NASA TECHNICAL NOTE

NASA TN D-4330

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

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SUMMARY

An analysis of VGH records collected on one type of four-engine turbojet transport during routine commercial operations on two airlines has provided information on acceleration, turbulence, and airspeed operating practices. The data cover operations of two airplanes by one airline on eastern United States and Caribbean routes and of one airplane operated by a second airline on routes which ranged along the east coast of the United States, across the Caribbean Sea and along the west coast of South America.

For the two airplanes operated by the same airline, the results were very similar in regard to the gust-velocity experiences and the accelerations caused by gusts, operational maneuvers, check-flight maneuvers, and landing impact. The results indicated that the acceleration experiences, the gust velocity experiences, and the airspeed operating practices were not significantly different for the airplanes operated by the two airlines. The amount of rough air encountered at various altitudes and the gust velocities experienced during both operations were in overall agreement with previously published estimates of the gust environment. In general, the airspeeds in rough air (gust velocity $\geqq 2$ fps (0.6 m/sec)) were approximately equal to the airspeeds in smooth air. The results indicated, however, that the airspeeds in heavy turbulence (gust velocities higher than 20 fps (6.1 m/sec)) were generally lower than the average operating speeds.

INTRODUCTION

Concurrent with the introduction of turbine-powered airplanes into commercial transport operations, the NASA initiated a program for collecting data on normal acceleration, airspeed, and altitude from routine airline operations. These measurements are being utilized to provide statistical data on a number of operational aspects of the turbine-powered aircraft, such as accelerations experienced during gusts, maneuvers, and oscillations; operating practices; and landing impact accelerations. This program is a continuation of the long-standing NACA/NASA effort to collect operational data on commercial transport airplanes. 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 6.

This paper presents an analysis of the accelerations experienced, the gust velocities encountered, and the operating airspeeds and altitudes of one type of four-engine turbojet transport during operations on two airlines. Some of the preliminary data from these operations have been reported in references 6 and 7, but are included herein to provide a summary of the operations. Information on exceedances of placard speeds is not included because it was presented in reference 7, and subsequent changes in the placard speed markings and overspeed warning margins detract from its present utility.

SYMBOLS

The units used for 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 aspect ratio

a_n incremental normal acceleration, g units

c wing chord, ft (meters)

g acceleration due to gravity, 32.2 ft/sec^2 (9.81 meters/second^2)

K_g gust factor, $\dfrac{0.88\mu_g}{5.3 + \mu_g}$

m lift-curve slope, per radian, $\dfrac{6\ A \cos \Lambda}{A + 2 \cos^2\Lambda} \left(\dfrac{A + 2 \cos \Lambda}{A\sqrt{1 - M^2\cos^2\Lambda} + 2 \cos \Lambda}\right)$

M Mach number

M_{NE} never-exceed Mach number

M_{NO} normal operating limit Mach number

S wing area, sq ft (meters^2)

U_{de} derived gust velocity, fps (meters/second)

V_e equivalent airspeed, fps (meters/second)

V_{NE} never-exceed speed, knots (indicated)

V_{NO} normal operating limit, airspeed, knots (indicated)

W airplane weight, lbf (newtons)

Λ sweep angle of wing quarter-chord line, deg

μ_g airplane mass ratio, $\frac{2W}{m \rho c g S}$

ρ atmospheric density, slugs/ft^3 (kilograms/meter^3)

ρ_o atmospheric density at sea level, slugs/ft^3 (kilograms/meter^3)

INSTRUMENTATION AND SCOPE OF DATA

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 located in the main-landing-gear wheel well near the airplane center of gravity. Pressure lines for the recorder were connected to the copilot's airspeed system.

The two airplanes of operation A were operated on routes covering the eastern half of the United States and part of the Caribbean Sea. The airplane of operation B was operated on routes which extended along the east coast of the United States, across the Caribbean Sea, and along the west coast of South America.

The scope of the data samples for the two airplanes (A-1 and A-2) of operation A and the one airplane (B-1) of operation B is summarized in table I. As shown in the table, the sizes of the data samples from the individual airplanes ranged from about 1240 flight hours to 1700 flight hours. Airplane check and pilot-training flights accounted for 53 to 134 flight hours per airplane. The histograms of flight durations are given in figure 1(a) and the histograms of altitude are given in figure 1(b) for the two operations.

As shown in table I, the data samples were collected between January 1960 and December 1962. The records were rather uniformly spaced throughout the recording period for airplanes A-2 and B-1. Although irregular intervals occurred between records received from airplane A-1, the longer recording period for this sample tended to compensate and to give, on a monthly basis, a uniform sample. Consequently, it is thought that each of the data samples is representative of year-round operations.

Airplane characteristics pertinent to the evaluation of the data are given in table II. Inasmuch as the two models of the airplane used in operations A and B are geometrically identical, single values are given for all characteristics except weights and wing loadings.

EVALUATION OF DATA AND RESULTS

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 were 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 continuous turbulent area which produced at least one acceleration corresponding to a gust velocity of about 2 fps (0.6 m/sec) or higher.

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 Due to Gusts

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. In the event that a gust acceleration was superimposed on a maneuver acceleration, the maneuver acceleration was used as the reference. The evaluation of gust accelerations consisted of reading positive and negative incremental acceleration peaks above a threshold of 0.2g using the

1 g position of the acceleration trace as a reference. Only the maximum peak for each crossing of the reference and threshold was read. For each acceleration peak read, the corresponding airspeed and altitude were also read.

The frequency distributions of the combined (positive and negative) accelerations by flight condition and for the total samples are given in table III for each airplane. The flight hours, nautical miles, and average true airspeed 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 2(a) the cumulative frequency distributions of accelerations per nautical mile are presented by flight condition for each airplane. These distributions were formed by progressively summing the frequency distributions of table III, beginning with the largest acceleration, and dividing each sum by the flight distance of the sample. The cumulative frequency per mile of accelerations for the total sample for each airplane of operation A is given in figure 2(b) and for the total sample of the two operations is given in figure 2(c).

Accelerations Experienced During Maneuvers

Operational and check-flight accelerations were evaluated by reading each peak acceleration greater than a value of ±0.1g relative to the 1 g reference. Only the maximum value for each crossing of the reference was read. Frequency distributions of the positive and negative operational accelerations by flight condition and total are given in table IV(a). Frequency distributions of positive and negative check-flight accelerations are given in table IV(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 spent in check flights are computed as the product of the overall average true airspeed and the total time listed in the table. Cumulative frequency distributions of positive and negative operational maneuver accelerations for each airplane are given in figure 3(a). Cumulative frequency distributions of combined operational maneuver accelerations by flight condition are given in figure 3(b). The distributions of figure 3(b) were divided by the flight distance of the sample, and the resulting distributions are presented in figure 3(c). Cumulative frequency distributions per mile of combined operational maneuver accelerations for operations A and B and for the airplane of reference 5 are given in figure 3(d). Cumulative frequency distributions per mile of positive and negative check-flight maneuver accelerations are given in figure 4. Total check-flight miles were used in computing each point for either positive or negative accelerations. The airplane of reference 5 was the same model as those flown in operation A but was flown by a third operator. The number of flight hours in the sample of reference 5 was about the same as that for airplane A-1.

Accelerations Experienced During Oscillations

Sample records shown in figure 5 illustrate four types of oscillations noted on records from the present airplanes. In some cases the motions were evident on the air-speed and altitude traces as well as on the acceleration trace. Accelerations were evaluated by counting peaks above a threshold of ±0.05g. The duration of each occurrence of oscillation was noted and used to calculate the percent of flight time spent in oscillations. The flight time and nautical miles of the sample evaluated and the percent of time oscillations occurred for each sample are listed in table V. Figure 6 indicates the percent of flight time that oscillations greater than a given magnitude occurred. The cumulative frequency distributions of oscillatory accelerations per mile of flight are shown in figure 7 for each airplane.

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 figures 8(a), (b), and (c) for airplanes A-1, A-2, and B-1, respectively. The distributions from the various sources were combined for each airplane as an indication of the total in-flight loads and are compared in figure 9.

Turbulence

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 calculating the ratio of the time in rough air to the total flight time for each altitude interval. The results are presented in figure 10 for operations A and B, together with similar data from reference 10 for a wide variety of aircraft.

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 11:

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

The airplane weights W were, as mentioned previously, based on weights obtained from each 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 part VI of reference 7 and is shown in figure 11.

Frequency distributions of derived gust velocities for combined positive and negative values are presented in table VI by altitude intervals of 10 000 feet (3.05 km).

Cumulative frequency distributions of derived gust velocity per mile of flight for the total sample of each of the three airplanes are presented in figure 12. In figure 13 similar distributions are presented by altitude increments of 10 000 feet (3.05 km) for operations A and B. The values of flight miles used in computing these distributions correspond to those flown within each altitude increment. For comparison, curves of estimated airplane gust experience based on the data of reference 10, are included in figure 13. A reduction in gust velocity by a factor of 20 percent had been made in the data of reference 10 to account for airplane flexibility. In order to make the comparison of the present data and that of reference 10 more compatible, this 20 percent has been restored to the data of reference 10. Frequencies at the lower values of gust velocity have been omitted from the figures because these points indicate an apparent dropoff in frequency caused by incomplete frequency counts near the reading threshold.

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 or smooth air. The average indicated airspeeds for operations A and B within each 5000-foot (1.52-km) altitude interval are plotted in figure 14 together with some of the placard and recommended operational speeds. As shown in figure 14, the recommended speed in rough air varies as a function of both gross weight and altitude. (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.)

The distributions of airspeeds in smooth and rough air by flight condition for operations A and B are presented in figure 15. The average airspeeds in rough and smooth air within each 5000-foot (1.52-km) altitude interval are shown in figure 16 for operations A and B. As an indication of the airspeed operating practices in heavier turbulence than that associated with the low threshold (2 fps, or 0.6 m/sec) on which the results of figures 15 and 16 were based, the average airspeeds and the range of airspeeds at which gust velocities higher than 20 fps (6.1 m/sec) were encountered are shown by altitude in figure 17. For comparison with these speeds, the overall average speeds in each altitude interval are also shown in the figure.

Accelerations Due to Landing Impacts

The initial positive impact acceleration was read for a number of landings for both operational and check flights. For check flights, every available landing record was read in order to obtain the largest possible sample. The samples range from 569 to 636 operational landings per airplane and from 85 to 222 check-flight landings per airplane. The probability distributions of landing-impact accelerations are presented in figure 18 for operational flights, check flights, and combined operational and check flights for each of the three airplanes.

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 7 and are estimated to be:

Acceleration, g units	±0.05
Indicated airspeed, knots:	
At 100 knots	±6
At 350 knots	±2

Indicated pressure-altitude errors are calculated as follows:

At 2000 feet (0.61 km)	±300 feet (91 m)
At 20 000 feet (6.10 km)	±500 feet (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 for gross errors 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, the number of counts above 0.3g may have a reliability of about ±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.

DISCUSSION

The distributions of flight durations given in figure 1(a) show that the flights for both operations ranged up to 5 hours' duration. There was a higher proportion of short (less than 1 hour) flights for operation A, however, with the result that the average flight durations were 120 minutes and 153 minutes for operations A and B, respectively.

Figure 1(b) shows that, for both operations, most of the flight time was spent between 25 000 and 35 000 feet (7.62 and 10.7 km) and that the maximum pressure altitude recorded was 42 000 feet (12.8 km). The percentages of total flight time spent at altitudes below 25 000 feet (7.62 km) were slightly larger for operation A than for operation B. The average altitude (from take-off to landing) was therefore slightly lower for operation A than for operation B (see table I).

Accelerations

Accelerations due to gusts.- The results in table III show that for each airplane the larger portion of the total gust accelerations greater than the 0.2g threshold occurred in the cruise condition. For the two airplanes of operation A, approximately one-half of the total gust accelerations occurred in cruise, and the least number occurred during climb. For operation B, approximately three-fourths of the total gust accelerations occurred during cruise, and the rest occurred about equally in the climb and descent conditions. Figure 2(a) shows, however, that for each airplane the cumulative frequency of gust accelerations per mile of flight was lowest during the cruise condition and about equal during the climb and descent. The results of figure 2(b) show that the total gust experiences for the two airplanes of operation A are almost identical for accelerations less than about ±0.6g. The difference between the two distributions for higher accelerations is ascribed to sampling variations. Consequently, the gust acceleration experiences for the two airplanes of operation A are considered to be essentially equal. Figure 2(c) shows that the gust acceleration experience of operation A is slightly greater than for operation B. As noted in table II, however, the airplane involved in operation B had a maximum wing loading approximately 12 percent higher than the airplanes of operation A and, with other factors being equal, this would account for the difference in gust acceleration experiences shown in figure 2(c).

