operations, ±0.1g for accelerations experienced during maneuvers, and ±0.05g for accelerations due to oscillations. The evaluation of landing-impact accelerations consisted of reading the peak corresponding to the initial positive impact acceleration for a number of landings of both operational and check flights.

Amount of rough air.- The percent of time in each 5000-foot (1.52-km) altitude interval that was spent in rough air was determined by dividing the time in rough air by the total flight time spent within each altitude interval.

Gust velocities.- A value of derived gust velocity U_{de} was calculated for each gust acceleration peak by means of the revised gust-load formula of reference 10

$$U_{de} = \frac{2Wa_n}{K_g \rho_o V_e m S}$$

The airplane weights were based on weights obtained from the operator and included the effects of fuel consumption. The variation of lift-curve slope m with Mach number was computed by use of the empirical formula given in section VI of reference 3 and is shown in figure 2.

Operating airspeeds and altitudes.- The indicated airspeed and pressure altitude were read from the VGH records at each 1-minute interval of flight. The airspeed and altitude data were classified by flight condition and by rough and smooth air.

Reliability of Data

The reliability of the data is affected by instrument error, installation error, and reading error. Total overall errors for the VGH recorder are discussed in section I of reference 3 and are estimated to be

Acceleration, g units	±0.05
Indicated airspeed, knots	
At 100 knots	±6
At 350 knots	±2
Indicated pressure altitude	
At 5000 ft (1.52 km)	±75 ft (23 m)
At 40 000 ft (12.2 km)	±500 ft (152 m)

Reading errors are believed to be small in terms of the magnitudes of the particular quantities read inasmuch as each tabulation is checked and corrected before use. The reading error for acceleration, although small, may seriously affect the count of accelerations exceeding given values. Reading checks have indicated that for individual records,

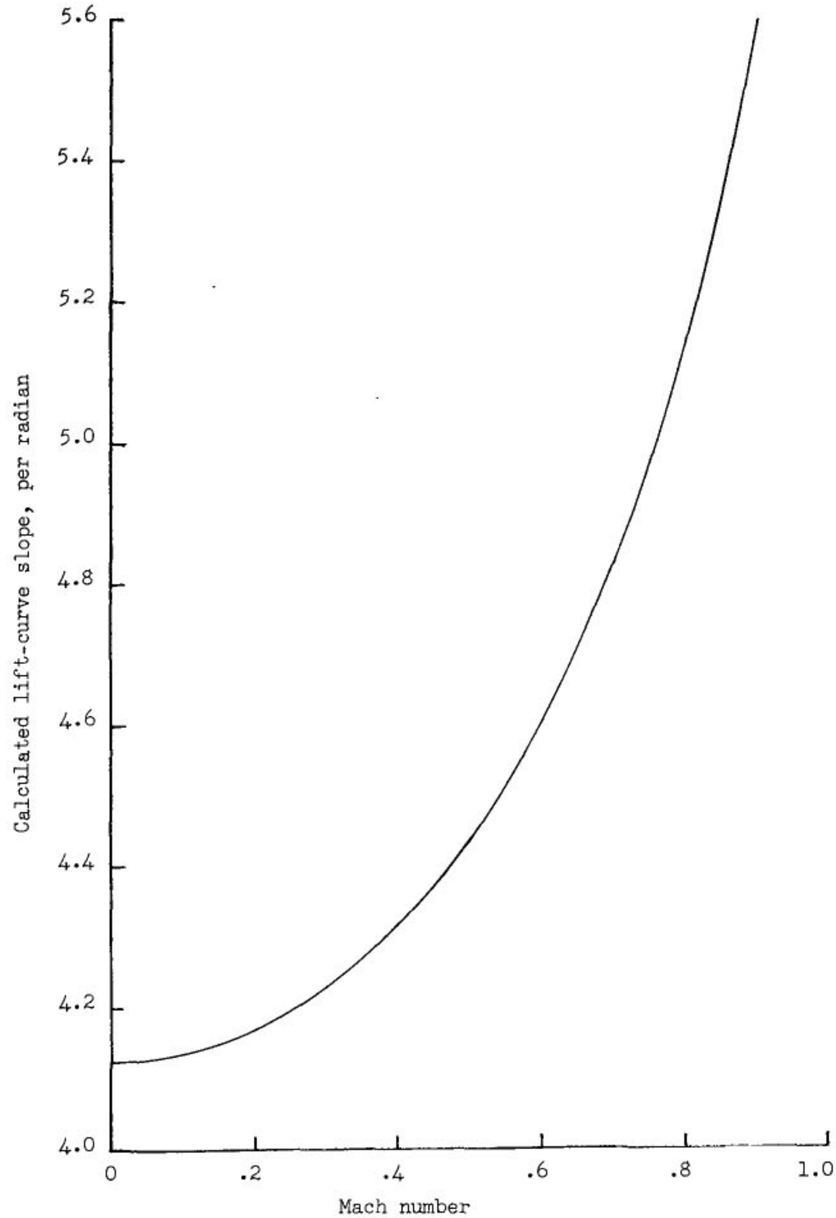


Figure 2.- Computed variation of lift-curve slope with Mach number.

the number of counts above 0.3g is reliable within ±30 percent. Inasmuch as the reading errors tend to balance out as the sample size increases, the values of cumulative frequency per mile for the overall distributions of gust and maneuver accelerations and of gust velocity are estimated to be reliable within ±20 percent.

Past experience has indicated that 1000 hours of VGH data constitute a representative sample of the operational experience of an individual airplane. For applicability to extended periods of operation approaching the lifetime of a fleet of airplanes, however, it is estimated that the counts of gust and maneuver accelerations and of gust velocity are reliable within a factor of 3 to 4.

RESULTS AND DISCUSSION

Flight Environment

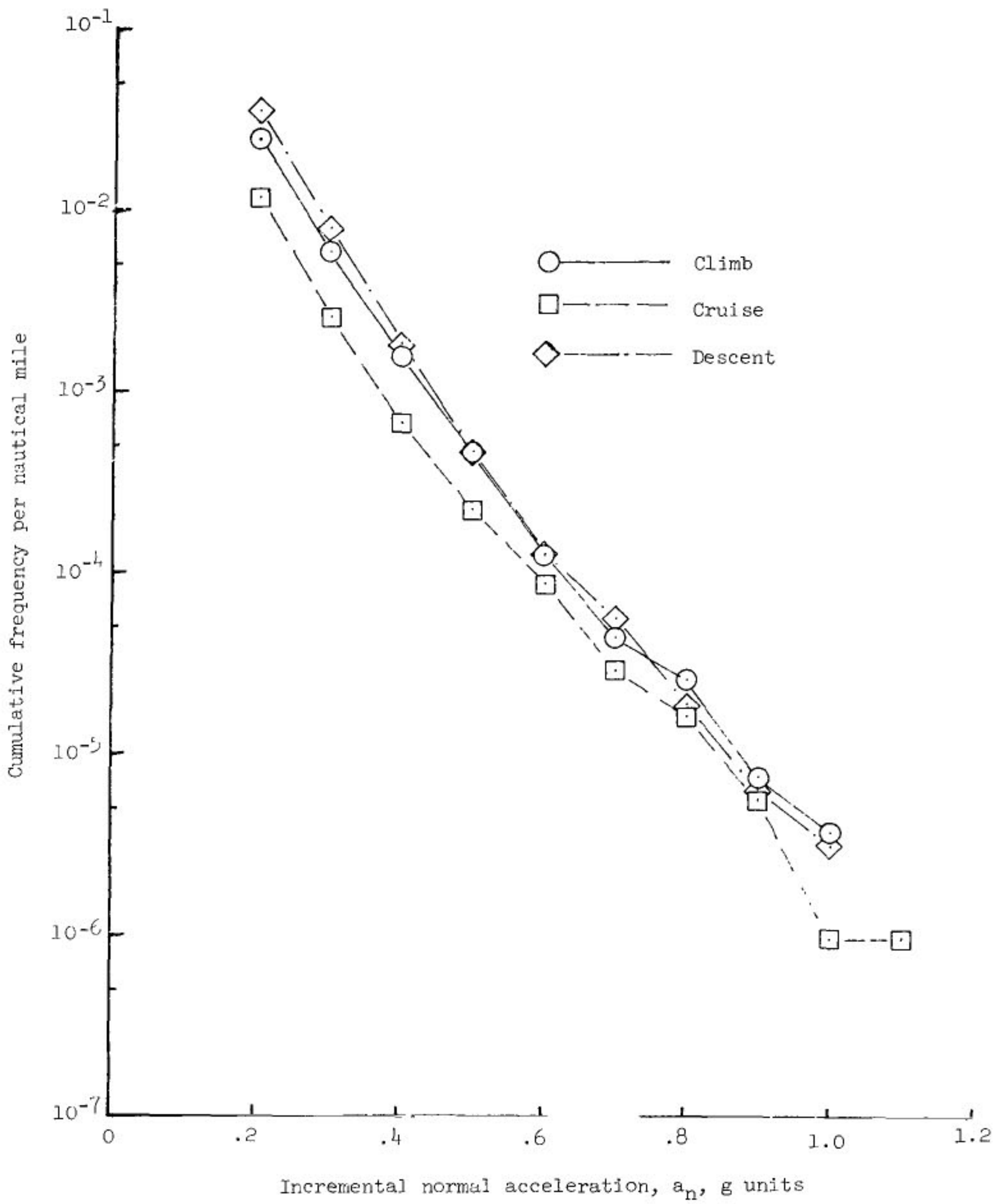
The histogram of flight duration in figure 1(a) shows that the largest number of flights had durations between 30 and 45 minutes and that flights extended to 270 minutes. The average duration for the operation (combined sample) was 90.4 minutes as indicated in table I. Figure 1(b) shows that the largest percent of total time was spent in the interval from 30 000 to 35 000 feet (9.14 to 10.7 km) although table I indicates that the average altitude for the operation was 24 430 feet (7.45 km). The average duration and altitude for the individual airplanes shown in table I were unusually similar.

Accelerations Due to Gusts

The frequency distributions of the combined (positive and negative) accelerations due to gusts are given in table II by flight condition and for the total samples for each airplane. The flight hours, average true airspeed, and nautical miles associated with each distribution are listed. The flight miles used throughout this report are nautical miles, computed by multiplying appropriate values of time in hours and average true airspeed in knots. In figure 3(a) the cumulative frequency distributions of accelerations

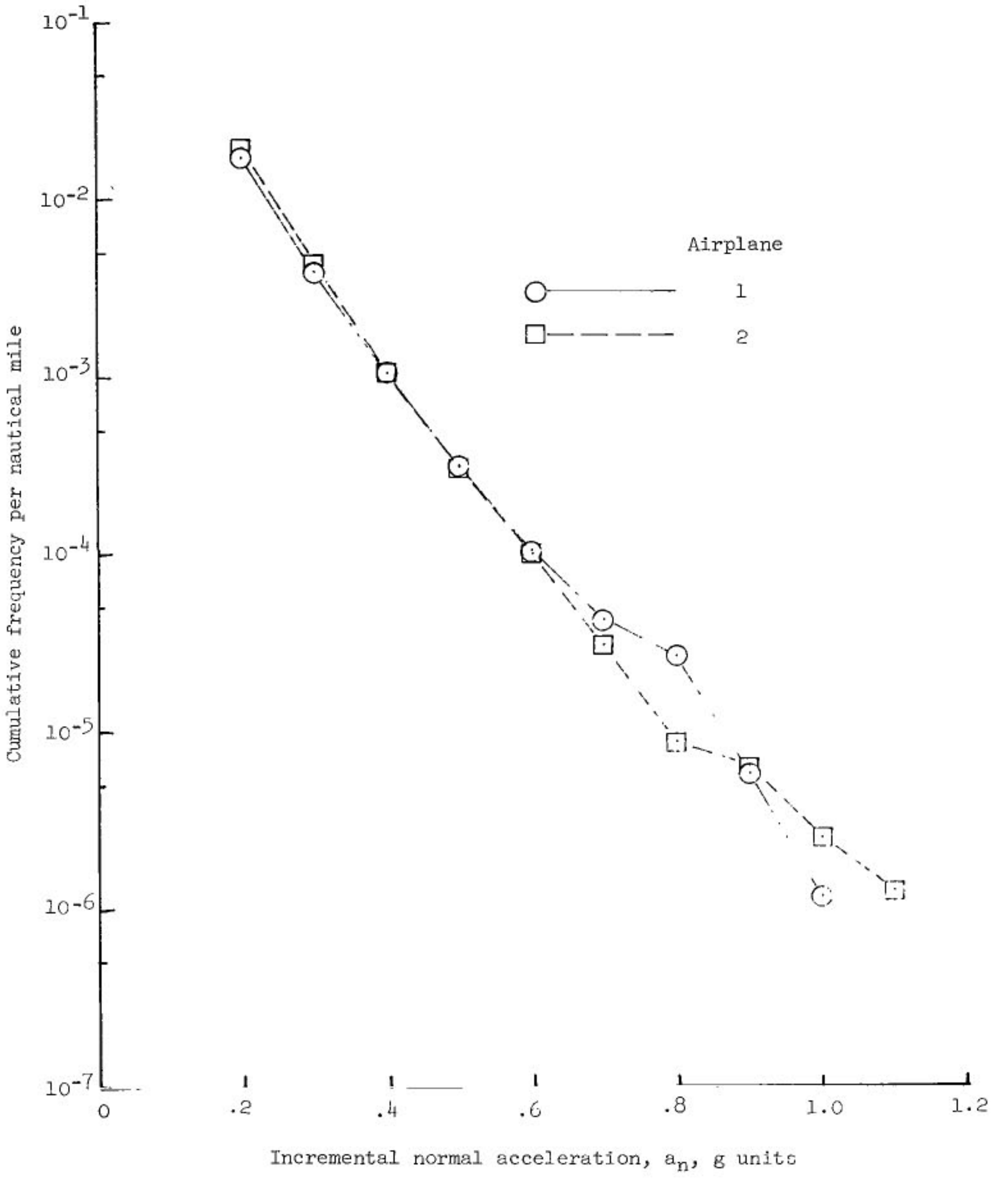
TABLE II.- FREQUENCY DISTRIBUTIONS OF INCREMENTAL NORMAL ACCELERATIONS DUE TO GUSTS BY FLIGHT CONDITION