Operational maneuver accelerations.- The results in figure 3(a) show that for each airplane the total number of operational maneuver accelerations higher than ±0.1g were divided approximately equally between positive and negative values. However, in each case the distribution for the positive values has a smaller slope and extends to higher values than the distribution for the negative values. Thus, for the present airplanes the distributions of accelerations are not symmetrical about 1g, but rather, show that incremental accelerations tend to be larger in magnitude for positive maneuvers than for negative maneuvers.

The results in figure 3(b) show that for each airplane the total accelerations were roughly equal for the climb, cruise, and descent flight conditions. In terms of the frequency of occurrence per mile of flight, however, figure 3(c) shows that the frequency during cruise was roughly one-tenth that for the climb and descent flight conditions. The reason that the frequencies for the climb and descent conditions are significantly higher than those for cruise is that more frequent turns and changes in altitude and attitude are inherently required during climbout, descent, and approach operations.

Figure 3(d) shows that above 0.5g operational maneuver accelerations occurred roughly three times as frequently in operation A as in operation B. The frequencies for both operation A and operation B are higher than those for the operations of reference 5. These differences apparently reflect differences in operating practices and requirements. Such variations have been noted for operations involving other types of airplanes and are not considered to be unusual.

Check-flight maneuver accelerations.- Figure 4 shows differences of roughly 3 to 1 among the check-flight maneuver-acceleration experiences for airplanes A-1, A-2, and B-1. The frequencies of the present investigation are an order of magnitude higher than those of the operations of reference 5. The percentages of the total flight times which were spent in check flights are given in the following table:

Airplane	Percent of total flight time
A-1	10.8
A-2	4.9
B-1	3.1
Ref. 5	1.4

Thus, there is approximately an 8:1 variation among the airplanes with respect to the amount of time spent in check flights. This accounts to a large extent for the differences noted in the check-flight maneuver-acceleration experiences shown in figure 4. Similar differences among the check-flight experiences of other types of airplanes have been observed in previous analyses. (See ref. 6.)

The results in figure 4 show that positive check-flight maneuver accelerations occurred more frequently than did negative accelerations. This asymmetry is similar to that previously noted for operational maneuver accelerations (fig. 3(a)).

Oscillatory accelerations.- Two distinct types of oscillatory accelerations were recorded on the present airplanes. These two types have been denoted as constant-amplitude oscillations (see figs. 5(a), 5(b), and 5(c)) and divergent oscillations (see fig. 5(d)). The most frequent oscillations were of the constant-amplitude type. Generally, they were symmetrical about 1 g, had periods from about 10 to 40 seconds, and had amplitudes between ±0.05g and ±0.2g. They persisted from a few minutes to several hours.

Oscillations of the divergent type (fig. 5(d)) occurred infrequently, had maximum amplitudes of ±0.5g, and, in some cases, apparently resulted from the degeneration of a constant-amplitude oscillation into a divergent condition.

Oscillatory accelerations similar to those in figures 5(a), (b), and (c) are not peculiar to the present airplanes in that they have been noted with several other types of turbine-powered transports (ref. 7). Specific causes of the oscillations of the present airplanes are not known. It is thought, however, that they resulted mainly from "hunting" of the autopilot in combination with the airplane stability and control system characteristics.

Figure 6 shows that the percent of total flight time that oscillations higher than ±0.05g were experienced ranged from about 6 percent for airplane A-1 to 20 percent for airplane B-1. Accelerations higher than about ±0.20g, however, were experienced a larger percentage of the flight time by airplane A-1 than by the other two airplanes.

Figure 7 shows that the frequencies of occurrence of oscillatory accelerations for the three airplanes differ by a factor of about 5 for accelerations below or equal to ±0.1g and about 10 for higher accelerations. These differences appear to be a direct reflection of the differences among the percentages of flight time that the three airplanes experienced oscillations. (See fig. 6.)

Summary of Flight Accelerations

Comparison of accelerations from various sources.- Figure 8 shows that the relative contributions of the various acceleration sources to the total acceleration experience were essentially the same for the three airplanes. In each case, the frequency of occurrence per mile for accelerations higher than about 0.3g followed a decreasing order from check-flight maneuvers to gusts to operational maneuvers. For lower values of accelerations, the frequencies associated with the three sources differ by a factor of less than about 3, with gusts being the predominant source. Oscillatory accelerations appear to be negligible in comparison with the accelerations caused by gusts and maneuvers.

Comparison of total acceleration experiences.- The combined distributions of accelerations from the various in-flight sources (fig. 9) indicate little difference in the total acceleration experiences for the two airplanes of operation A. The distribution for airplane B-1 indicates frequencies of the order of 50 percent of those of the airplanes of operation A.

Turbulence

Amount of rough air.- Figure 10 shows that, for altitudes below approximately 20 000 feet (6.1 km), the percentage of the flight time spent in rough air was greater for operation A than for operation B. At higher altitudes, the percentages of rough air encountered in the two operations were approximately equal. From the overall point of view, the results for both operations are in good agreement with the estimated variation in the amount of rough air with altitude given in reference 10.

Gust-velocity experience.- The results in figure 12 show that the gust-velocity experiences for the two airplanes of operation A were very similar. The gust-velocity experience for operation B is approximately one-half that for operation A. This result is apparently due mainly to rough air having been encountered a smaller percentage of the time in operation B than in operation A, particularly at low altitudes. (See fig. 10.)

The results in figure 13 show that, for the most part, the gust experiences within given altitude intervals were roughly the same for operations A and B. The largest difference is in the altitude range from 0 to 10 000 feet (3.1 km) where the gust experience for operation B is approximately one-half that for operation A. In figure 13, differences of about 2 to 1 are noted in some instances between the present results and the estimated gust-velocity distributions based on reference 10. (As previously mentioned, the gust-velocity values from ref. 10 have been multiplied by a factor of 1.2 as a means of approximately accounting for dynamic amplification.)

In general, however, there is no consistent trend in the differences between the present results and those of reference 10, and existing differences are within the sampling reliability of the present data. From the overall point of view, therefore, the present results and those of reference 10 are considered to be in good agreement.

Airspeeds

The results in figure 14 show that the average indicated airspeeds for operations A and B differed by less than 10 knots except in the altitude range of 10 000 to 25 000 feet (3.1 to 7.6 km). In this altitude range, the average airspeeds for operation A were approximately 20 knots higher than the average speeds for operation B. For both operations, the average speeds increased with altitude up to about 30 000 feet (9.1 km), and above this altitude decreased with increasing altitude. Below 30 000 feet, the average airspeeds were substantially less than the V_{NO} and M_{NO} airspeeds and at higher altitudes were approximately 10 knots lower than the M_{NO} speed. In the altitude range from 5000 to 35 000 feet (1.5 to 10.7 km), the average airspeeds were considerably higher than the recommended maximum speeds in rough air.

The results in figure 15 show that only small differences exist between the distributions of airspeeds in rough and smooth air within each flight condition for both operations. High speeds during descent were more frequent in operation A than in operation B. Both operations of figure 15 show evidence of slowdown in rough air, in contrast to piston-airplane practice, probably because the turbojet airplanes fly at speeds nearer design cruise speed than did piston airplanes.

Figure 16 shows that for operation A the average speeds in rough and smooth air were approximately equal except in the altitude range from 10 000 to 25 000 feet (3.1 to 7.6 km). In this altitude range, the average speeds in rough air were approximately 10 to 15 knots lower than the average speeds in smooth air. For operation B, the airspeeds in rough and smooth air were about equal throughout most of the altitude range. For both operations, the results show a higher airspeed in rough air than in smooth air for altitudes below 5000 feet (1.5 km). As previously mentioned, the results in figure 16 are based on a very low gust-velocity threshold (2 fps or 0.6 m/sec) as the definition of rough air. Consequently, the average airspeed values given in figure 16 for flight in rough air reflect a substantial amount of flight in light turbulence for which airspeed showdown would not be anticipated.

The results in figure 17 show that for both operations the average of the airspeeds at which gust velocities higher than 20 fps (6.1 m/sec) were encountered is substantially lower than the average speeds for overall operations. The results also show that some gusts greater than 20 fps (6.1 m/sec) were encountered at speeds higher than the overall average speeds. Thus, airspeeds were usually, but not always, reduced for traverse of heavy turbulence. (It may be noted in figure 17 that airspeeds as low as 110 knots are indicated for operation A between 20 000 and 25 000 feet (6.1 to 7.6 km). These low speeds represent underspeeding after an apparently deliberate slowdown to traverse turbulence. This particular case was reported in section VII of reference 7 as an "unusual event.")

Landing-Impact Accelerations

Figure 18(a) shows that there were no significant differences among the landing-impact accelerations experienced during operational flights of the three airplanes. The results in figure 18(b) show that the maximum landing-impact acceleration experienced during check flights was considerably higher for airplane A-2 than for the other two airplanes. The combined results for operational and check flights (see fig. 18(c)) show that, in general, the overall landing-impact acceleration experiences for the three airplanes are in good agreement. Regarding the maximum landing-impact acceleration, however, a single value of 1.8g was experienced by airplane A-2 (in a check flight), as compared with values of 0.8g and 0.9g for the other two airplanes.

CONCLUDING REMARKS

An analysis of VGH records collected on one type of four-engine turbojet transport during routine commercial operations on two airlines has provided information on the normal accelerations, turbulence, and airspeed operating practices. The data cover operations of two airplanes by one airline on eastern U.S. and Caribbean routes and of one airplane operated by a second airline on routes which ranged along the east coast of the United States, across the Caribbean Sea, and along the west coast of South America.

For the two airplanes operated by the same airline, the results were very similar in regard to the gust velocity experiences and the accelerations caused by gusts, operational maneuvers, check-flight maneuvers, and landing impacts. The results indicated that the acceleration experiences, the gust-velocity experiences, and the airspeed operating practices were not significantly different for the airplanes operated by the two airlines. The amount of rough air encountered at various altitudes and the gust velocities experienced during both operations were in overall agreement with previously published estimates of the gust environment. In general, the airspeeds in rough air (gust velocity greater than 2 fps or 0.6 m/sec) were approximately equal to the airspeeds in smooth air. The results indicated, however, that the airspeeds in heavy turbulence (gust velocities higher than 20 fps or 6.1 m/sec) were generally lower than the average operating speeds.

Langley Research Center,
National Aeronautics and Space Administration,
Langley Station, Hampton, Va., September 8, 1967,
126-61-01-01-23.

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TABLE I.- SCOPE OF DATA

	Airplane A-1	Airplane A-2	Airplanes A-1 and A-2 (operation A)	Airplane B-1 (operation B)
Total hours	1242	1426	2668	1705
Operational flights:				
Hours	1107.7	1356.2	2463.9	1651.7
Number	578	649	1227	647
Av. duration, min	115	125	120	153
Av. altitude, ft	27 900	25 700	25 300	27 600
Av. altitude, km	8.5	7.8	7.7	8.4
Av. indicated airspeed, knots	295.4	292.7	293.9	288.7
Climb condition:				
Hours	160.0	187.3	347.4	218.0
Av. altitude, ft	16 000	15 900	15 950	17 500
Av. altitude, km	4.9	4.8	4.9	5.3
Av. indicated airspeed, knots	292.5	290.1	291.2	292.1
Cruise condition:				
Hours	704.4	887.9	1592.3	1167.7
Av. altitude, ft	31 300	31 700	31 500	32 400
Av. altitude, km	9.5	9.7	9.6	9.9
Av. indicated airspeed, knots	306.4	301.9	303.9	297.8
Descent condition:				
Hours	243.2	281.0	524.2	266.0
Av. altitude, ft	12 500	13 000	12 800	14 500
Av. altitude, km	3.8	4.0	3.9	4.4
Av. indicated airspeed, knots	265.7	265.1	265.4	246.3
Check flights:				
Hours	134.5	69.6	204.1	53.4
Number	224	88	312	124
Percent of total time	10.8	4.9	7.6	3.1
Recording period	Jan, 1960 to Dec. 1962	Jan. 1960 to Dec. 1961	Jan. 1960 to Dec. 1962	May 1960 to Sept. 1962

TABLE II.- AIRPLANE CHARACTERISTICS

Span, ft (m)	142.4 (43.40)
Aspect ratio	7.32
Mean aerodynamic chord, ft (m)	22.1 (6.74)
Wing area, sq ft (m^2)	2772.5 (257.57)
Max. take-off weight, lb (N):	
Operation A	276 000 (1 227 709)
Operation B	310 000 (1 378 949)
Max. landing weight, lb (N):	
Operation A	193 000 (858 507)
Operation B	199 500 (887 420)
Wing loading based on max. take-off weight, lb/sq ft (N/m^2):	
Operation A	99.5 (4764.1)
Operation B	111.8 (5353.0)

TABLE III.- FREQUENCY DISTRIBUTIONS OF INCREMENTAL GUST ACCELERATIONS BY FLIGHT CONDITION

Normal acceleration (positive and negative), a_n, g units	Frequency of occurrence for –									Total frequency of occurrence		
	Climb			Cruise			Descent					
	Airplane A-1	Airplane A-2	Airplane B-1	Airplane A-1	Airplane A-2	Airplane B-1	Airplane A-1	Airplane A-2	Airplane B-1	Airplane A-1	Airplane A-2	Airplane B-1
0.2 to 0.3	1157	1000	652	2355	3886	3922	1876	2116	713	5388	7002	5287
0.3 to 0.4	361	256	180	364	659	736	445	421	163	1170	1336	1079
0.4 to 0.5	109	85	49	70	124	182	130	124	38	309	333	269
0.5 to 0.6	25	15	16	21	35	46	40	45	9	86	95	71
0.6 to 0.7	12	9	4	4	17	20	8	12	8	24	38	32
0.7 to 0.8	4	2	3	1	5	4	3	2	2	8	9	9
0.8 to 0.9	2	2	0		2	2	1	3	0	3	7	2
0.9 to 1.0			1		1			1	1		2	2
1.0 to 1.1					1						1	
1.1 to 1.2					1						1	
Total	1670	1369	905	2815	4731	4912	2503	2724	934	6988	8824	6751
Hours	160.1	187.3	218.0	704.4	887.9	1167.7	243.2	281.0	266.0	1107.7	1356.2	1651.7
Av. true airspeed, knots	367.8	364.7	375.9	484.3	481.3	480.6	318.0	320.2	304.2	431.0	431.8	438.4
Nautical miles	5.89×10^4	6.83×10^4	8.19×10^4	3.41×10^5	4.27×10^5	5.61×10^5	7.73×10^4	9.00×10^4	8.09×10^4	4.77×10^5	5.86×10^5	7.24×10^5

TABLE IV.- FREQUENCY DISTRIBUTIONS OF MANEUVER ACCELERATIONS

(a) Operational maneuver accelerations by flight condition

Normal acceleration, a_n, g units	Frequency of occurrence for - Climb			Cruise			Descent			Total frequency of occurrence		
	Airplane A-1	Airplane A-2	Airplane B-1	Airplane A-1	Airplane A-2	Airplane B-1	Airplane A-1	Airplane A-2	Airplane B-1	Airplane A-1	Airplane A-2	Airplane B-1
-0.9 to -1.0												
-0.8 to -0.9												
-0.7 to -0.8												
-0.6 to -0.7					1						1	
-0.5 to -0.6	3	2	2		1		1	1		4	4	2
-0.4 to -0.5	26	11	8	4	14		3	2	1	33	27	9
-0.3 to -0.4	100	66	52	43	34	15	15	35	19	158	135	86
-0.2 to -0.3	575	401	282	236	455	197	318	361	188	1 129	1 217	667
-0.1 to -0.2	4 301	2671	2666	5 273	5 126	3221	4 823	3 767	2874	14 397	11 564	8 761
Neg. Total	5 005	3151	3010	5 556	5 631	3433	5 160	4 166	3082	15 721	12 948	9 525
0.1 to 0.2	4 645	3276	3319	5 253	4 642	3334	6 004	5 186	3944	15 902	13 104	10 597
0.2 to 0.3	965	698	689	352	477	362	923	882	699	2 240	2 057	1 750
0.3 to 0.4	212	179	182	81	59	40	163	200	145	456	438	367
0.4 to 0.5	73	44	34	16	10	12	35	39	20	124	93	66
0.5 to 0.6	17	14	6	5	7	3	6	13	6	28	34	15
0.6 to 0.7	3	2	2	1	1		2	2	1	6	5	3
0.7 to 0.8	1	1			1			1	1	1	3	1
0.8 to 0.9	0	1								0	1	
0.9 to 1.0	1									1		
Pos. Total	5 917	4215	4232	5 708	5 197	3751	7 133	6 323	4816	18 758	15 735	12 799
Total pos. and neg.	10 922	7366	7242	11 264	10 828	7184	12 293	10 489	7898	34 479	28 683	22 324
Hours	160.1	187.3	218.0	704.4	887.9	1167.7	243.2	281.0	266.0	1107.7	1356.2	1651.7
Av. true airspeed, knots	367.8	364.7	375.9	484.3	481.3	480.6	318.0	320.2	304.2	431.0	431.8	438.4
Nautical miles	5.89×10^4	6.83×10^4	8.19×10^4	3.41×10^5	4.27×10^5	5.61×10^5	7.73×10^4	9.00×10^4	8.09×10^4	4.77×10^5	5.86×10^5	7.24×10^5

TABLE IV.- FREQUENCY DISTRIBUTIONS OF

MANEUVER ACCELERATIONS – CONCLUDED

(b) Check-flight maneuver accelerations

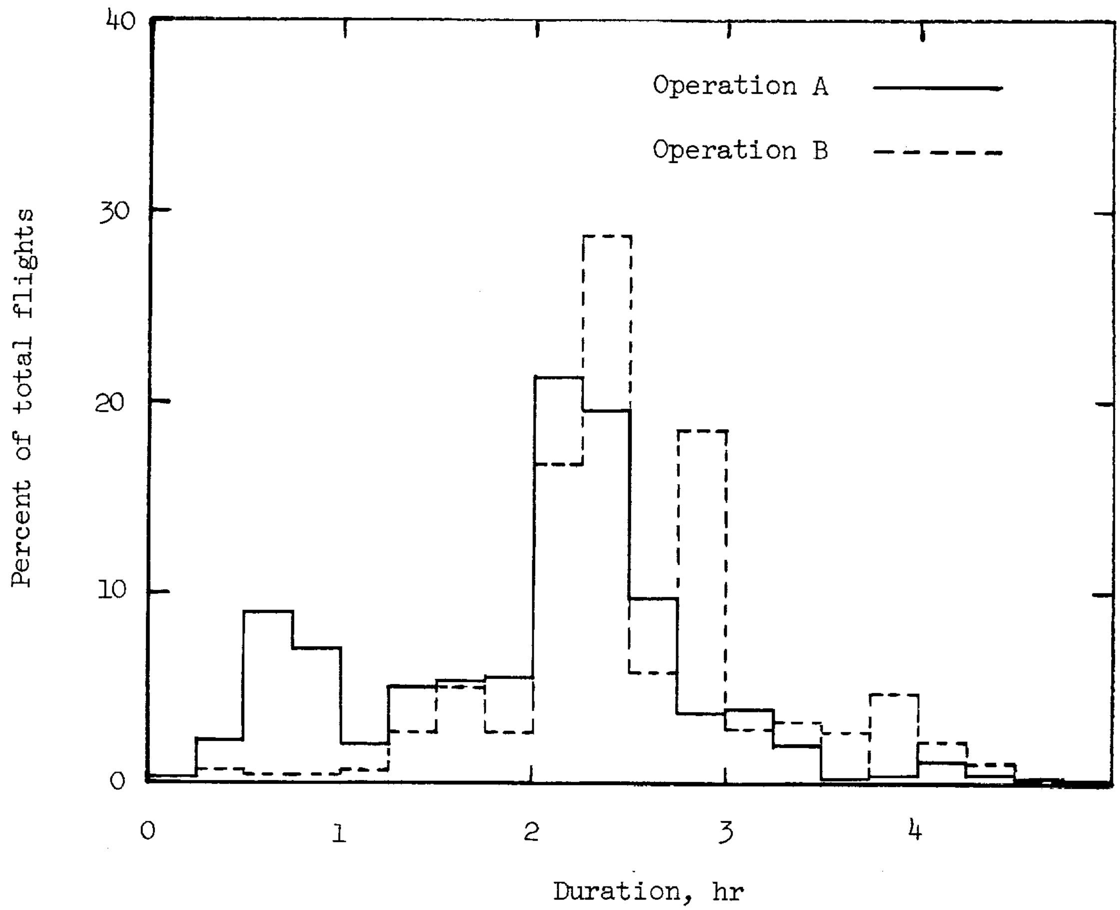
Normal acceleration, a_n, g units	Frequency of occurrence for –		
	Airplane A-1	Airplane A-2	Airplane B-1
1.2 to 1.3	1		
1.1 to 1.2	1	2	
1.0 to 1.1	9	6	
0.9 to 1.0	11	9	6
0.8 to 0.9	24	24	15
0.7 to 0.8	64	78	30
0.6 to 0.7	128	82	68
0.5 to 0.6	266	176	157
0.4 to 0.5	405	256	273
0.3 to 0.4	719	716	526
0.2 to 0.3	2 074	1415	1 755
0.1 to 0.2	5 646	2857	3 916
-0.1 to -0.2	5 269	2217	3 218
-0.2 to -0.3	1 151	521	587
-0.3 to -0.4	243	173	151
-0.4 to -0.5	77	56	37
-0.5 to -0.6	29	25	14
-0.6 to -0.7	10	9	9
-0.7 to -0.8	5	2	1
-0.8 to -0.9	5	1	2
-0.9 to -1.0	1	1	
-1.0 to -1.1		1	
Total	16 138	8627	10 765
Check-flight hours	134.5	69.6	53.4
Total hours	1242.2	1425.8	1705.1
Nautical miles	5.35×10^5	6.16×10^5	7.48×10^5

TABLE V.- DATA SAMPLES EVALUATED FOR ACCELERATIONS EXPERIENCED DURING OSCILLATIONS

Airplane	Hours		Nautical miles		Percent time in oscillations	
A-1	299.95	974.60	1.3×10^5	4.3×10^5	5.8	12.8
A-2	674.65		3.0×10^5		15.9	
B-1	488.05		2.1×10^5		21.4	