Incremental normal acceleration, a_n, g units	Frequency of occurrence for –						Total frequency of occurrence	
	Climb		Cruise		Descent			
	Airplane 1	Airplane 2	Airplane 1	Airplane 2	Airplane 1	Airplane 2	Airplane 1	Airplane 2
0.2 to 0.3	2285	2724	4531	4897	4385	4332	11 201	11 953
0.3 to 0.4	606	568	895	1119	1013	964	2 514	2 651
0.4 to 0.5	184	120	222	251	214	195	620	566
0.5 to 0.6	56	35	74	73	53	53	183	161
0.6 to 0.7	14	8	29	32	8	15	51	55
0.7 to 0.8	2	3	5	9	7	5	14	17
0.8 to 0.9	5	0	9	2	4	0	18	2
0.9 to 1.0		1	4	1	0	1	4	3
1.0 to 1.1		1		0	1		1	1
1.1 to 1.2				1				1
Total	3152	3460	5769	6385	5685	5565	14 606	15 410
Hours	350.7	319.7	1114.9	1044.6	483.4	452.7	1949.0	1817.0
Av. true airspeed, knots	403.9	404.3	490.4	488.1	340.7	339.0	437.7	436.2
Nautical miles	1.41×10^5	1.29×10^5	5.47×10^5	5.10×10^5	1.65×10^5	1.53×10^5	8.53×10^5	7.92×10^5



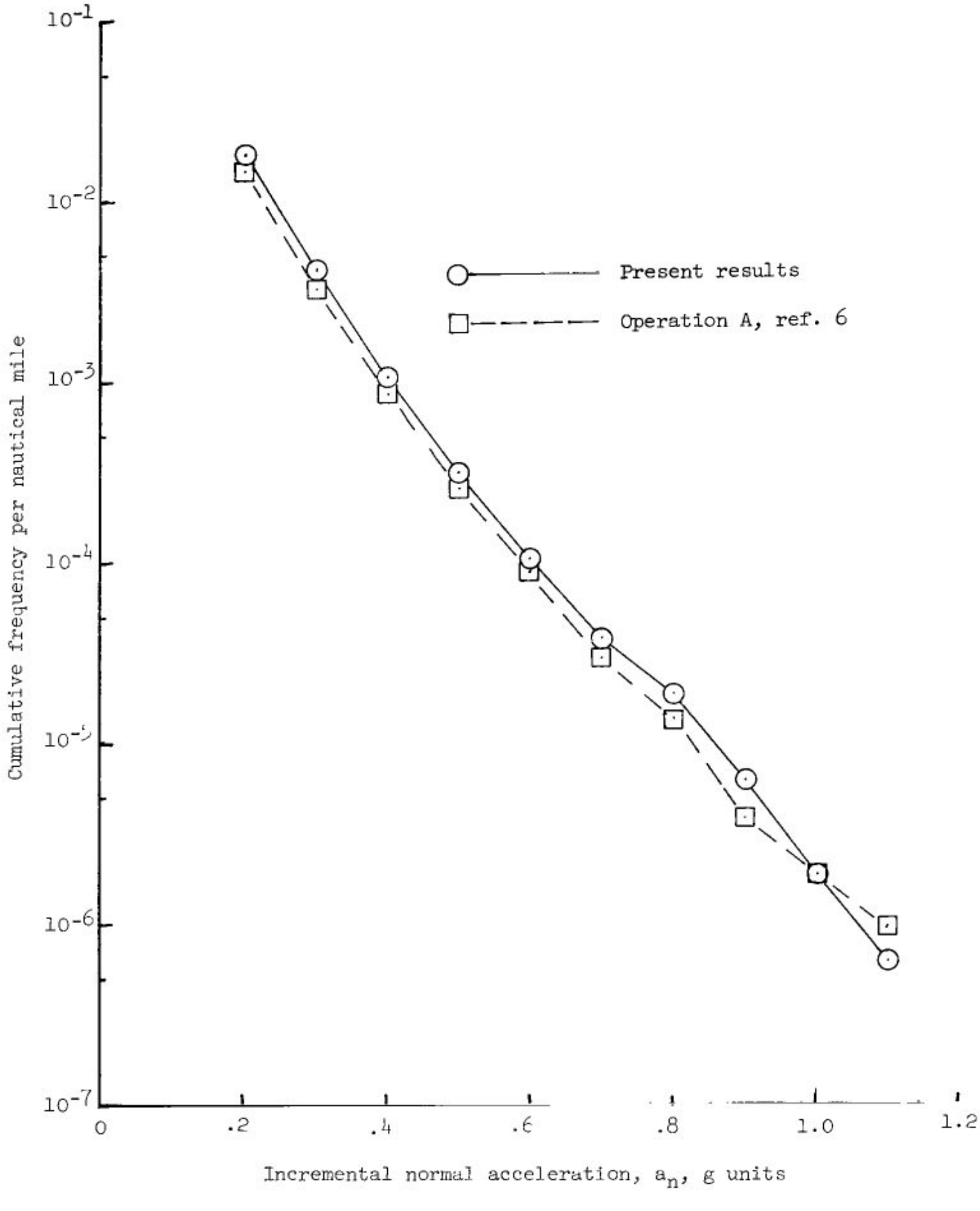
(a) By flight condition.

Figure 3.- Cumulative frequency distributions of incremental gust accelerations per nautical mile.



(b) Individual airplane samples.

Figure 3.- Continued.



(c) Comparison of two operations.

Figure 3.- Concluded.

per nautical mile are presented by flight condition for the combined sample (both airplanes). These distributions were formed by progressively summing the frequency distributions of table II, beginning with the largest acceleration, and dividing each sum by the flight distance of the sample. The cumulative frequency of accelerations per mile for the individual airplanes are presented in figure 3(b) and a comparison of the accelerations for the combined sample with those of operation A of reference 6 is shown in figure 3(c).

The frequency distributions of table II show that for each airplane the total number of gust accelerations greater than $\pm 0.2g$ was roughly the same for the cruise and descent conditions but the climb condition accounted for only about half as many accelerations as either cruise or descent condition. Figure 3(a) shows, however, that for the combined sample the cumulative frequency of gust accelerations per mile was lowest during the cruise condition and about equal during the climb and descent. Figure 3(b) shows that the overall gust experience for the two individual airplanes was very similar. In figure 3(c) the comparison of overall gust accelerations for the present operation and those of operation A of reference 6 also shows good agreement.

Accelerations Experienced During Maneuvers

Operational maneuvers.- Frequency distributions of the positive and negative operational maneuver accelerations by flight condition and by total count are given in table III(a) for each airplane. Cumulative frequency distributions of operational maneuver accelerations per mile are given for the combined sample (both airplanes by flight condition in fig. 4(a) and by positive and negative accelerations in fig. 4(b)). A comparison of accelerations experienced by the individual airplanes of the present operation is shown in figure 4(c). In figure 4(d) the accelerations for the combined sample are compared with those of operation A of reference 6.

The results in table III(a) show that the total number of accelerations greater than $\pm 0.1g$ for each airplane are about equal for climb and cruise conditions. For the descent condition, the count of accelerations was about twice that for climb or cruise. However, the number per mile for the combined sample, shown in figure 4(a), is least for the cruise condition and about equal for climb and descent. Thus, the numerous maneuvers inherent in climbout and approach for the shorter distances covered overshadow the maneuvers which occur while covering the longer distances in cruise. The total positive and total negative accelerations of table III(a), plotted in figure 4(b) in terms of cumulative frequency per mile, show that although the total count of positive and negative accelerations are about equal, the positive accelerations are more frequent by factors of up to about 3 at the middle and higher values of acceleration. Comparisons of total operational maneuver accelerations are presented for the individual airplanes of the present operation in figure 4(c) and for the present operation and operation A of reference 6 in figure 4(d); both comparisons show little or no difference in experience. The results of both comparisons are to be expected on the basis of similarity of operation. For the latter comparison, the airplanes are similar and were operated over similar route structures. In addition, reference 5 points out that most transport airplanes, both piston- and turbine-powered, have shown relatively little variation in operational maneuver acceleration experience.

Check-flight maneuvers.- Frequency distributions of positive and negative check-flight accelerations for each airplane are given in table III(b). The amount of time spent in check flights, the total of operational and check-flight record hours, and the nautical miles associated with each distribution are listed. The nautical miles associated with check flights were computed as the product of the average true airspeed for operational flights and the total time listed in the table and therefore correspond to the total distance traveled during the recording period. The use of total distance for check-flight maneuvers makes these distributions more directly comparable to those for gust and operational maneuver accelerations.

TABLE III.- FREQUENCY DISTRIBUTIONS OF POSITIVE AND NEGATIVE MANEUVER ACCELERATIONS

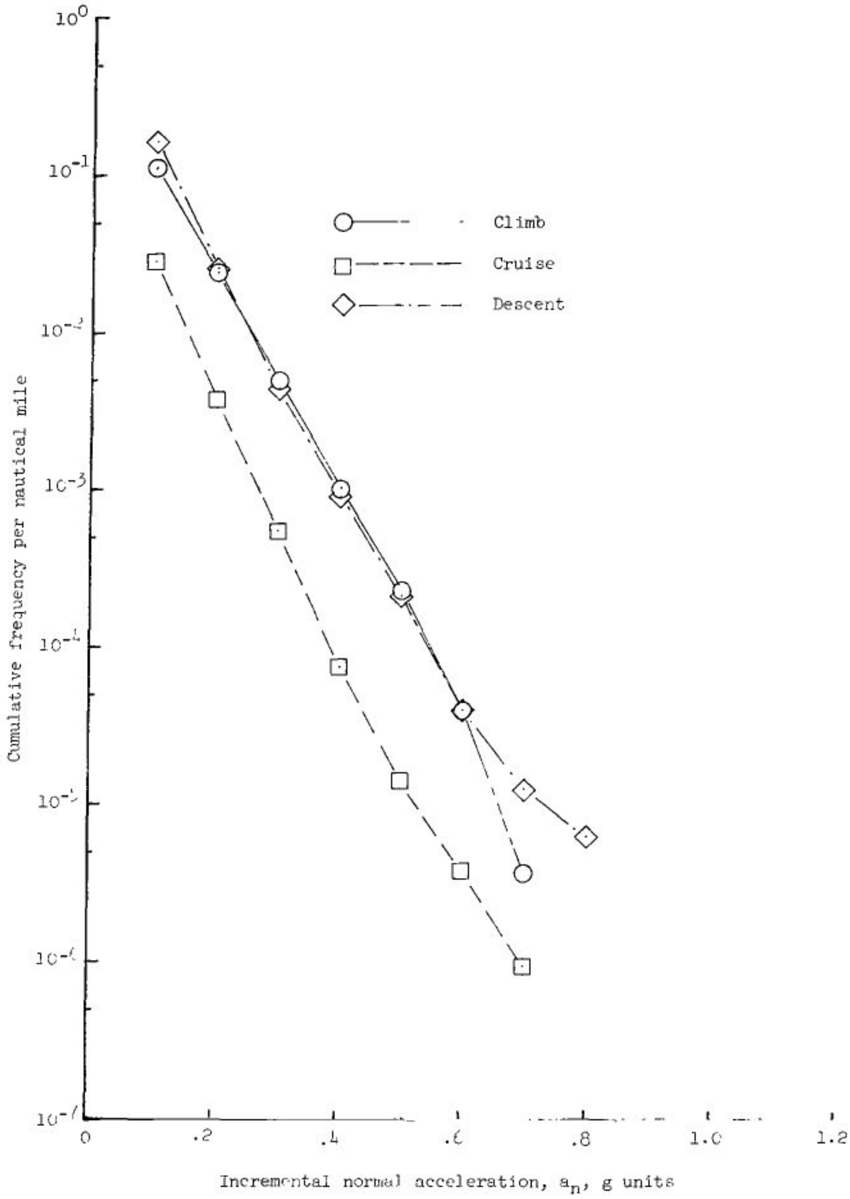
(a) Operational maneuver accelerations by flight condition