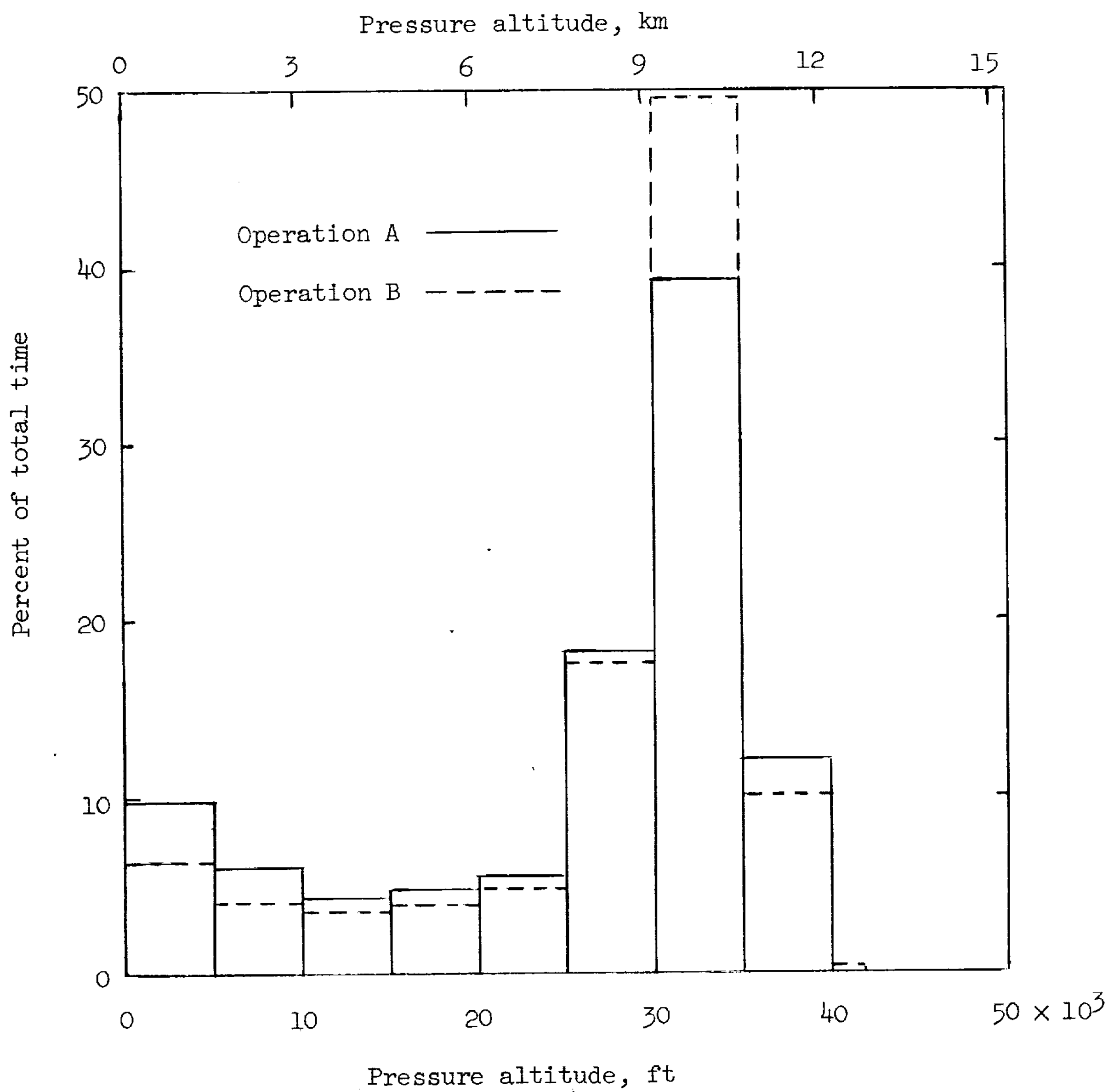
TABLE VI.- FREQUENCY DISTRIBUTIONS OF DERIVED GUST VELOCITIES

Derived gust velocity, U_{de}		Frequency of occurrence for –											
		0 to 10 000 ft (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 A-1	Airplane A-2	Airplane B-1	Airplane A-1	Airplane A-2	Airplane B-1	Airplane A-1	Airplane A-2	Airplane B-1	Airplane A-1	Airplane A-2	Airplane B-1
4 to 8	1.22 to 2.44	89	43		142	116	13	615	959	767	1308	2229	1205
8 to 12	2.44 to 3.66	1334	1158	397	454	566	199	384	530	599	754	1346	2346
12 to 16	3.66 to 4.88	736	631	343	138	144	90	92	75	142	76	210	231
16 to 20	4.88 to 6.10	569	480	168	35	69	43	19	7	24	13	47	58
20 to 24	6.10 to 7.32	123	107	36	11	15	13	15	8	15	2	14	17
24 to 28	7.32 to 8.53	41	31	15	3	7	4	3	1	4		3	6
28 to 32	8.53 to 9.75	17	6	7	3	3	3	1	2	1	2	2	
32 to 36	9.75 to 10.97	4	9	1	2	1	2					1	
36 to 40	10.97 to 12.19	1	2					1				1	
40 to 44	12.19 to 13.41	1					1		1				
44 to 48	13.41 to 14.63						1						
48 to 52	14.63 to 15.85												
	Total	2915	2467	967	788	921	369	1130	1583	1552	2155	3853	3863
Hours		183.65	203.13	171.10	112.02	114.60	124.12	271.40	314.73	368.18	540.12	723.75	984.57
Av. true airspeed, knots		248.36	241.79	240.73	390.09	387.00	362.22	477.23	469.85	463.81	485.92	485.29	477.17
Nautical miles		45 612	49 115	41 189	43 697	44 350	44 957	129 521	147 877	170 769	262 454	351 227	469 807



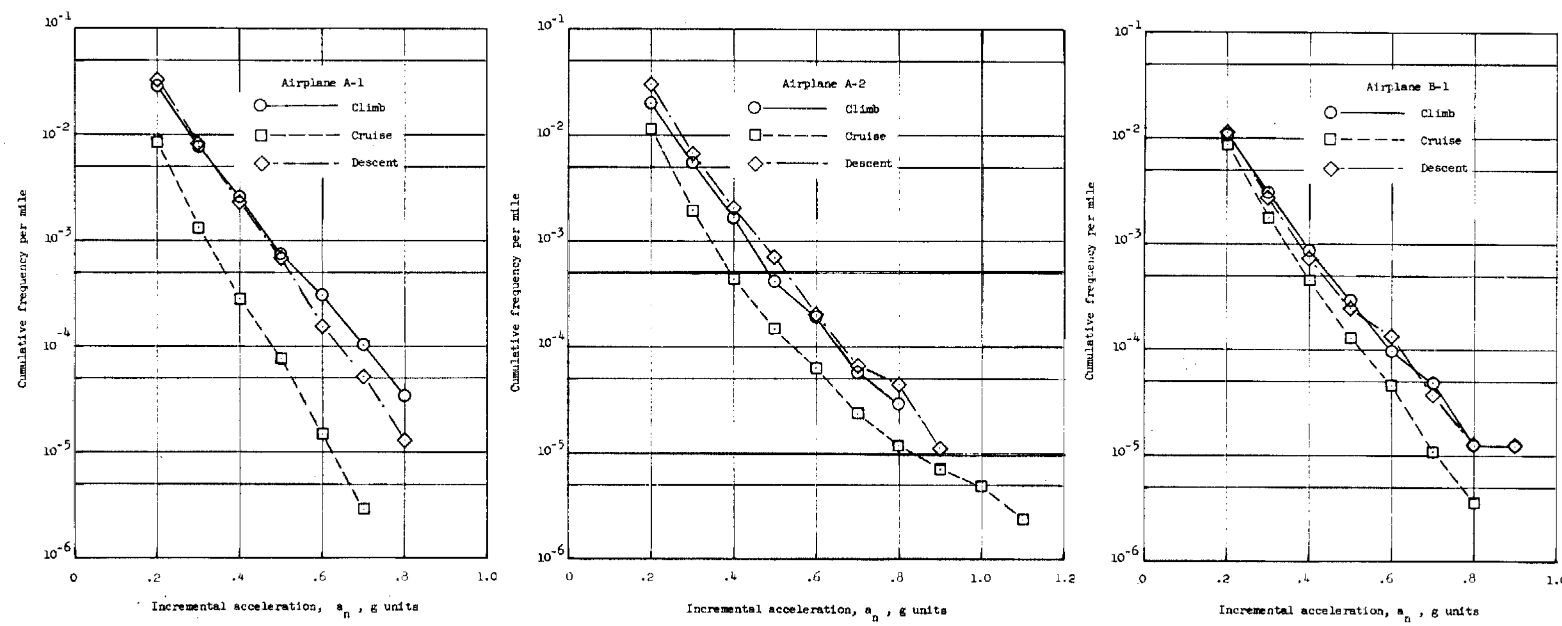
(a) Histogram of flight durations in one-quarter intervals.

Figure 1.- Description of operations.



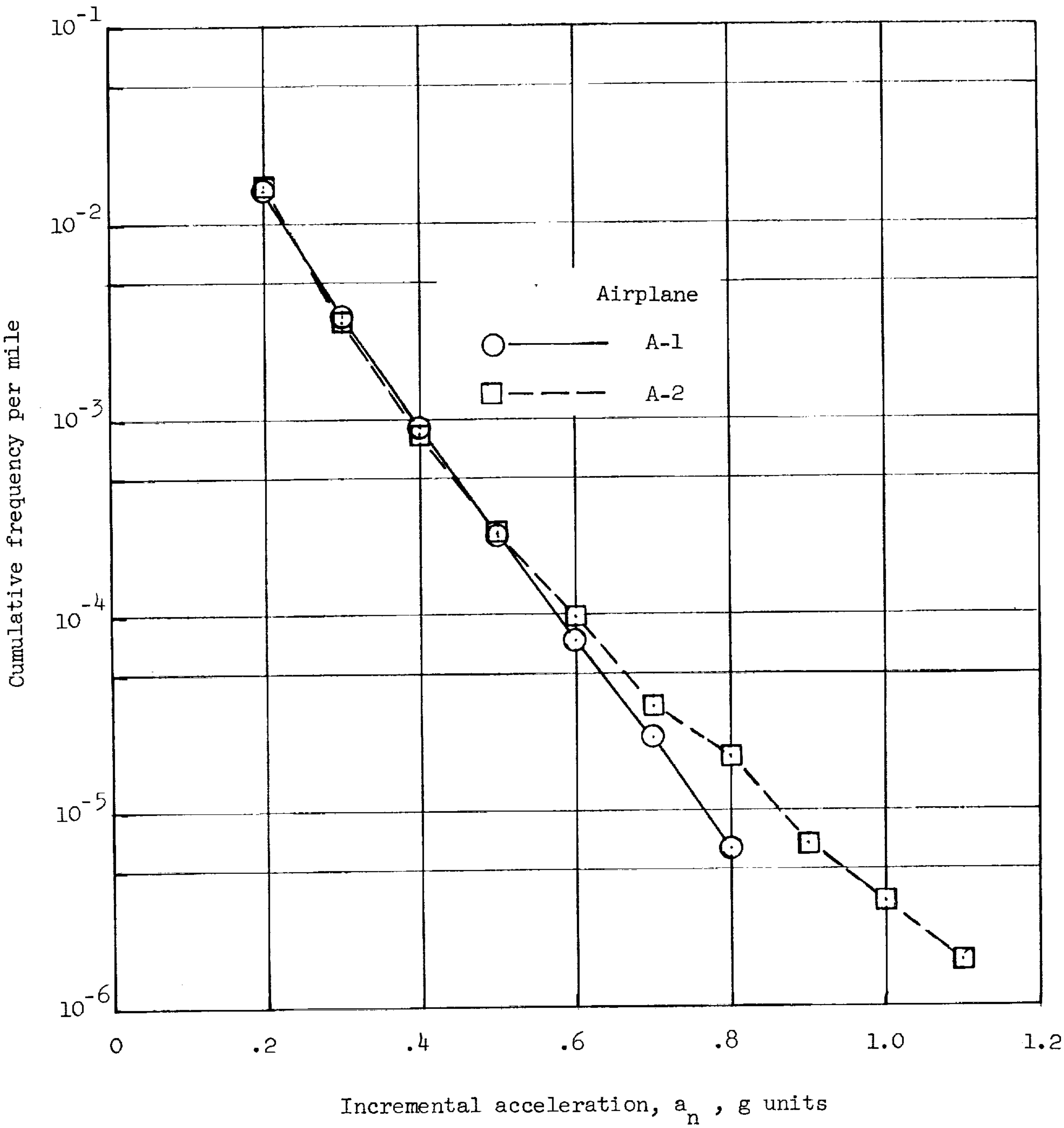
(b) Histogram of altitudes in 5000-foot (1.5-km) intervals.

Figure 1.- Concluded.



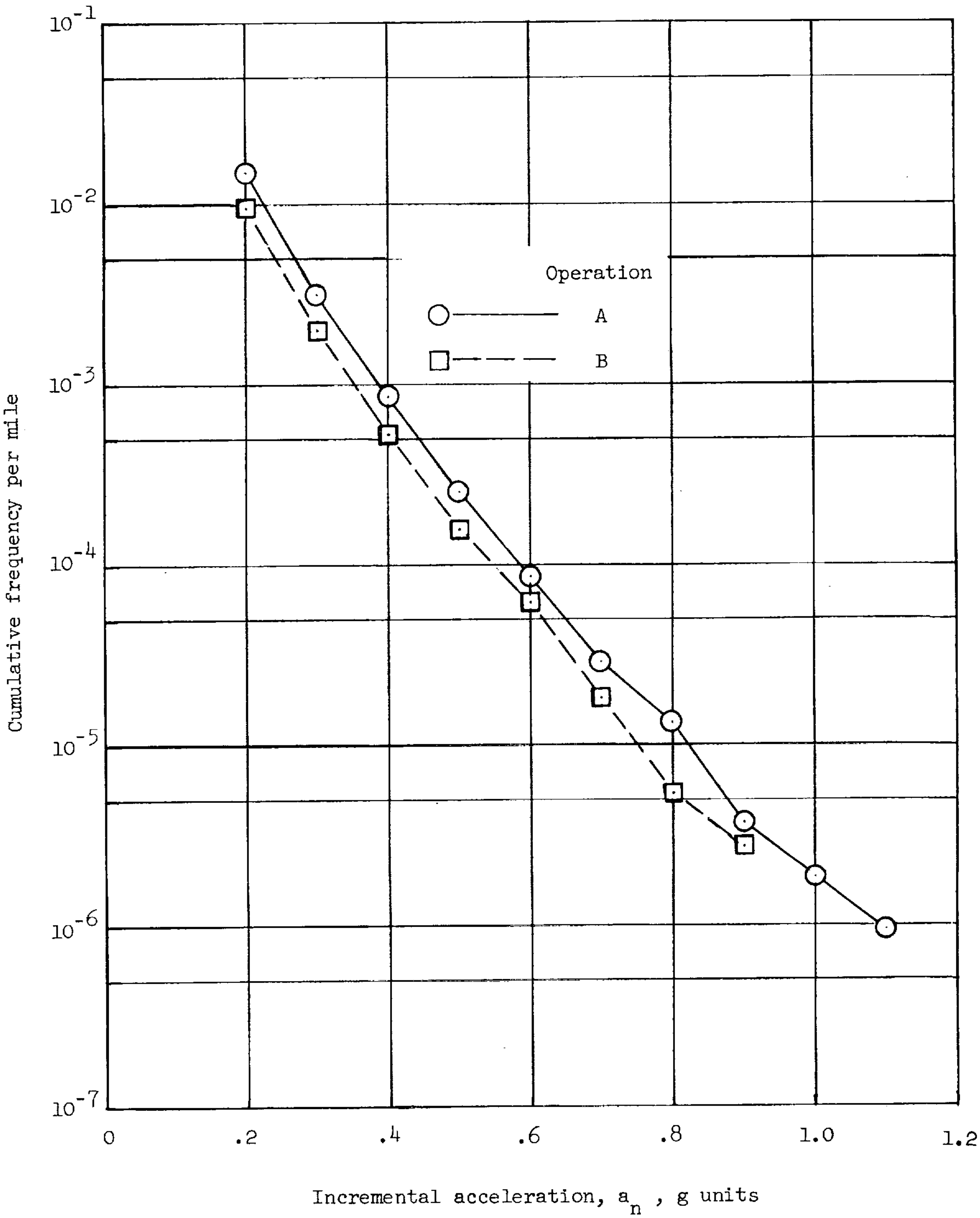
(a) Individual airplane samples.

Figure 2.- Cumulative frequency distributions of incremental gust accelerations per nautical mile.



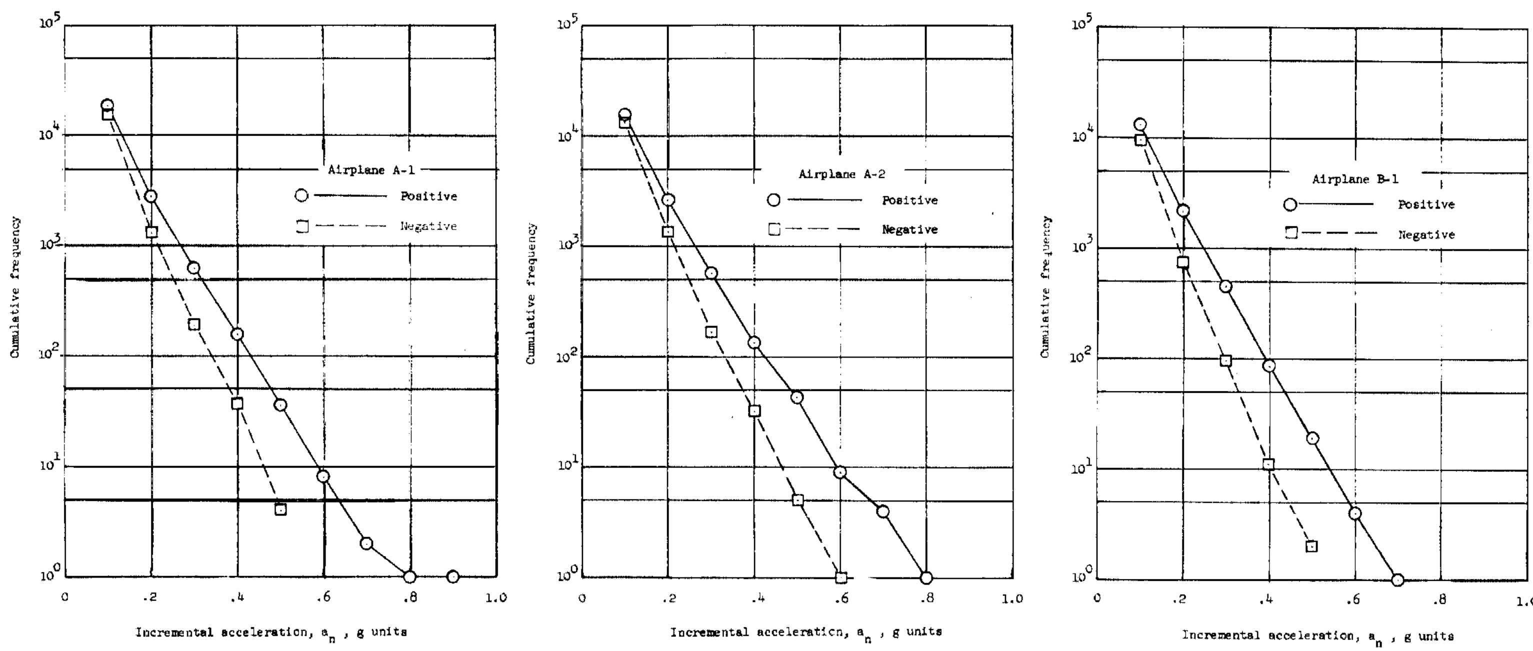
(b) Comparison of two airplanes of operation A.

Figure 2.- Continued.



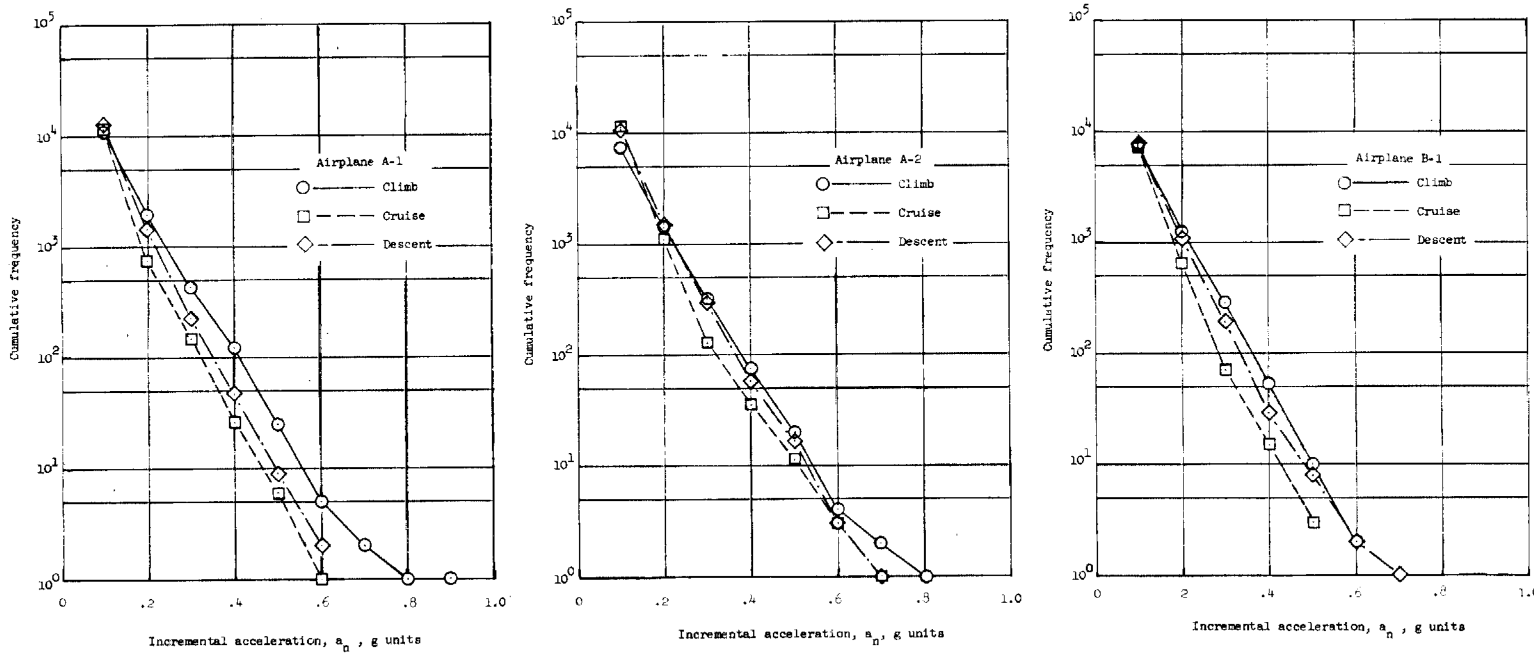
(c) Comparison of two operations.

Figure 2.- Concluded.



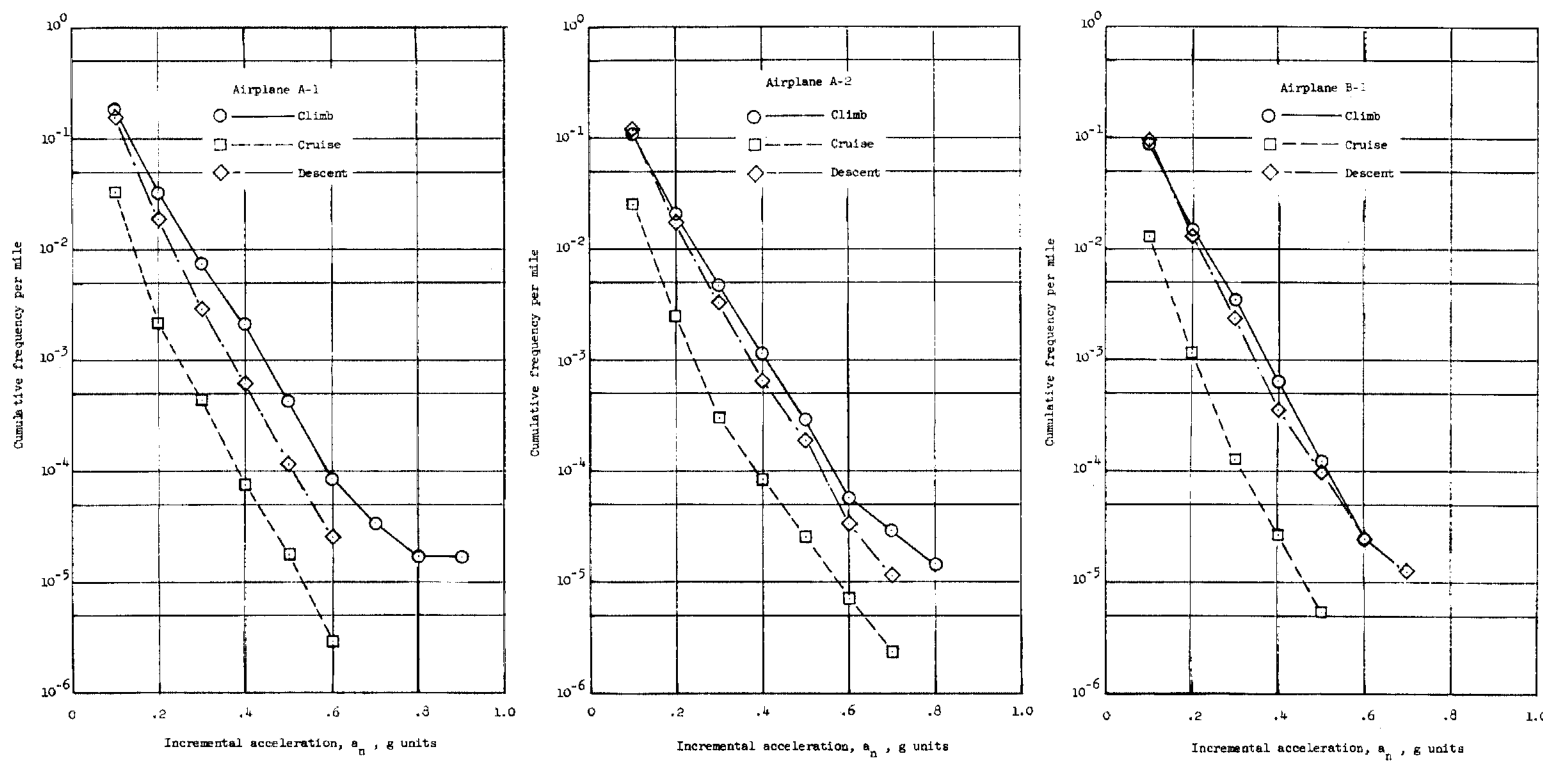
(a) Cumulative frequency distributions of positive and negative incremental accelerations.