Incremental normal acceleration, a_n, g units	Frequency of occurrence for – Climb, Airplane 1	Climb, Airplane 2	Cruise, Airplane 1	Cruise, Airplane 2	Descent, Airplane 1	Descent, Airplane 2	Total frequency of occurrence, Airplane 1	Total frequency of occurrence, Airplane 2
-0.8 to -0.9					2		2	
-0.7 to -0.8		1			0		0	1
-0.6 to -0.7		0	1		0	1	1	1
-0.5 to -0.6	3	7	1	2	3	2	7	11
-0.4 to -0.5	22	38	9	16	17	17	48	71
-0.3 to -0.4	167	243	99	78	128	147	394	468
-0.2 to -0.3	1 090	1 423	725	855	1 138	1 317	2 953	3 595
-0.1 to -0.2	6 470	7 152	6 801	7 457	10 624	11 224	23 895	25 833
Negative total	7 752	8 864	7 636	8 408	11 912	12 708	27 300	29 980
0.1 to 0.2	5 085	6 197	6 004	6 441	11 115	10 954	22 204	23 592
0.2 to 0.3	1 084	1 580	829	972	2 170	2 104	4 083	4 656
0.3 to 0.4	265	402	159	176	419	426	843	1 004
0.4 to 0.5	74	84	20	22	110	80	204	186
0.5 to 0.6	17	26	3	5	26	24	46	55
0.6 to 0.7	7	3	1	1	3	5	11	9
0.7 to 0.8				1	1	1	1	2
Positive total	6 532	8 292	7 016	7 618	13 844	13 594	27 392	29 504
Total pos. and neg.	14 284	17 156	14 652	16 026	25 756	26 302	54 692	59 484
Hours	350.7	319.7	1114.9	1044.6	483.4	452.7	1949.0	1817.0
Av. true airspeed, knots	403.9	404.3	490.4	488.1	340.7	339.0	437.7	436.2
Nautical miles	1.41×10^5	1.29×10^5	5.47×10^5	5.10×10^5	1.65×10^5	1.53×10^5	8.53×10^5	7.92×10^5

TABLE III.- FREQUENCY DISTRIBUTIONS OF POSITIVE AND NEGATIVE MANEUVER ACCELERATIONS – Concluded

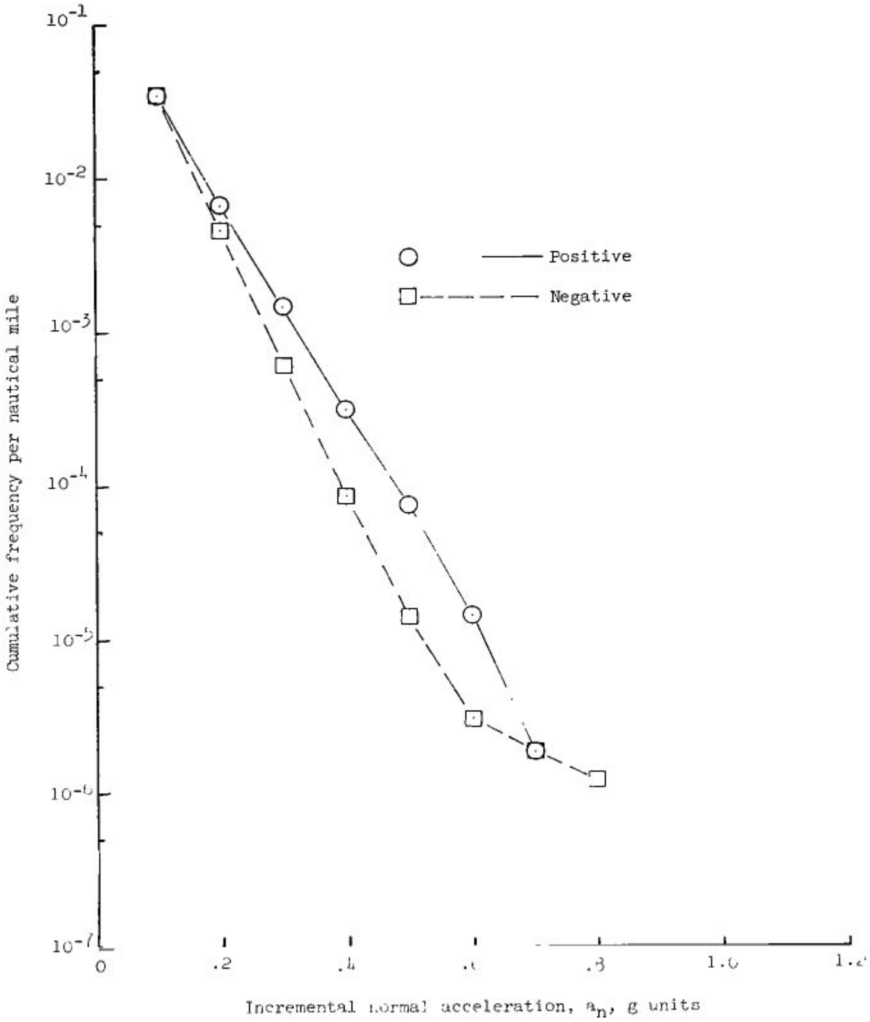
(b) Check-flight maneuver accelerations

Incremental normal acceleration, a_n, g units	Frequency of occurrence for –	
	Airplane 1	Airplane 2
-0.9 to -1.0		1
-0.8 to -0.9		2
-0.7 to -0.8	1	8
-0.6 to -0.7	8	7
-0.5 to -0.6	19	29
-0.4 to -0.5	64	87
-0.3 to -0.4	295	286
-0.2 to -0.3	1 188	1 097
-0.1 to -0.2	3 547	4 470
Negative total	5 122	5 987
0.1 to 0.2	3 112	3 882
0.2 to 0.3	1 290	1 259
0.3 to 0.4	414	436
0.4 to 0.5	142	134
0.5 to 0.6	83	68
0.6 to 0.7	35	41
0.7 to 0.8	14	26
0.8 to 0.9	11	11
0.9 to 1.0	5	5
1.0 to 1.1	1	2
1.1 to 1.2	0	1
1.2 to 1.3	1	0
1.3 to 1.4	1	0
1.4 to 1.5		1
Positive total	5 109	5 866
Total pos. and neg.	10 231	11 853
Check-flight hours	132.9	86.8
Total hours	2081.9	1903.8
Total nautical miles	9.11×10^5	8.30×10^5



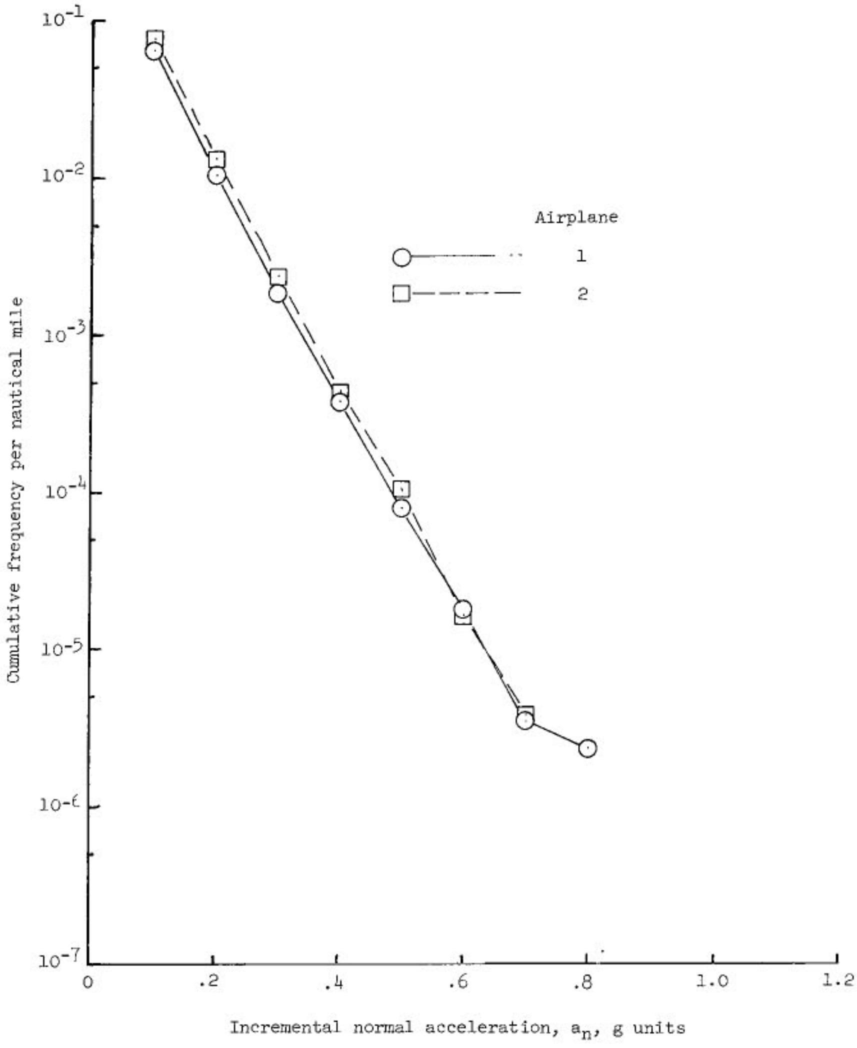
(a) By flight condition.

Figure 4.- Cumulative frequency distributions of operational maneuver accelerations per nautical mile.



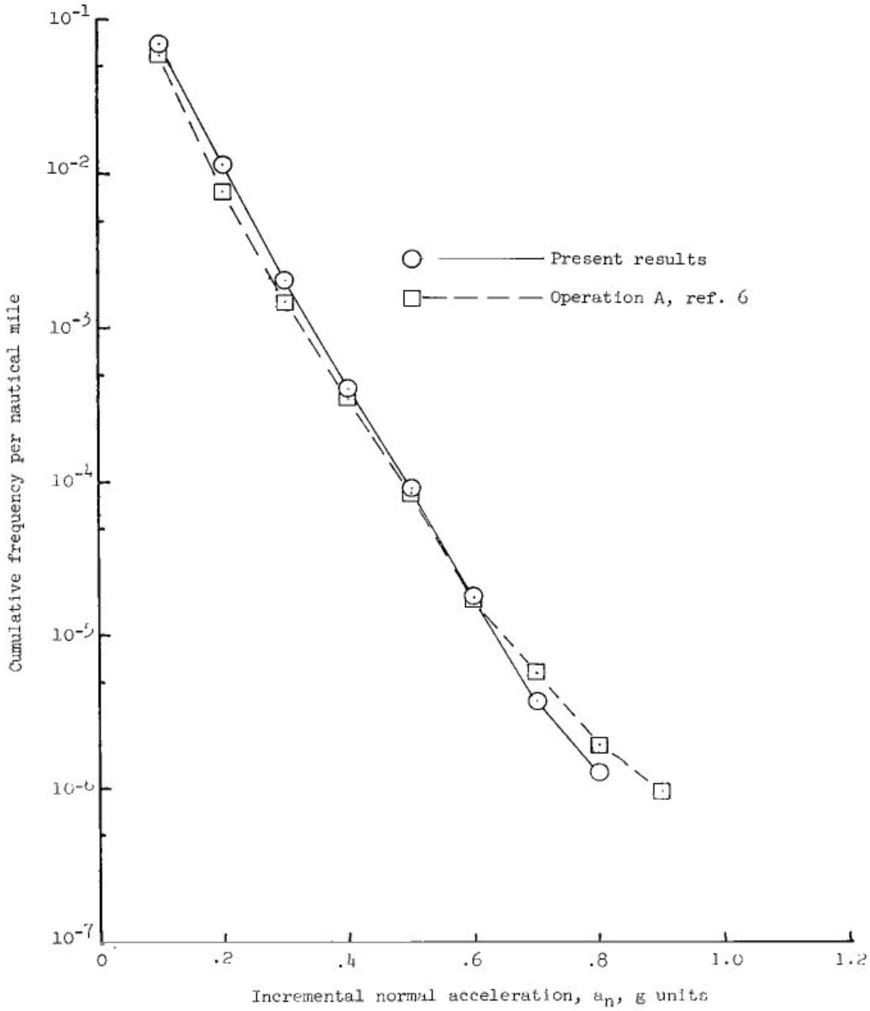
(b) Positive and negative accelerations for the operation.