Figure 3.- Operational maneuver accelerations.



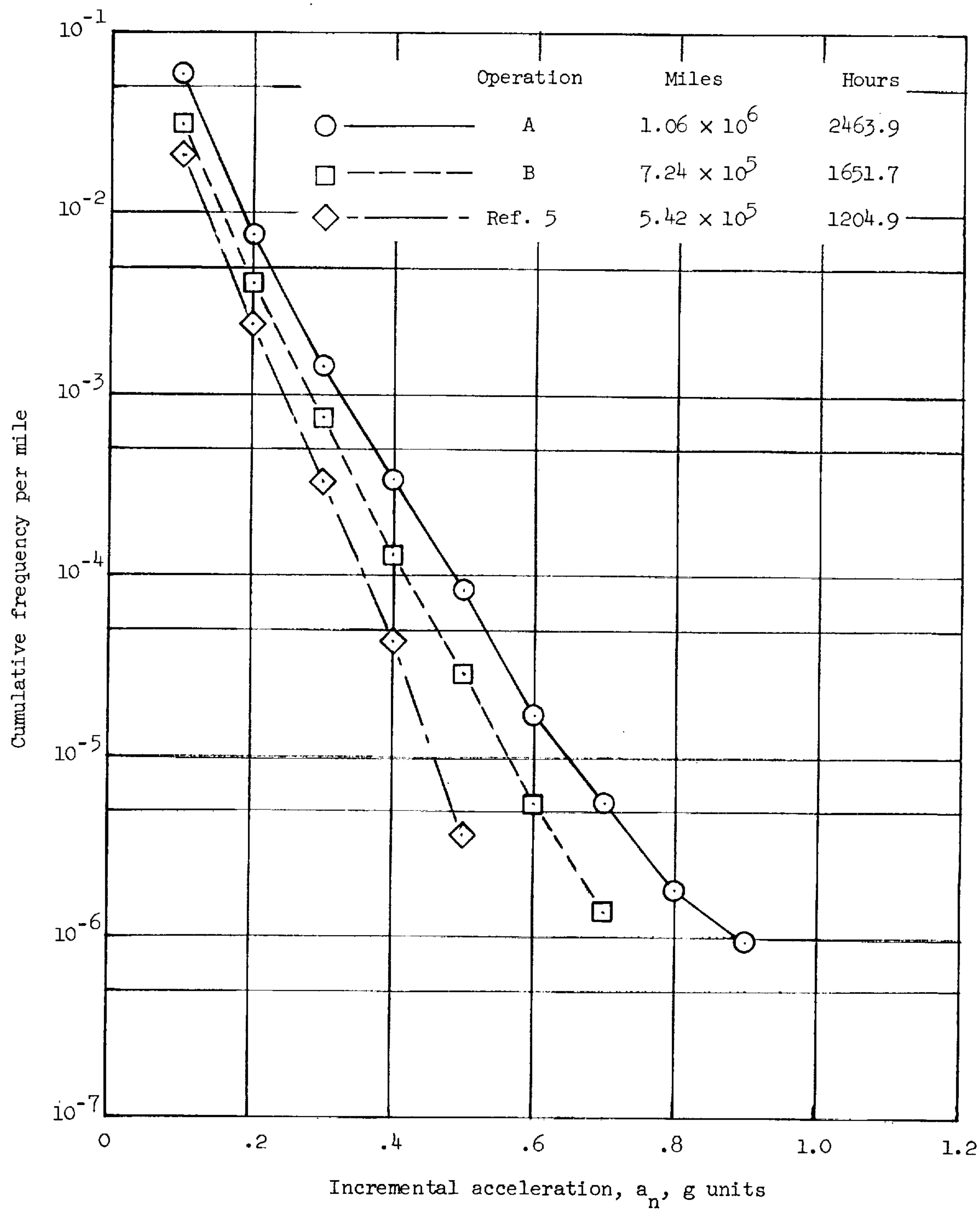
(b) Cumulative frequency distributions of combined positive and negative incremental accelerations by flight condition.

Figure 3.- Continued.



(c) Cumulative frequency distributions of combined positive and negative incremental accelerations per nautical mile by flight condition.

Figure 3.- Continued.



(d) Cumulative frequency distributions of combined positive and negative incremental accelerations per nautical mile for three operations.

Figure 3.- Concluded.

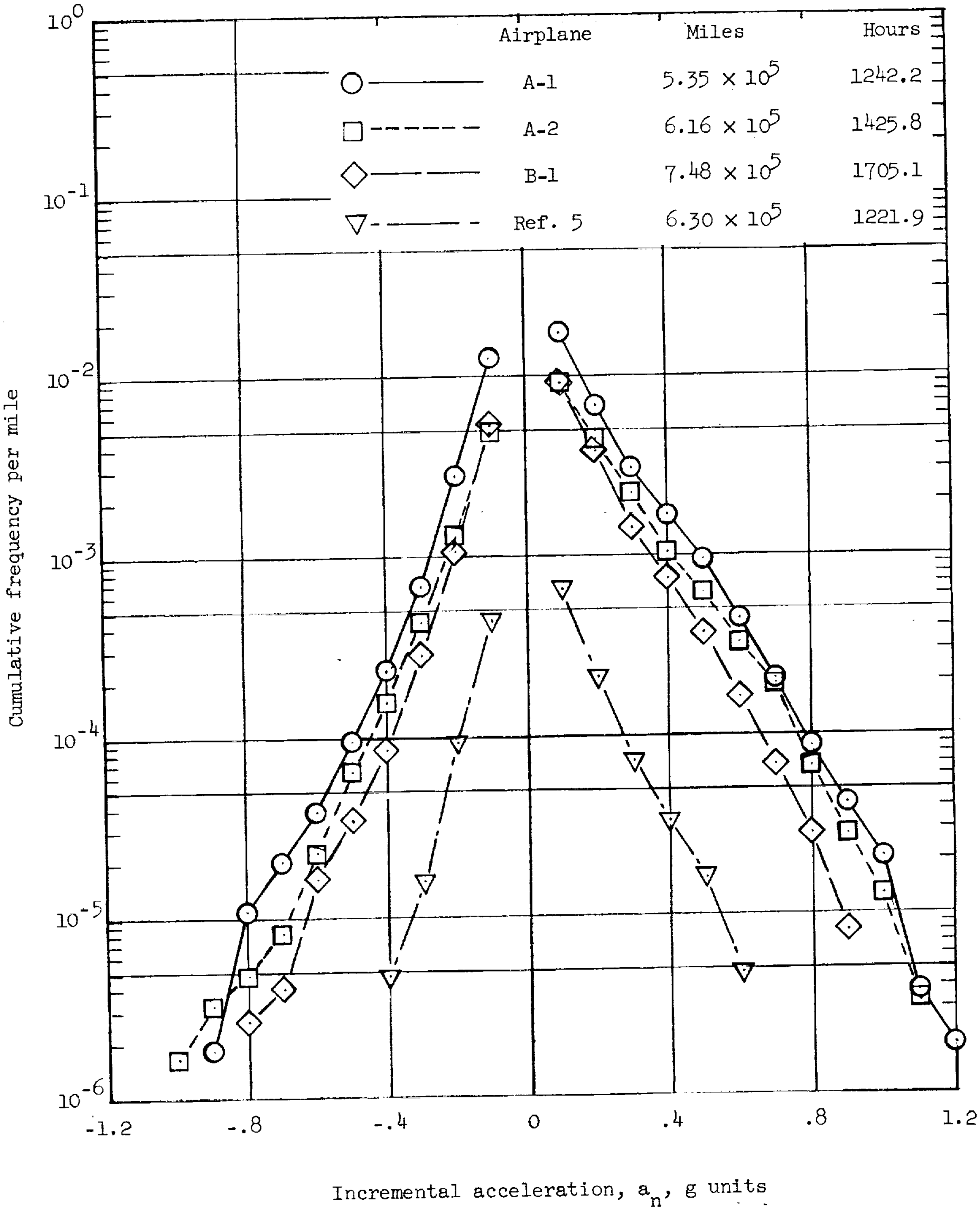
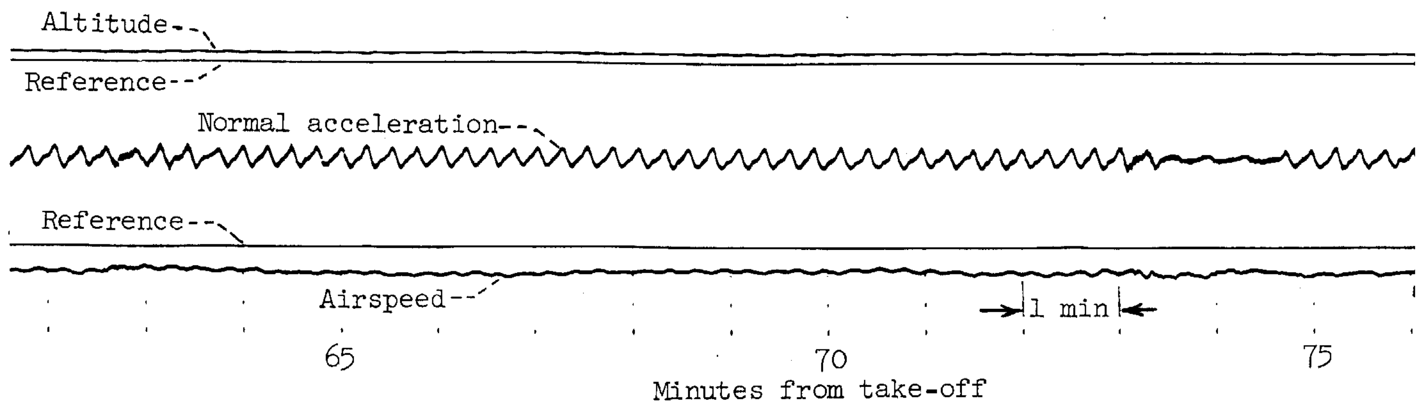
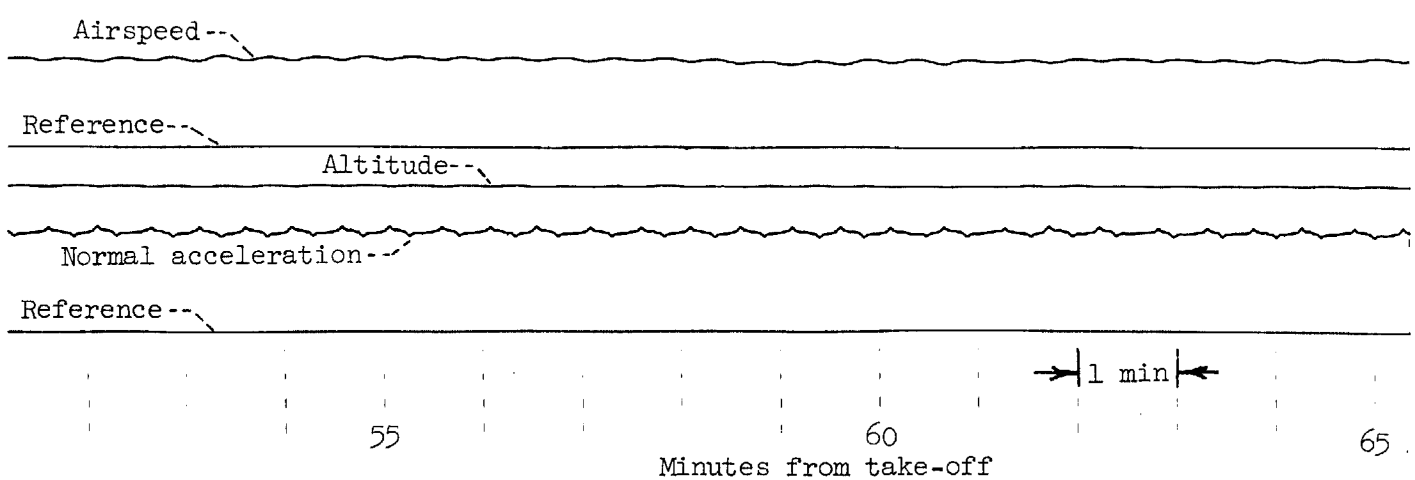


Figure 4.- Cumulative frequency distributions of positive and negative check-flight maneuver accelerations per nautical mile.