Figure 4.- Continued.



(c) Individual airplane samples.

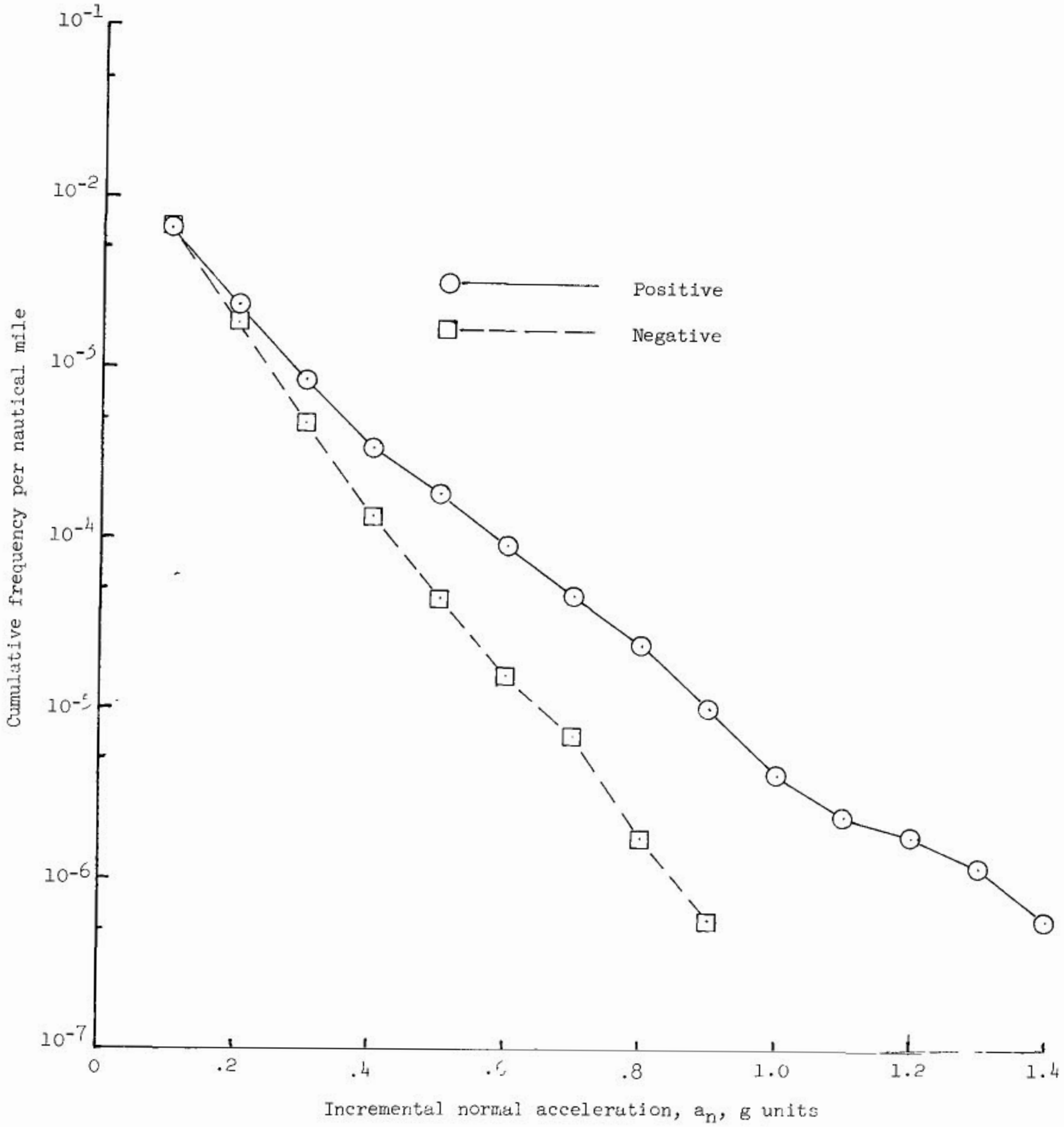
Figure 4.- Continued.



(d) Comparison of two operations.

Figure 4.- Concluded.

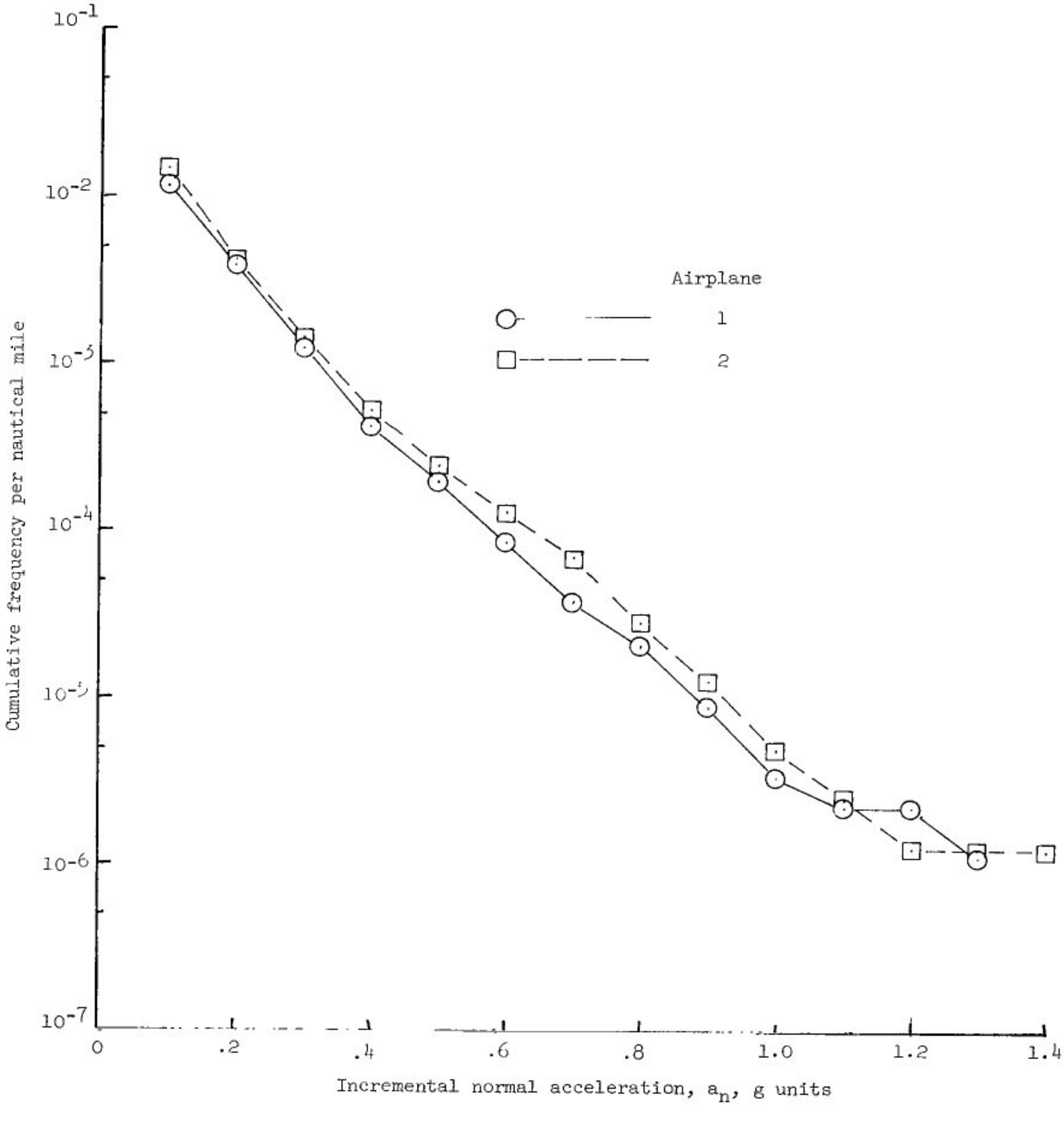
Cumulative frequency distributions of check-flight maneuver accelerations per mile are presented in figure 5(a) for positive and negative accelerations of the combined sample, in figure 5(b) for the combined positive and negative accelerations for the individual airplanes, and in figure 5(c) for the combined sample of the present operation and the corresponding accelerations for operation A of reference 6. Figure 5(a) shows that although the total positive and total negative accelerations per mile (indicated by the values plotted at 0.1g) are essentially equal, the positive accelerations are more frequent



(a) Positive and negative accelerations for the operation.

Figure 5.- Cumulative frequency distributions of check-flight maneuver accelerations per nautical mile.

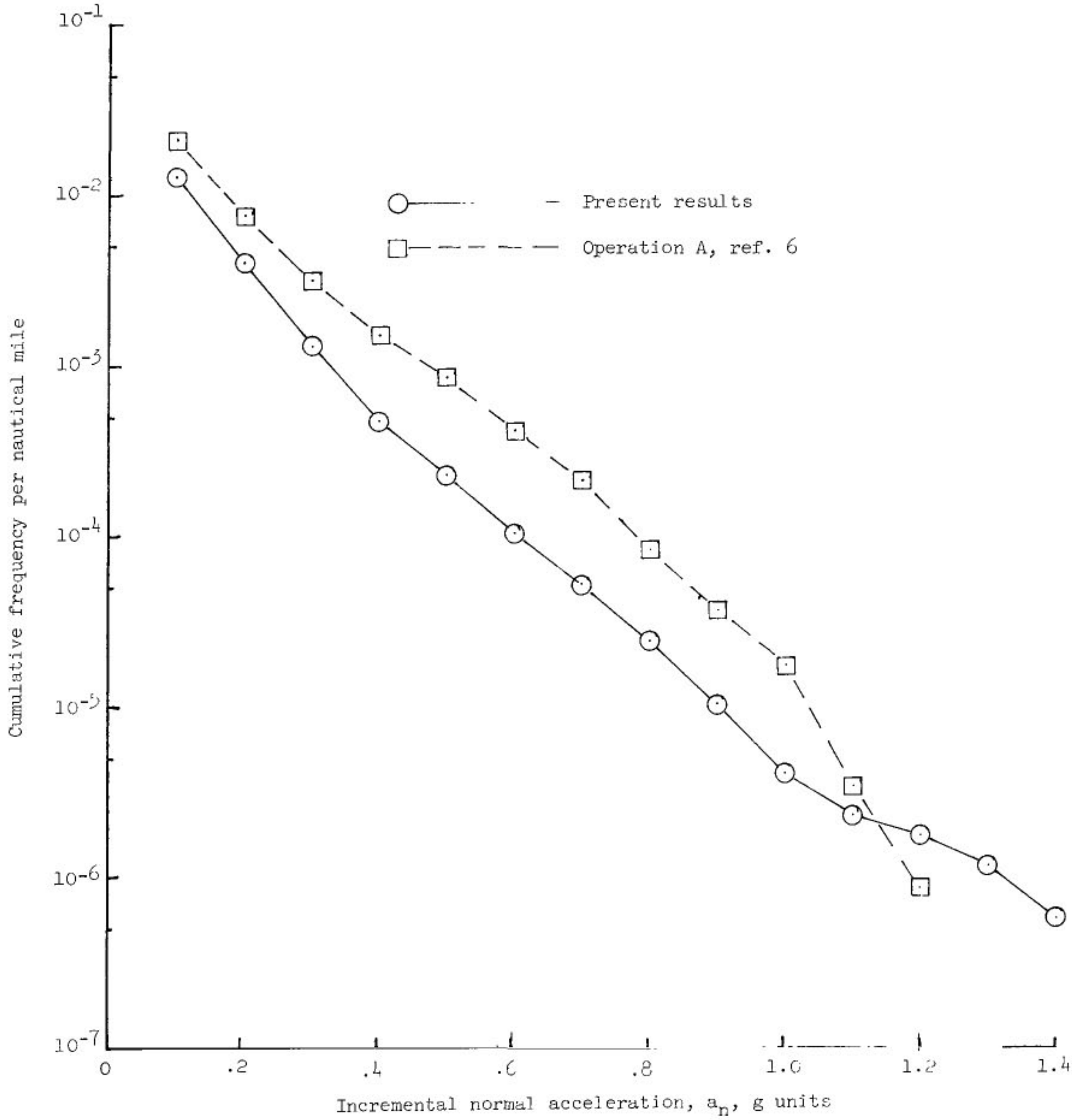
at the higher values of acceleration by factors of up to 20. The distributions of check-flight maneuver accelerations for the individual airplanes of the present operation, shown in figure 5(b), are reasonably similar although the accelerations for airplane 2 are slightly more frequent than for airplane 1. A comparison of check-flight maneuver experience for the present operation with that of operation A of reference 6 in figure 5(c) indicates that the present operation was somewhat less severe than the reference operation. Obviously, the severity of check-flight maneuver experience is primarily a function of the



(b) Individual airplane samples.

Figure 5.- Continued.

type and number of maneuvers called for by the airline check-flight syllabus. Previous VGH results have shown that a degree of correlation exists between the severity of check-flight maneuver experience and the percent of time spent in check flights for those cases where the check-flight syllabi are similar. The airplanes of the present operation were flown in check flights for a lower percentage of total time than were the reference airplanes (see table I of the present paper and table I of ref. 6); thus, the lesser severity of the check-flight maneuver experience for the present operation is not unexpected.



(c) Comparison of two operations.

Figure 5.- Concluded.

TABLE IV.- DATA SAMPLES EVALUATED FOR INCREMENTAL NORMAL ACCELERATIONS EXPERIENCED DURING OSCILLATIONS

Airplane	Hours	Nautical miles	Percent time in oscillations
1	401.6	1.76×10^5	6.47
2	246.3	1.06×10^5	0.73
Combined sample	647.9	2.82×10^5	4.29

Accelerations Experienced During Oscillations

The data samples evaluated for the occurrence of oscillations and listed in table IV are considerably smaller than the complete data samples listed in table I; however, they are considered representative of the oscillation experience of the airplanes. The table gives the sample sizes in terms of both flight time and nautical miles represented and also shows the percent of flight time spent in oscillations. The occurrence of oscillations varied considerably between the individual airplanes, as is indicated by the large difference in percent of time spent in oscillations shown in table IV. The cumulative frequency distribution of oscillatory accelerations per mile of flight for the combined sample is shown in figure 6 together with a distribution from operation A of reference 6. The comparison of oscillation experience presented in figure 6 shows a great similarity despite a large difference in

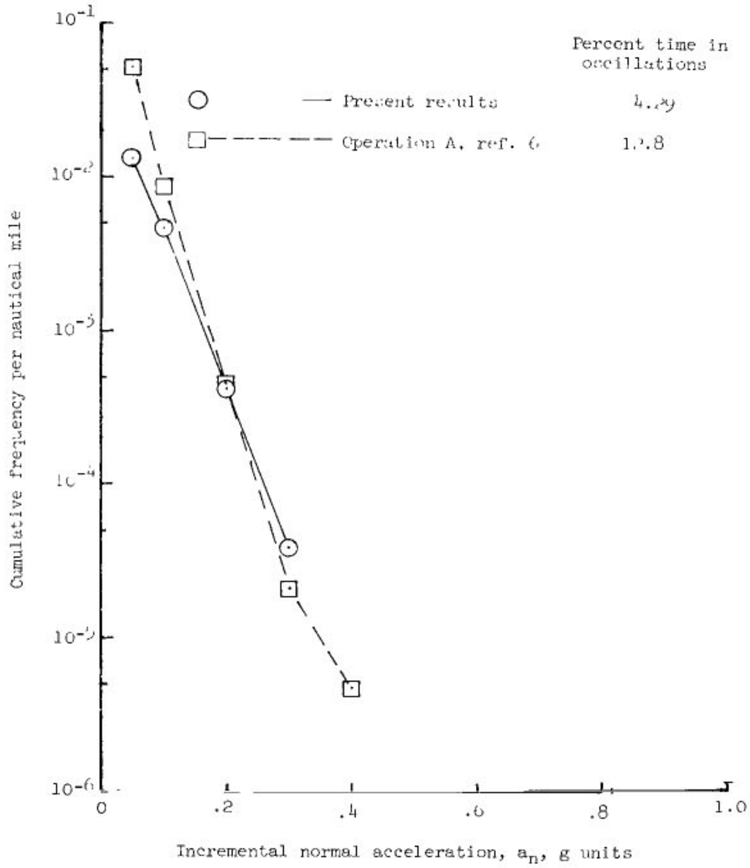


Figure 6.- Cumulative frequency distributions of oscillatory accelerations per nautical mile for two operations.

percent of total time spent in oscillations for the two operations. These oscillations generally occurred during the earlier portions of the operation of these airplanes and were apparently a result of either minor autopilot malfunction or friction and wear in control-system components. Detailed information of types and causes of oscillations are given in section V of reference 3.

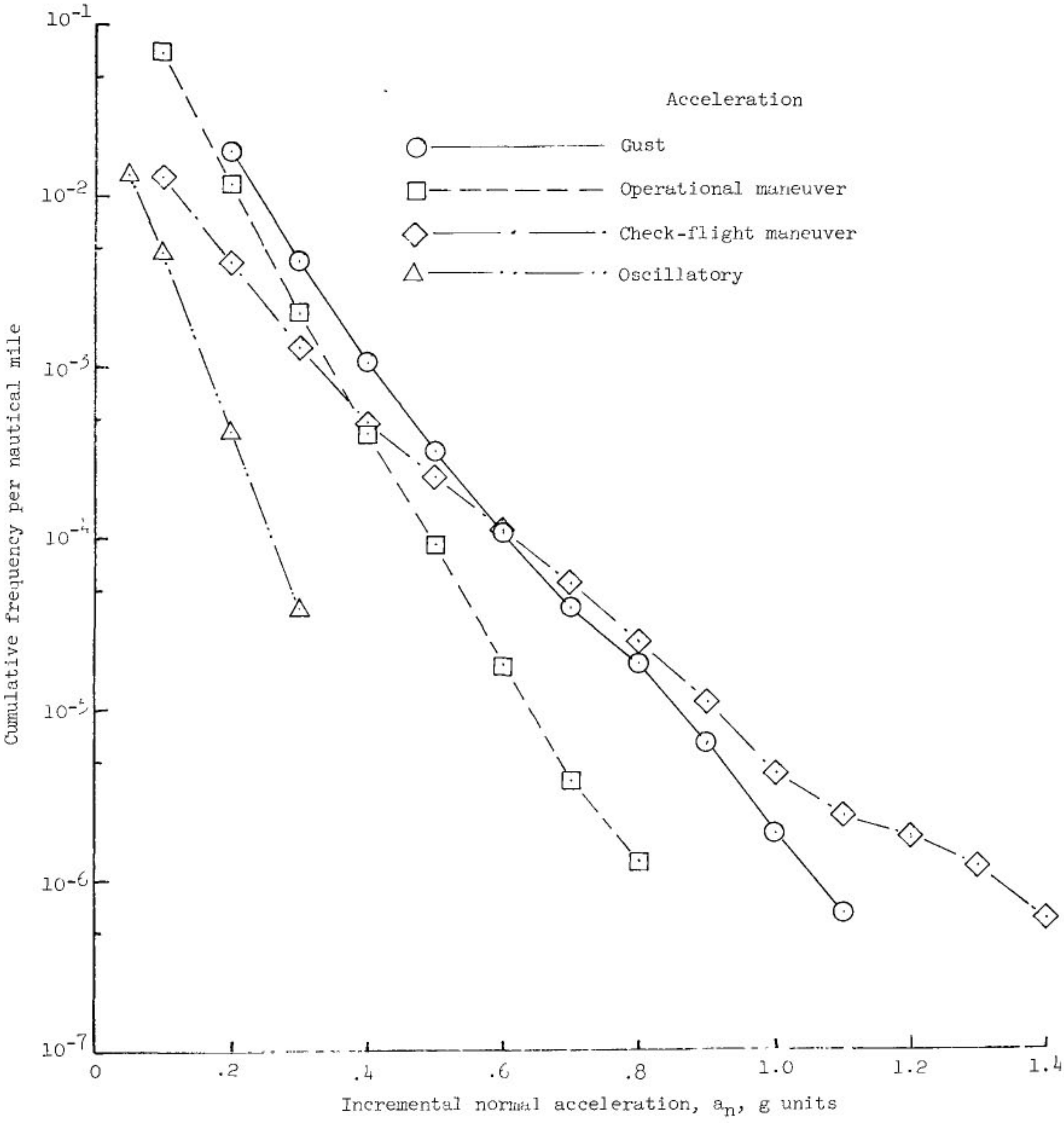


Figure 7.- Comparison of accelerations from various in-flight sources.

Flight Loads Summary

In order to indicate the relative importance of accelerations from various sources, the cumulative frequency distributions of gust, operational maneuver, check-flight maneuver, and oscillatory accelerations per mile of flight are shown in figure 7 for the combined sample. This comparison shows that, for incremental accelerations less than about 0.4g, gust accelerations were most frequent, followed in sequence by accelerations from operational maneuvers and check-flight maneuvers. For accelerations greater than 0.6g, accelerations from check-flight maneuvers were most frequent, but accelerations due to gusts

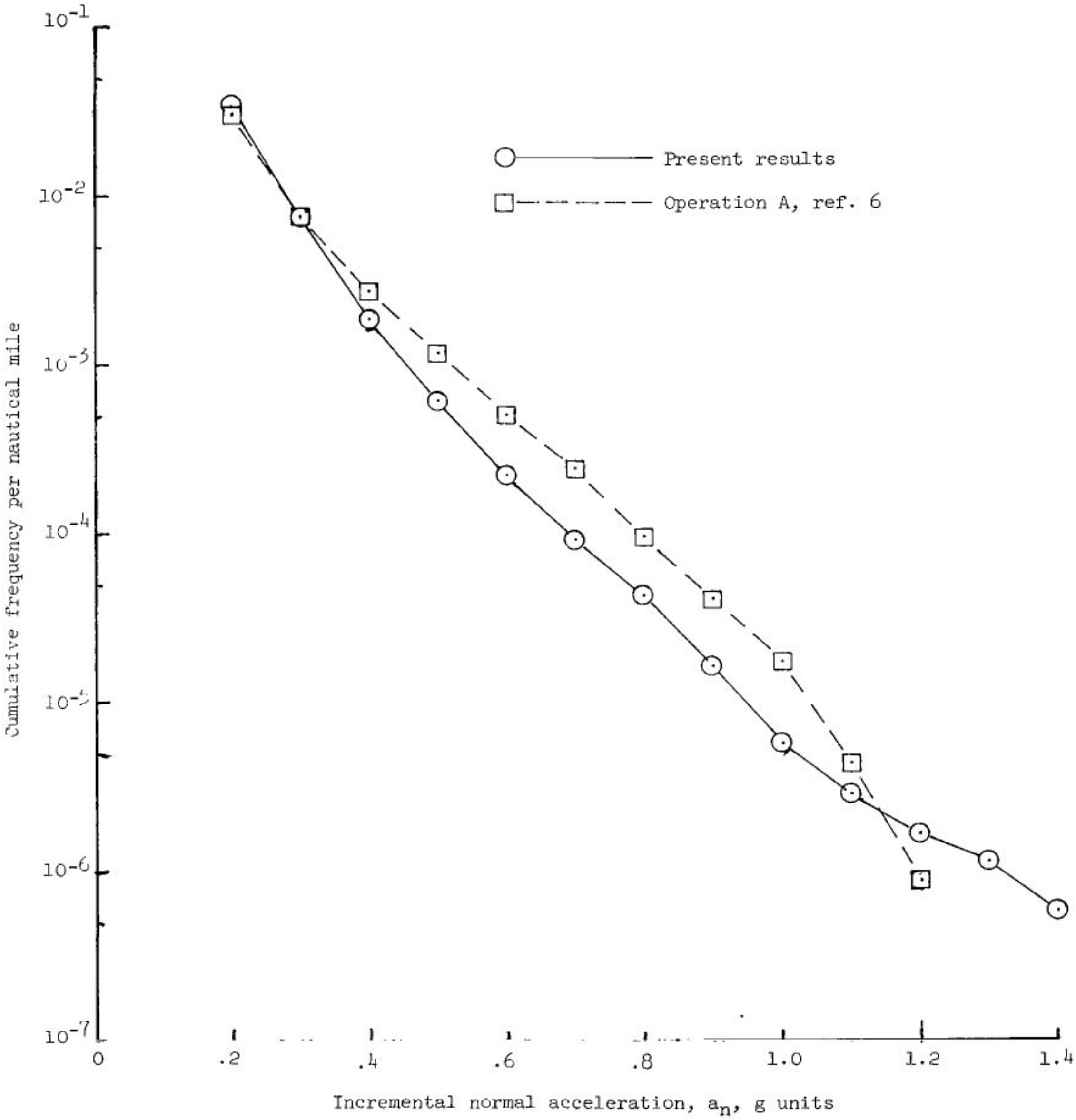


Figure 8.- Combined distributions of accelerations from various in-flight sources.

still contributed about half as many as did the check-flight maneuvers. Operational maneuvers contributed about 1/10 as many accelerations as did check-flight maneuvers. Oscillations contributed little to the total at any acceleration level. These trends are consistent with results for other jet transports. (See refs. 6 and 7.)