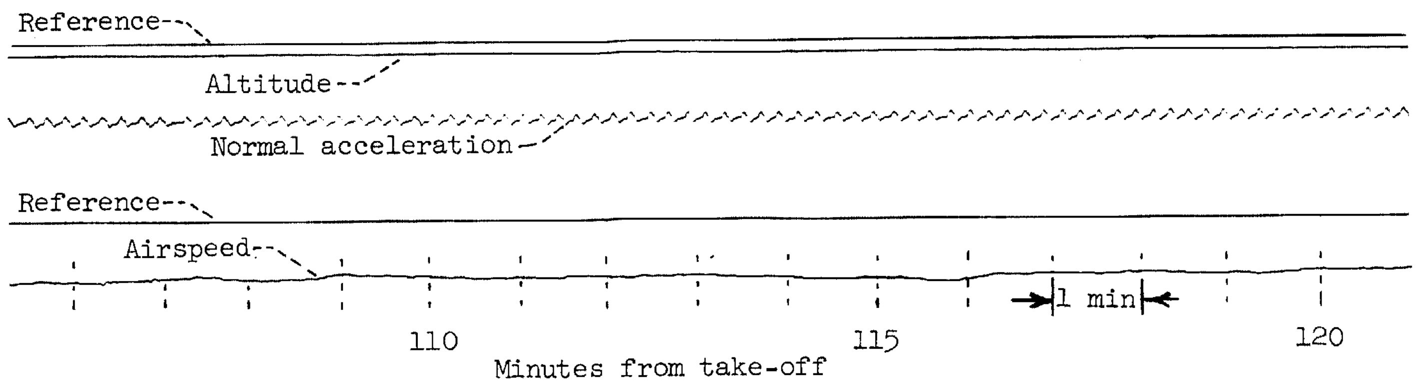


(a) Constant-amplitude oscillation, ±0.2g; period, 15 sec; airspeed, 352 knots (indicated); Mach number, 0.83; altitude, 25 000 ft (7.62 km).

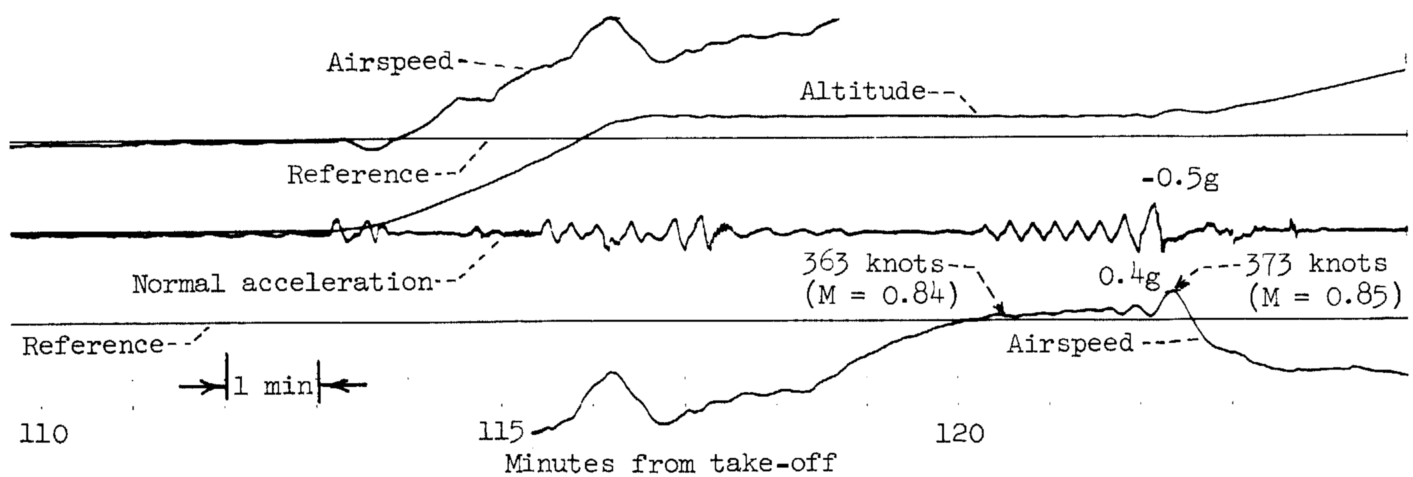


(b) Constant-amplitude oscillation, ±0.08g; period, 25 to 37 sec; airspeed (indicated), 320 knots ± 1 during oscillation; Mach number, 0.83; altitude, 29 000 ft (8.84 km).

Figure 5.- Samples of oscillation records.



(c) Constant-amplitude oscillation, ±0.08g; period, 12 sec; airspeed, 344 knots (indicated); Mach number, 0.82; altitude, 25 300 ft (7.71 km).



(d) Divergent oscillation with maximums of +0.4g and -0.5g; period, 17 sec; altitude, 24 000 ft (7.32 km).

Figure 5.- Concluded.

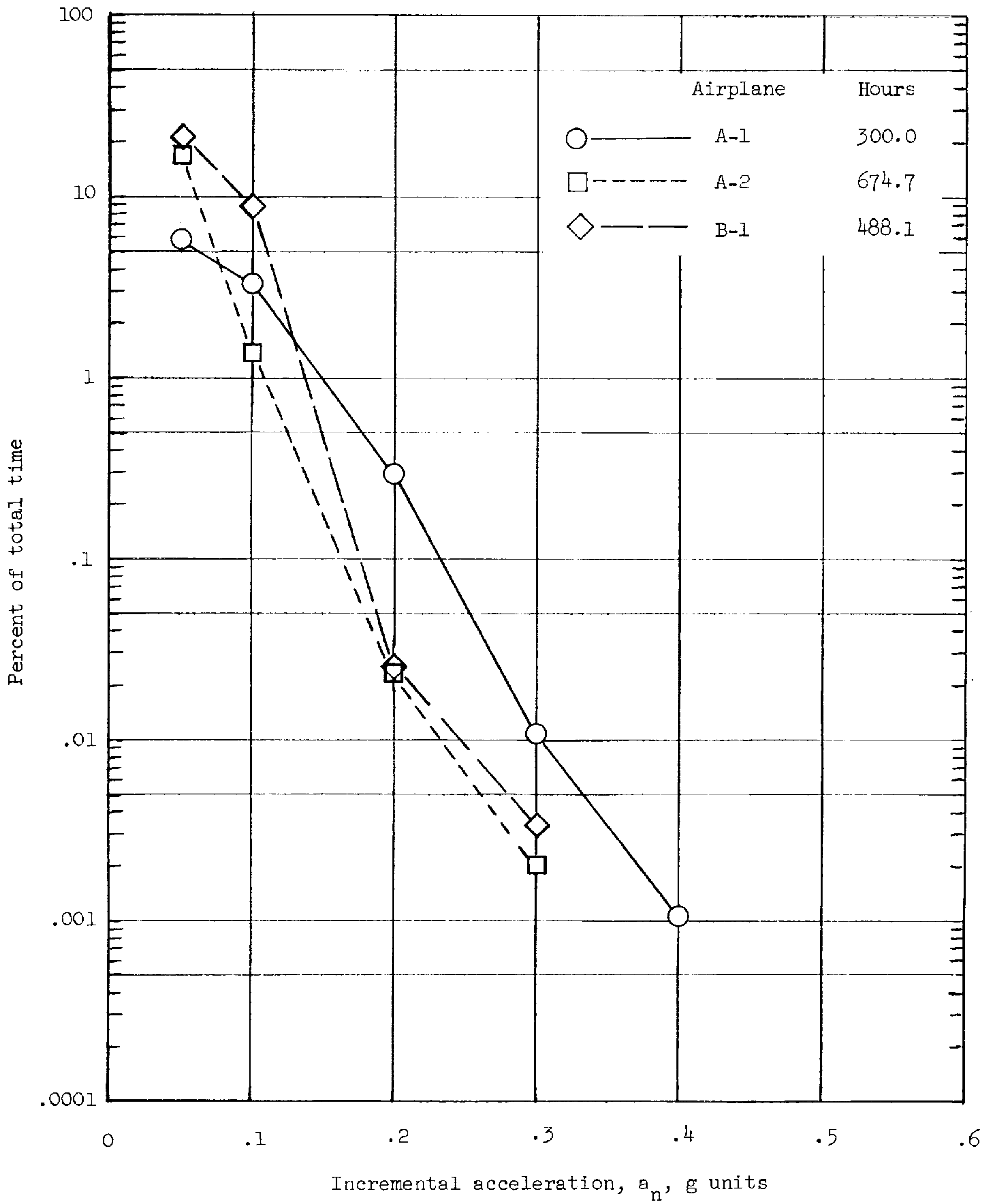


Figure 6.- Percent of total time spent in oscillations exceeding various amplitudes.