Total in-flight acceleration distributions, formed by combining distributions for gust, maneuver, and oscillatory accelerations, are presented in figure 8 for the present operation and for operation A of reference 6. The more severe experience shown for operation A is a reflection of the more severe check-flight maneuver experience for that operation, since the gust and operational maneuver experience for the two operations was nearly the same.

Turbulence

Amount of rough air.- The percent of time in each 5000-foot (1.52-km) altitude interval that was spent in rough air is presented in figure 9 for the present operation and operation A of reference 6, together with estimated data from reference 11 which were based on results from a wide variety of aircraft. The data in figure 9 indicate that the airplanes in the present operation experienced rough air within given altitude intervals a greater percent of time than did the airplanes of operation A of reference 6 and also a greater percent of time than the estimates taken from reference 11, at least for altitudes below 30 000 feet (9.14 km). Because of the large variations in speed, altitude, and weight which occur in modern jet-transport operations, the relationship between values of gust acceleration and derived gust velocity is subject to large variations throughout the flight

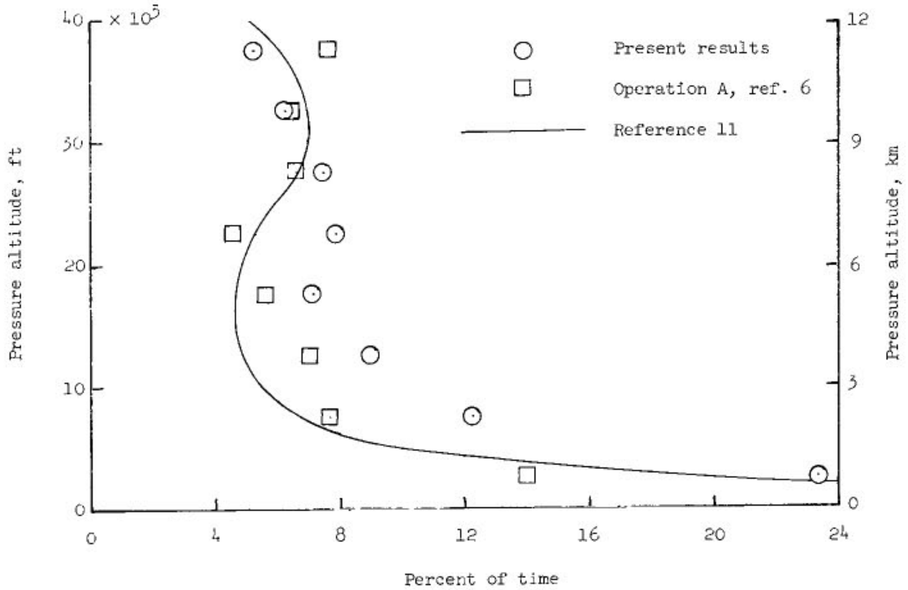


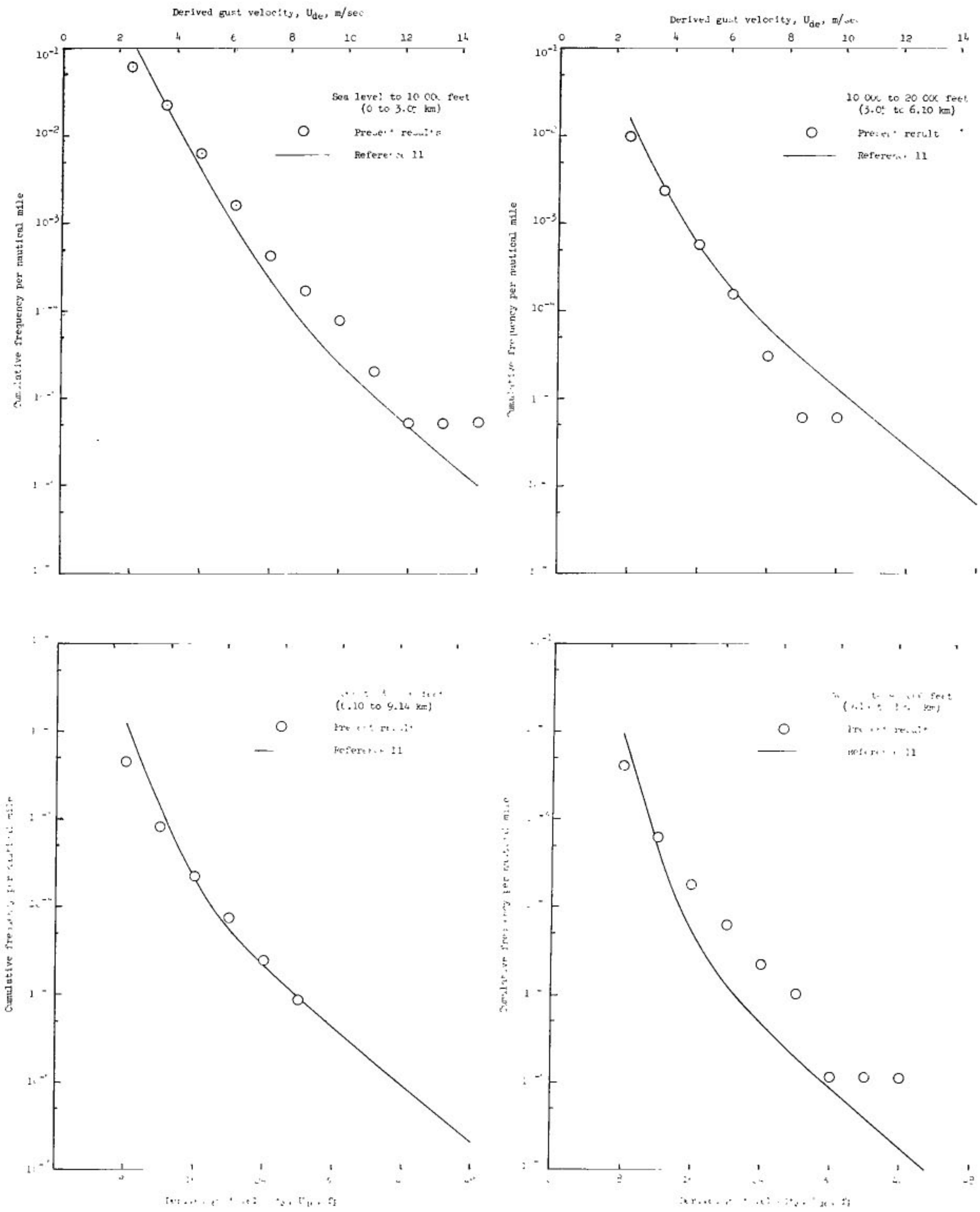
Figure 9.- Percent of time in each 5000-ft (1.52-km) altitude interval spent in rough air.

regime. This causes difficulty in insuring a constant gust velocity threshold for defining rough air. Consequently, it is not known whether the differences shown in figure 9 are real or are due wholly or in part to evaluation procedures.

Gust velocities.- Frequency distributions of derived gust velocities are presented in table V by altitude intervals of 10 000 feet (3.05 km) for each airplane. Cumulative frequency distributions of derived gust velocity per mile of flight by altitude intervals of 10 000 feet for the combined sample are presented in figure 10(a) together with estimated distributions from reference 11 based on past investigations. The values of flight miles used in computing the values of cumulative frequency per mile correspond to those flown within each altitude interval. The comparison shown in figure 10(a) of the present operation and the estimated distributions taken from reference 11 indicates, in general, good agreement for the middle altitude intervals and more severe experience for the present operation at the lowest and highest altitude intervals. The distributions from reference 11 represent rigid airplane response, whereas the present results include some flexibility effects of unknown amplitudes. Elimination of the flexibility effects from the present results would probably have the effect of making the present results less severe. The lower slopes of the data for the present operation at the lower values of derived gust velocity compared with the slopes of the curves from reference 11 is believed to be a result of the variable threshold discussed in the preceding section. As was indicated earlier in this paper, the airplanes of the present operation and those of operation A of reference 6 were flown over much of the same geographic area and at almost the same

TABLE V.- FREQUENCY DISTRIBUTIONS OF DERIVED GUST VELOCITIES BY 10 000-FOOT (3.05-km) ALTITUDE INTERVALS

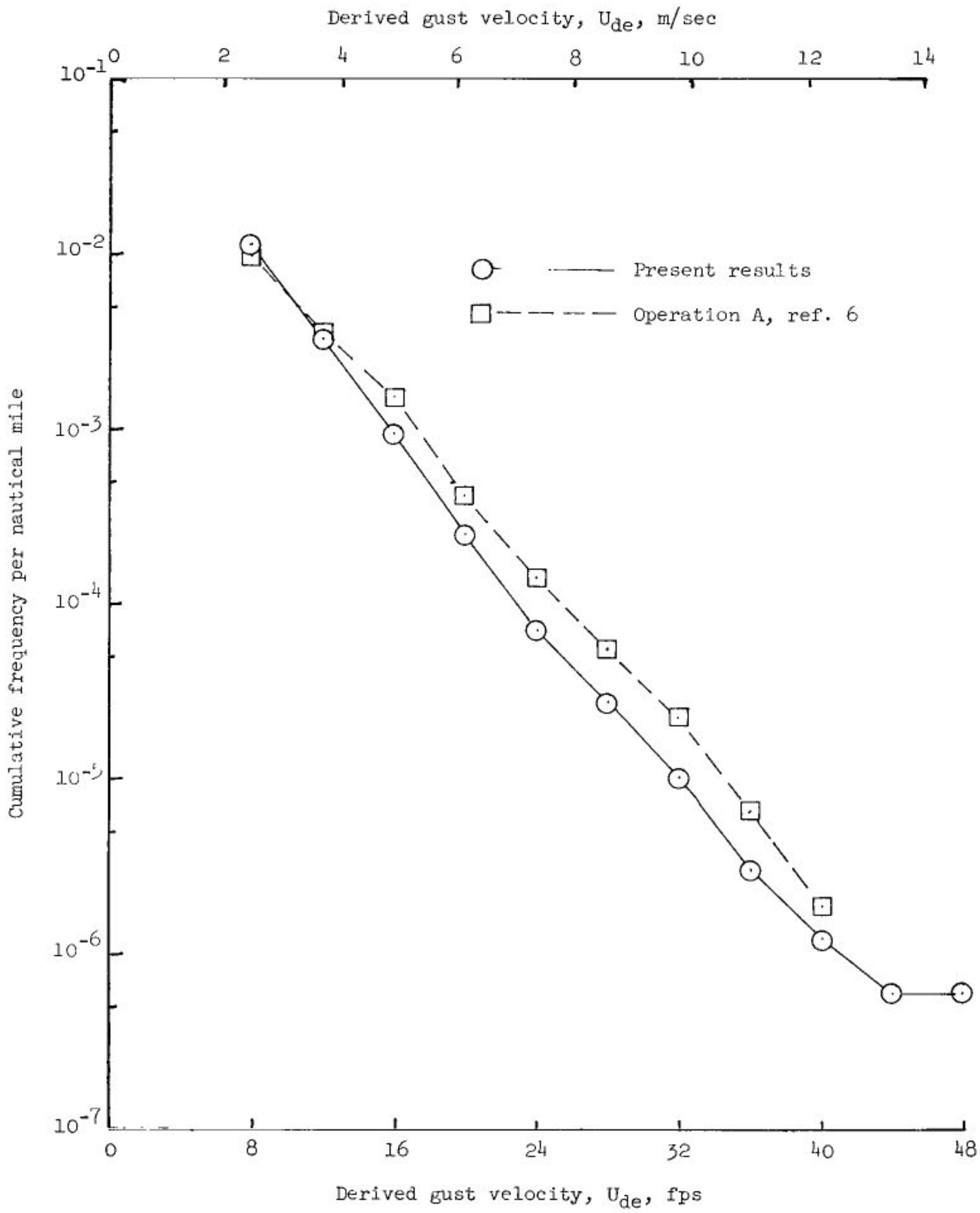
U_{de}		Frequency of occurrence for –							
		0 to 10 000 ft (0 to 3.05 km)		10 000 to 20 000 ft (3.05 to 6.10 km)		20 000 to 30 000 ft (6.10 to 9.14 km)		30 000 to 40 000 ft (9.14 to 12.19 km)	
fps	m/sec	Airplane 1	Airplane 2	Airplane 1	Airplane 2	Airplane 1	Airplane 2	Airplane 1	Airplane 2
4 to 8	1.22 to 2.44	785	612	701	940	1824	1890	1914	2003
8 to 12	2.44 to 3.66	3678	3758	571	642	804	911	1379	1612
12 to 16	3.66 to 4.88	1573	1435	135	162	142	129	152	224
16 to 20	4.88 to 6.10	486	417	37	31	39	32	50	42
20 to 24	6.10 to 7.32	138	104	15	8	21	5	14	20
24 to 28	7.32 to 8.53	31	21	5		5	2	4	8
28 to 32	8.53 to 9.75	13	11	0		4		6	2
32 to 36	9.75 to 10.97	8	3	1				0	0
36 to 40	10.97 to 12.19	4	0					0	0
40 to 44	12.19 to 13.41	0	1					0	1
44 to 48	13.41 to 14.63	0						1	
48 to 52	14.63 to 15.85	1							
Totals		6717	6362	1465	1783	2839	2969	3520	3912
Hours		365.9	353.0	195.3	189.6	509.3	419.3	877.4	855.0
Av. true airspeed, knots		265.7	267.1	426.6	432.2	490.7	490.0	489.7	490.1
Nautical miles.		9.72×10^4	9.43×10^4	8.33×10^4	8.20×10^4	2.50×10^5	2.05×10^5	4.30×10^5	4.19×10^5



(a) Altitude intervals of 10 000 feet (3.05 km).

Figure 10.- Cumulative frequency distributions of derived gust velocity per nautical mile.

period of time so that the environment of the two operations would be expected to be similar. In figure 10(b) a comparison is presented of derived gust velocity for the combined sample and that for operation A of reference 6. Because of an incomplete count near the reading threshold, the frequencies at the lower values of gust velocity are considered inaccurate; therefore, the frequencies for derived gust velocities less than 8 fps (2.4 m/sec) have been omitted from the figures. The curves of figure 10(b) show the



(b) Comparison of two operations.

Figure 10.- Concluded.

present operation to be slightly less severe, but the agreement between the two is nevertheless reasonably good.

Operating airspeeds and altitudes.- A comparison of the overall average airspeeds within 5000-foot (1.52-km) altitude intervals with various airplane placard and recommended operational speeds is shown in figure 11. It may be seen in the figure that, over most of the altitude range, the average airspeeds were higher than both the maneuvering speed V_A and the gust penetration speed V_B. The difference between the average speed and V_{NO}/M_{NO} speeds becomes smaller as altitude increases. The minimum difference occurs in the altitude interval from 35 000 to 40 000 feet (10.7 to 12.2 km). For that altitude interval, the weighted average altitude is closer to 36 000 feet (11 km) than to 37 500 feet (11.4 km) so that the minimum difference between average airspeeds and M_{NO} is somewhat larger than is shown in the figure. Although the average speeds at altitudes above 30 000 feet (9.1 km) are close to the placard speed, data on exceedances of the placard speed for the present operation given in section IV of reference 3 (airplane type III) show that no exceedances occurred above 20 000 feet (6.1 km). Although no later evaluation was made of placard-speed exceedances for the present operation than that reported in reference 3, general record examination and evaluations made of other operations indicated that a noticeable decrease in the number and amplitudes of exceedances of

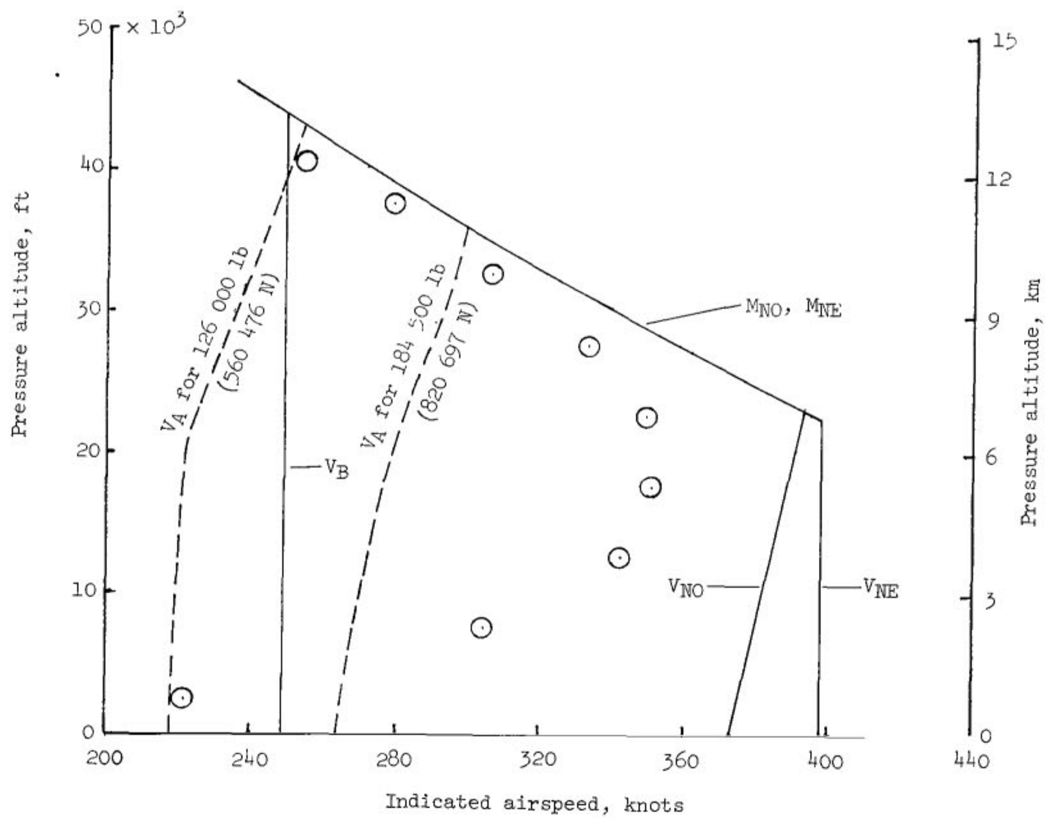


Figure 11.- Average indicated airspeeds in 5000-foot (1.52-km) altitude intervals.

the placard speed occurred following changes in the placard-speed markings and overspeed-warning margins subsequent to the collection of the data presented in reference 3. The operational limits V_{NO}/M_{NO} and V_{NE}/M_{NE} have been superseded in Federal Aviation Regulations but were in effect at the time the present data were collected.

As an indication of the airspeed operating practices in turbulence, figure 12 shows the average and range of airspeed at which derived gust velocities of 20 fps (6.1 m/sec) or greater were experienced together with the average airspeeds and V_B taken from figure 11. The speeds at which the more severe turbulence was encountered are generally much lower than the average speeds, indicating that slowdown for turbulence was practiced. The speeds at the higher end of the ranges shown generally occurred near the beginning of a patch of turbulence before the pilot had an opportunity to slow the airplane. The airplanes were equipped with weather radar, but airline practice regarding the use of it is not known. Except at altitudes below 5000 feet (1.52 km) and above 40 000 feet (12.2 km), most of the speeds at which turbulence was encountered were in excess of the gust penetration speed. Data for the highest altitude interval are plotted at 40 500 feet (12.3 km) in figures 11 and 12 since all the recorded time above 40 000 feet was spent between 40 000 and 41 000 feet (12.2 and 12.5 km).

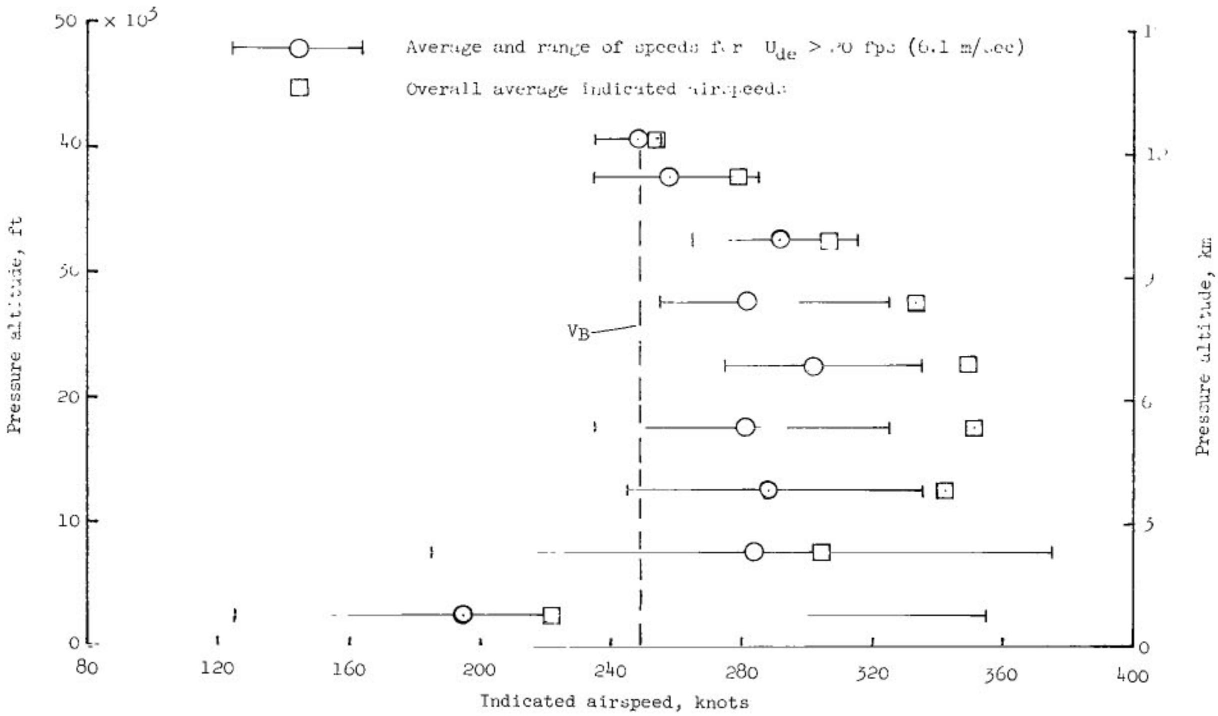
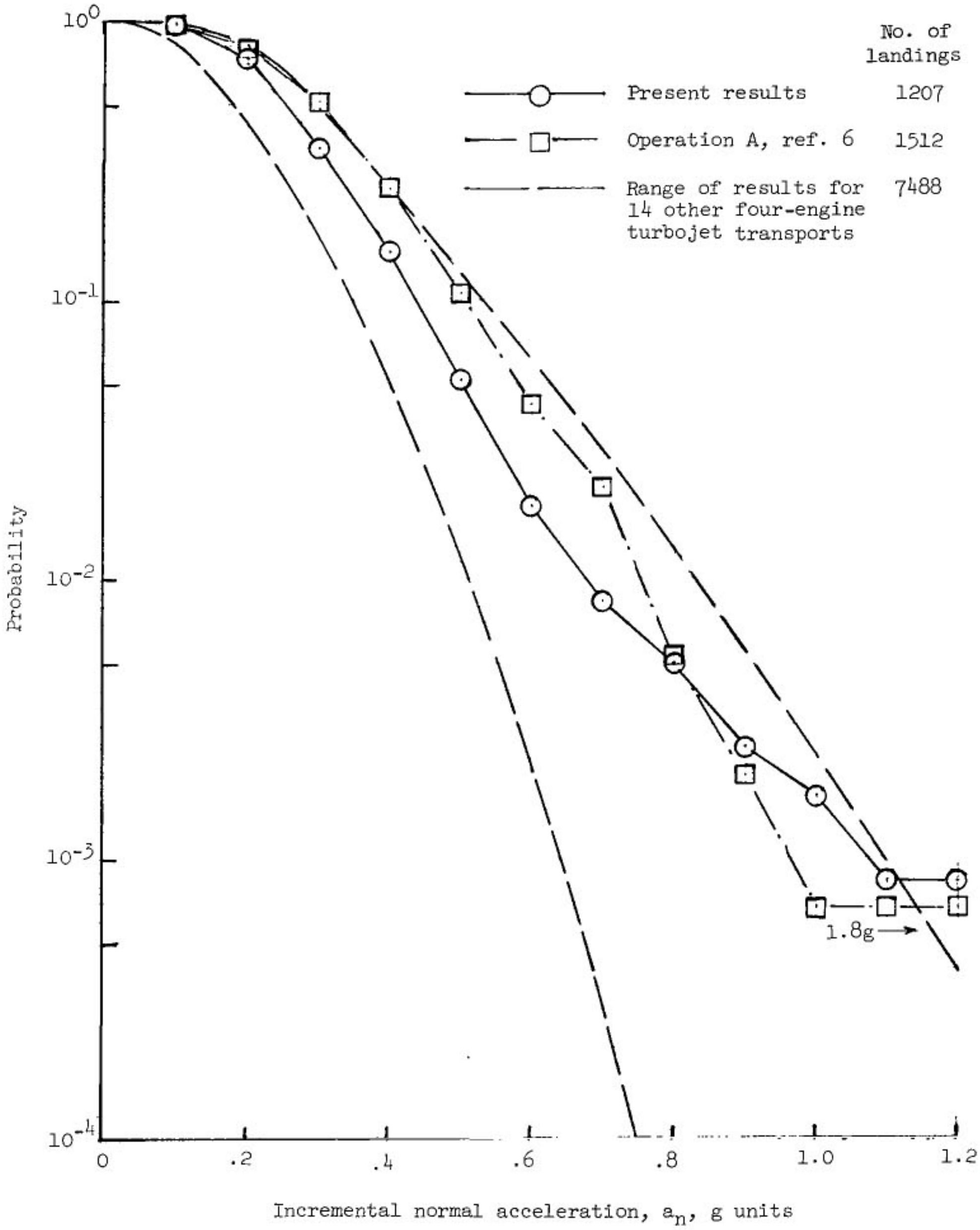


Figure 12.- Average and range of airspeeds at which derived gust velocities greater than 20 fps (6.1 m/sec) were encountered.