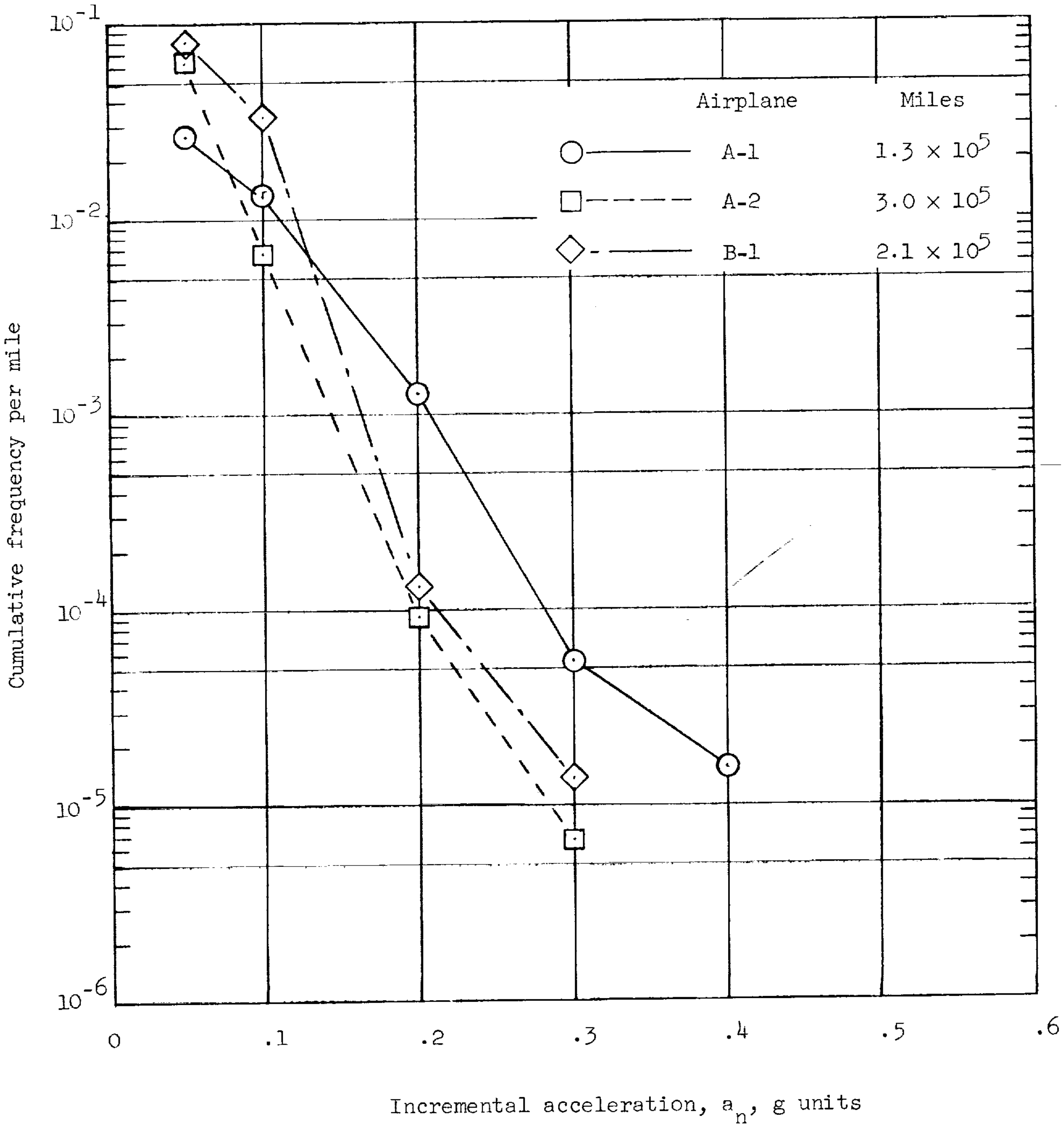
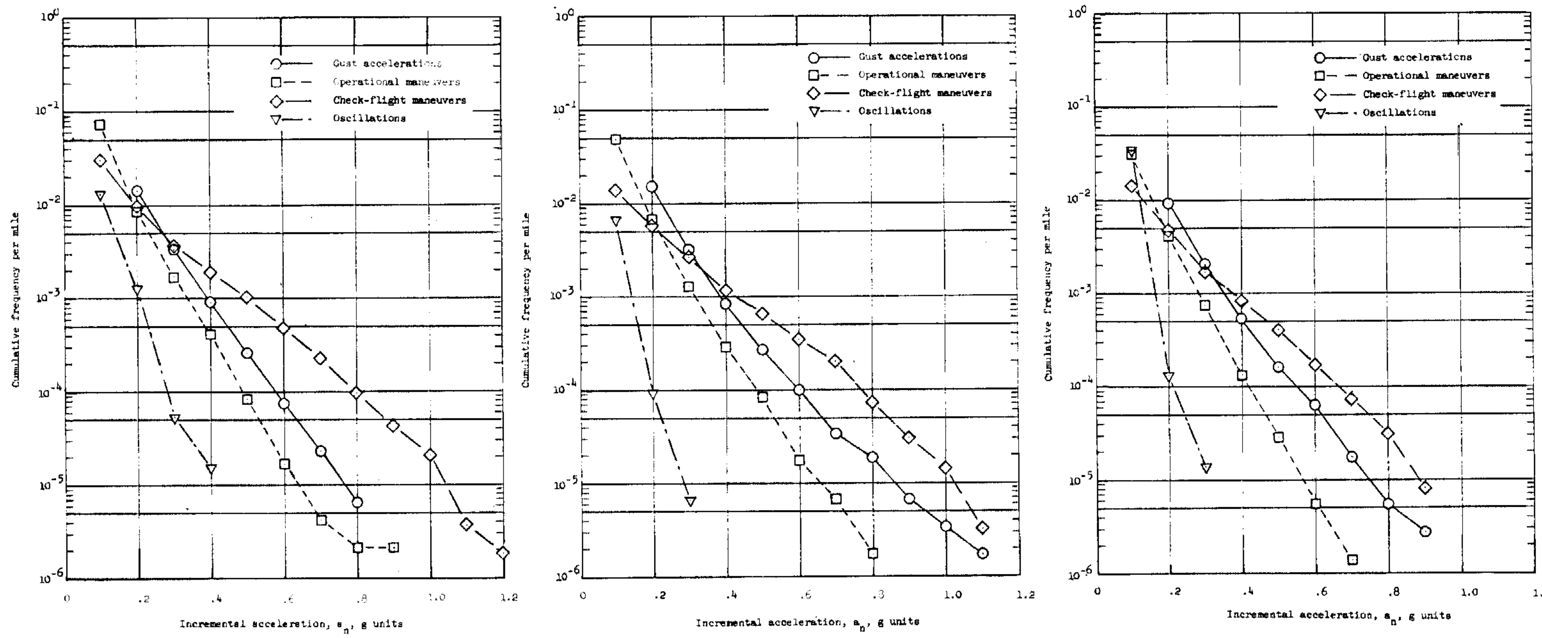


Figure 7.- Cumulative frequency of oscillatory accelerations per nautical mile for three airplanes.



(a) Airplane A-1.

(b) Airplane A-2.

(c) Airplane B-1.

Figure 8.- Comparison of accelerations from various in-flight sources.

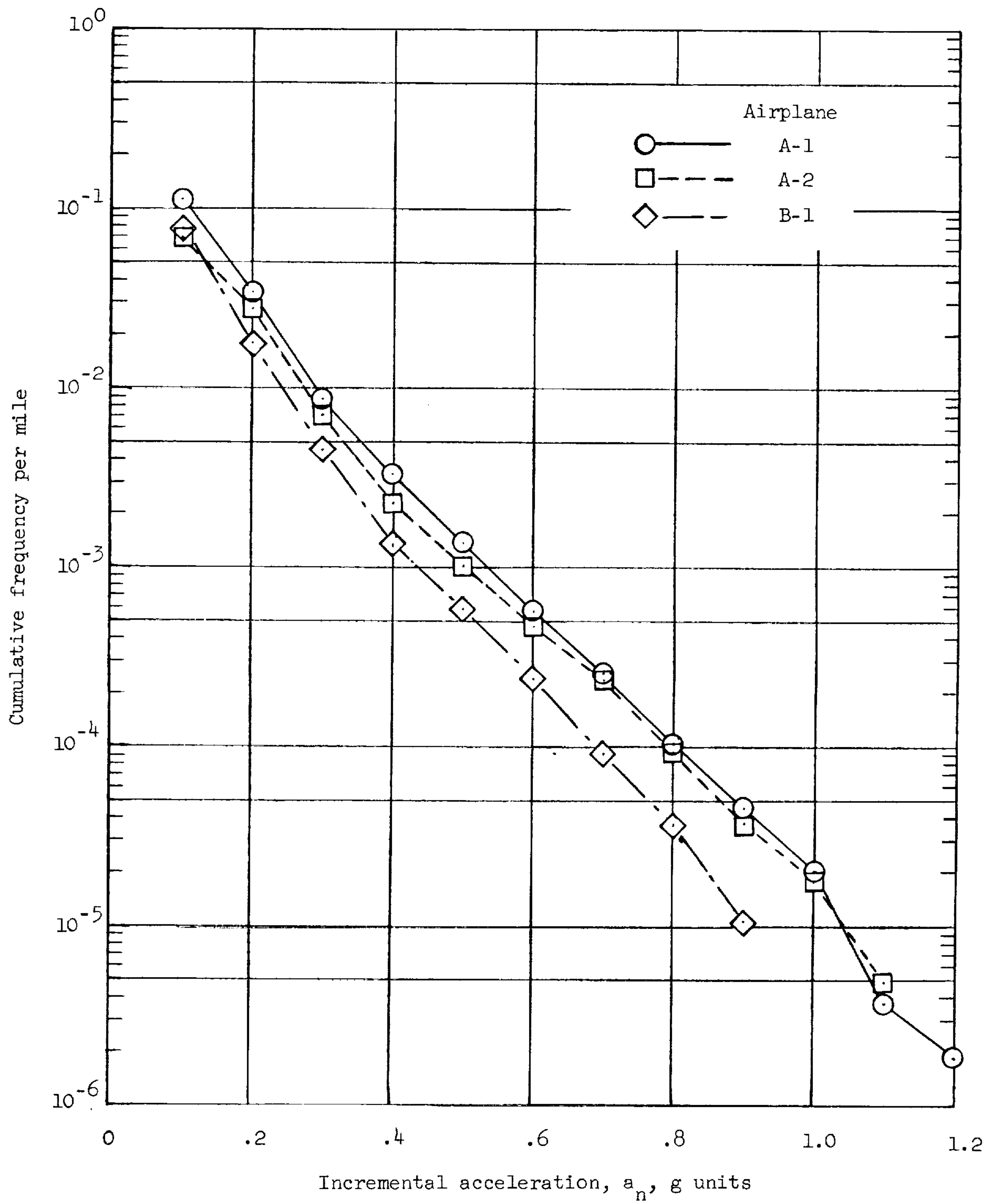


Figure 9.- Combined distributions of accelerations from various in-flight sources.

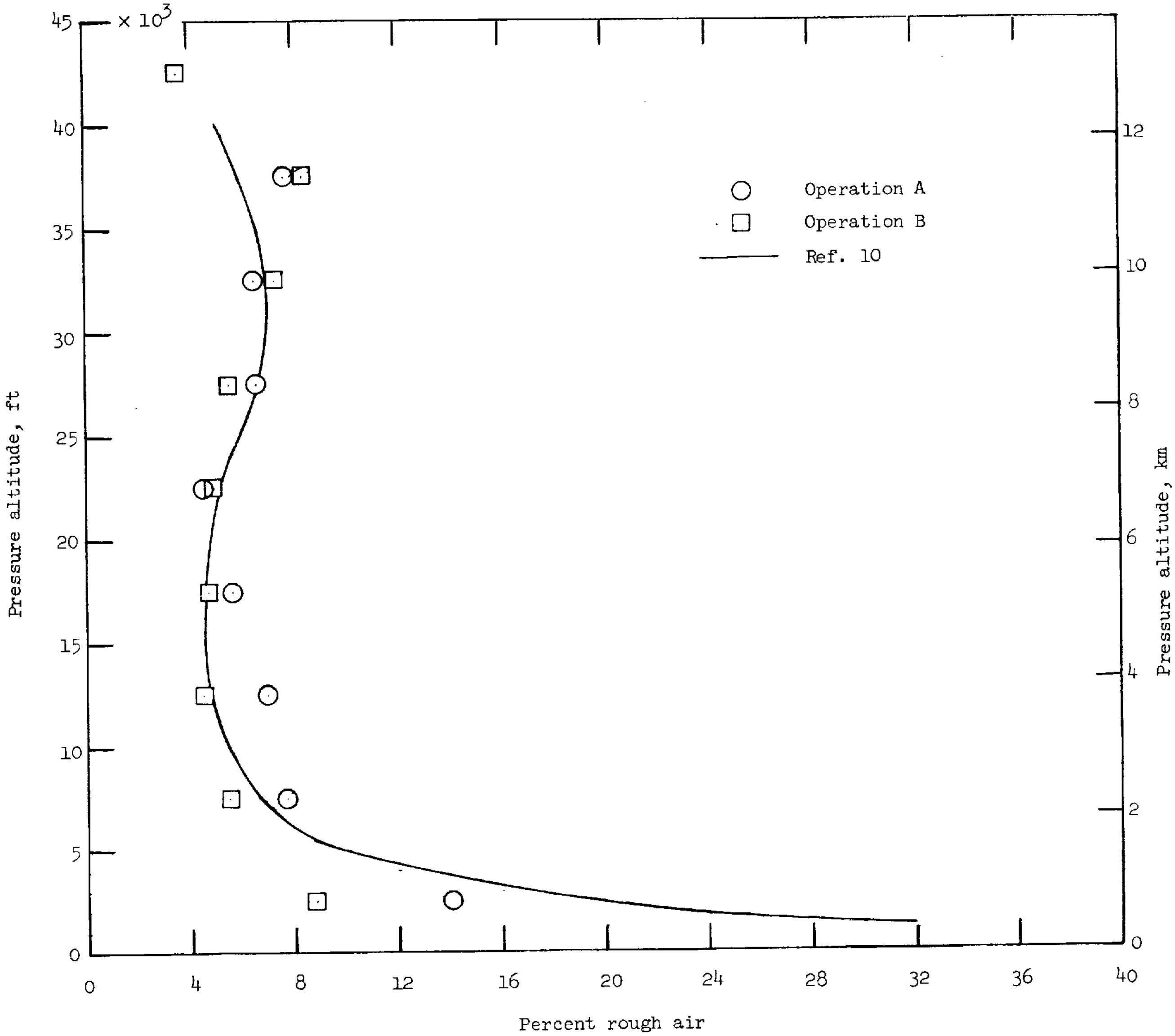


Figure 10.- Percent of time in each 5 000-foot (1.52-km) altitude interval spent in rough air.