Accelerations Due to Landing Impacts

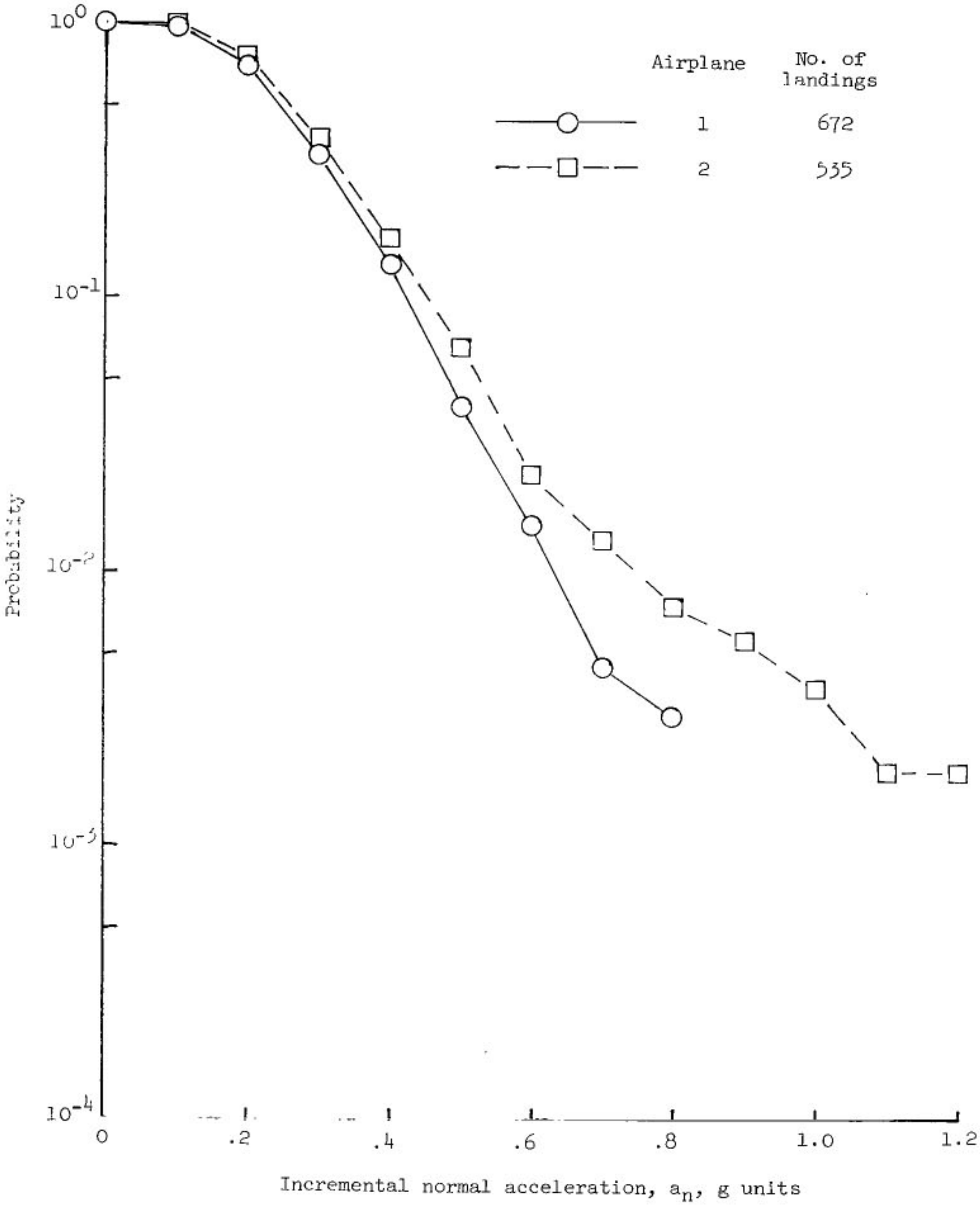
The probability of exceeding given values of incremental normal acceleration at landing impact shown for the present operation by the circular symbols in figure 13(a) indicates that the experience for the present operation falls near the middle of the range of results of 7488 landings for 14 other four-engine turbojet transports. The results of



(a) Comparison of two operations and 14 other turbojet transports.

Figure 13.- Probability of exceeding given amplitudes of landing-impact accelerations.

the present operation are less severe than that of operation A of reference 6 over most of the acceleration range. The maximum landing impact for the present operation was 1.2g whereas that for operation A of reference 6 was 1.8g. In each case, these extreme values represent only one landing. The results shown in figure 13(b) indicate that no significant



(b) Individual airplane samples.

Figure 13.- Concluded.

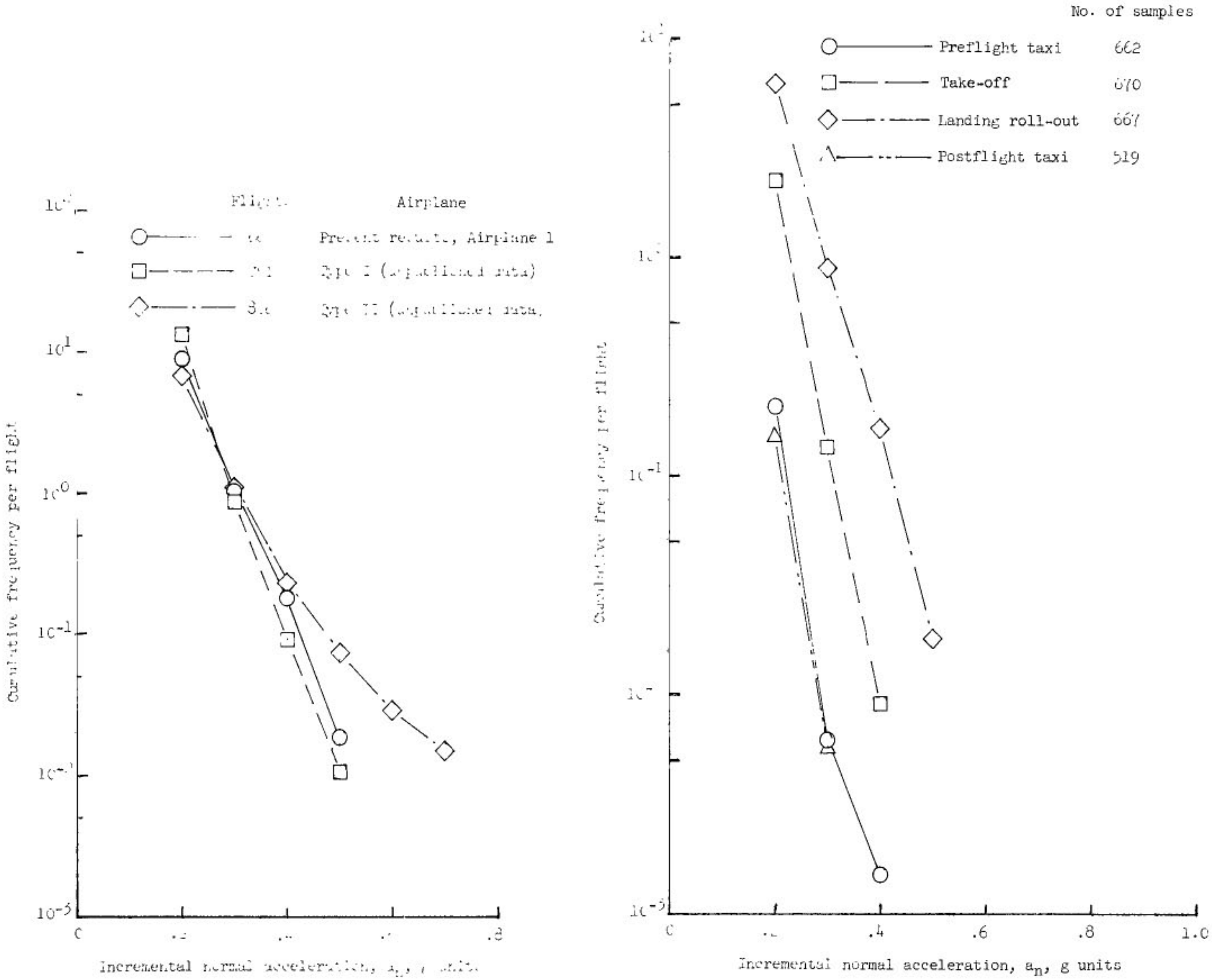
difference in landing-impact experience existed between the two individual airplanes except for the extreme values which were 0.8g and 1.2g for airplanes 1 and 2, respectively.

Accelerations Due to Ground Operations

Frequency distributions of positive and negative accelerations classified as occurring during preflight taxi, take-off, landing roll-out, and postflight taxi and by airspeed intervals for take-off and landing roll-out are listed in table VI. The cumulative frequency distribution of total ground-induced accelerations (i.e., total of four ground-operation classifications) per flight is shown in figure 14(a) together with corresponding distributions for unpublished data for two other types of four-engine turbojet transports. The number of flights indicated for each distribution represent the average of the number of data samples in the four classifications into which the data were divided. Except for the higher maximum acceleration for the type II airplane, the three distributions are quite similar. Cumulative frequency distributions of accelerations per flight for the major classifications of preflight taxi, take-off, landing roll-out, and postflight taxi are shown in figure 14(b). Accelerations were experienced most frequently during the landing roll-out, followed by take-off, and the two taxi phases. The difference in frequency of occurrence between successive levels at 0.4g is approximately ten to one. The reason for the high frequency count for the landing roll-out is the existence of the large number of landing accelerations immediately associated with the initial impact. This also

TABLE VI.- FREQUENCY DISTRIBUTIONS OF INCREMENTAL NORMAL ACCELERATIONS EXPERIENCED DURING GROUND OPERATIONS

Incremental normal acceleration, a_n, g units	Frequency of occurrence for -								Total frequency of occurrence
	Preflight taxi	Take-off			Landing roll-out			Postflight taxi	
		0 to 80 knots	80 to 120 knots	120 to 140 knots	140 to 120 knots	120 to 80 knots	80 to 0 knots		
-0.5 to -0.6					2	2			4
-0.4 to -0.5			1	2	34	4			41
-0.3 to -0.4	1		7	47	201	49	4		309
-0.2 to -0.3	49	36	202	426	1271	590	161	38	2773
Negative total	50	36	210	475	1508	645	165	38	3127
0.2 to 0.3	85	94	272	366	967	430	127	39	2380
0.3 to 0.4	3	6	11	12	197	31	2	3	265
0.4 to 0.5	1			3	55	3	1		63
0.5 to 0.6					7	1			8
Positive total	89	100	283	381	1226	465	130	42	2716
Total pos. and neg.	139	136	493	856	2734	1110	295	80	5843
Number of samples	662	670	670	670	667	667	667	519	



(a) Comparison of three operations.

(b) By portion of ground operation. Airplane 1.

Figure 14.- Cumulative frequency of ground-induced accelerations per flight.

accounts for the slightly larger maximum accelerations which occur within the landing roll-out classification.

CONCLUDING REMARKS

An analysis of VGH records collected on two identical four-engine turbojet transport airplanes during routine commercial operations of a single airline has provided information on incremental normal accelerations and turbulence experienced and on airspeed operating practices. The data cover operations on routes which extended over the eastern half of the United States, with a few additional flights being made to the west coast and to northern South America.

No significant differences were seen in the results for the two individual airplanes operated by the same airline. Comparison of the present results with those for another type of four-engine jet transport operated over a very similar route structure indicated similar experience in gust and operational maneuver accelerations and in derived gust velocities. The present airplanes experienced slightly less severe check-flight maneuver and landing-impact accelerations than did the airplanes used for comparison. The airplanes were operated at speeds close to the placard limit, particularly at the higher altitudes where the airplane was Mach limited. The observance of speed reduction for turbulence was apparent from the data when higher levels of turbulence were considered. The frequency of occurrence of landing-impact accelerations and accelerations resulting from ground operations for the present results were of the same order of magnitude as for other types of turbojet transport airplanes.

Langley Research Center,
National Aeronautics and Space Administration,
Langley Station, Hampton, Va., October 7, 1969.

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