A Review of NASA High-Altitude Clear Air Turbulence Sampling Programs

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The NASA sample of clear air turbulence from flight operations of U-2 airplanes has been extended to nearly 820,000 miles for altitudes between 20,000 and 75,000 ft. The flight measurements indicate that for the higher altitudes (40,000 to 75,000 ft), turbulence is both less frequent and less severe than for the lower altitudes (20,000 to 40,000 ft). Turbulence appears to be present at the high altitudes less than 1% of the time. The intensity of the turbulence decreases in an orderly pattern with increasing altitude and less than 50% of the turbulent areas exceeded 10 miles in length. The maximum measured value of derived gust velocity was 20 fps at an altitude of 52,000 ft. On the basis of rough approximations, this value corresponds to a true gust velocity of 58 fps.

Introduction

THE U. S. Air Force and NASA have cooperated in high-altitude flight-research programs for a number of years to obtain meteorological information for various geographical areas of the northern hemisphere. The objective of NASA in the programs is to obtain information on the amount and intensity of clear air turbulence at high altitudes for application to response studies of launch vehicles and airplanes such as the supersonic transport. The objective of the Air Force was to obtain other meteorological information such as temperature and pressure variations for operational and meteorological analyses. As a means of obtaining such atmospheric data above transport airplane operating levels, the Lockheed U-2 airplane that has altitude capabilities to 75,000 ft is used in the investigation. The U-2 program is a continuation of several other flight projects conducted first by NACA and later by NASA during the past decade or more to define characteristics of clear air turbulence encountered by airplanes in normal routine operations.

Some of the results on the frequency and intensity of the turbulence encountered at altitudes between 20,000 and 75,000 ft over western and southern U. S., western Europe, Turkey, and Japan are reported in Ref. 1. The published sample covers U-2 flight operations totaling slightly more than 300,000 miles at altitudes above 20,000 ft with 90% of the flight distance at altitudes above 40,000 ft. A continuation of the flight program with U-2 airplanes has extended the NASA sample of clear air turbulence measurements to more than 800,000 miles at altitudes between 20,000 and 75,000 ft. It is the purpose of this paper to review the NASA U-2 clear air turbulence program, its results, and some implications of the measurements and also to comment briefly on other NASA clear air turbulence programs dating back 15 or more years. This review is considered particularly pertinent at this time in view of current interest in the turbulence environment to be expected in supersonic transport operations at cruising altitudes of 60,000 to 75,000 ft.

Past and Present Sampling Programs

Experimental investigations of atmospheric turbulence were initiated by the NACA in the 1930's with the development and installation of V-G recorders on commercial airplanes. The V-G recorder describes an envelope of the maximum normal accelerations as a function of airspeed for a period of time, such as 100 flight hours (see Ref. 2 for a description of the V-G recorder). With the development of the time-history type VGH recorder[3] in about 1947, more detailed information could be obtained concerning the characteristics of the turbulence from the recorded traces of airspeed, normal acceleration, and altitude. The VGH recorders were installed on commercial airplanes for sampling of routine operations and on governmental airplanes for special investigations of the turbulence in given weather conditions, such as hurricanes or jet streams, as well as in routine operations of service airplanes.

Examples of military operations in which measurements of clear air turbulence were obtained are listed in Table 1. The table gives the dates of operation, the airplanes used, the altitudes surveyed, the amount of time spent in turbulence, and the total sample size in terms of flight hours. The airplane was considered to be in turbulence whenever the accelerometer trace was disturbed and contained gust velocities greater than 2 fps. The airplanes were normally selected for use in the measurement programs because of their high-altitude capabilities. It may be noted that the programs, as early as 1950 to 1953, covered the altitudes that are representative of current commercial jet transport operations. The U-2 airplane, since 1956, has sampled the atmosphere to an altitude of 75,000 ft, the maximum expected operating altitude of the supersonic transport.

The flight operations in Table 1 increase in extent from the earlier samples from the B-45 and B-47 airplanes of 60 to 300 flight hours to 1800 flight hours for the U-2 airplanes. Generally, 1000 flight hours is considered a reasonable sample to define routine commercial operations. Adequate samples have therefore been obtained from the B-36 and U-2 operations. The B-47 and F-3D flights (designated as "jet stream") were made solely to sample the turbulence and other meteorological parameters in or near the jet stream. It may be noted that

Table 1 Clear air turbulence medium to high altitude

Date	Airplane	Altitude, ft	Turbulence, hr	Total sample, hr
1950–1952	B-45	5,000–45,000	. . .	60
1952	B-47	5,000–45,000	. . .	300
1951–1953	B-36	5,000–20,000	100	750
1951–1953	B-36	20,000–50,000	60	1100
	B-47	25,000–35,000		
1953–1956			35	330
	F-3D	jet stream		
1956–	U-2	20,000–75,000	25	1800

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the relative amount of turbulence for these flights is greater than for the other routine operations.

The U-2 airplane flights are current programs and, inasmuch as they extend to the higher altitudes, they will be considered in greater detail in Table 2. In Table 2, the flight hours have been converted to flight distance within given altitude brackets from 20,000 to 75,000 ft. It is noted that the flight distances increased with altitude, and approximately 720,000 miles or 88% of the total are above the 50,000-ft altitude. These higher altitudes could not be sampled by the earlier aircraft listed in Table 1. The miles in turbulence at the different altitudes vary from approximately 1250 to 3300 miles. The 9 miles of turbulence and 7000 flight miles in the 70,000-ft and higher altitude range are too small a sample to be considered in detail.

The flights summarized in Table 2 were made over Western Europe, Turkey, Japan, and the U. S. The flights over the U. S. comprise about 80% of the total flight distance.

Description of Clear Air Turbulence

In this section of the paper, the results of the flights will be used to describe the average turbulence conditions encountered by airplanes in routine operations. Routine operations normally use turbulence avoidance procedures to reduce the flight distance in turbulence in contrast to flights specially made to seek out turbulent conditions. Such selective procedures were used in the special flight investigations of the Thunderstorm Project,[4] the Severe Storms Project,[5] and jet-stream flights.

Percentage of Flight Distance in Rough Air

The percentage of the flight distance in clear air turbulence is presented in Fig. 1 as a function of altitude. The solid line is a previous estimate based on earlier data summarized in Ref. 6. The circled data points represent the results of the present U-2 sample. The dashed curve is faired through the data points and is a suggested revision to the previous estimates. The results show that for altitudes between 50,000 and 75,000 ft, clear air turbulence was generally encountered less than 1 or 2% of the time.

All of the sets of data show a maximum peak at altitudes near 30,000 ft. The increase in the amount of clear air turbulence at this altitude is probably caused by the high winds and wind shears associated with jet streams that are normally prevalent at these altitudes for the mid latitude areas covered by the data. It is to be noted that the present estimate indicates a somewhat increased percentage of turbulence at this altitude over previous estimates. However, a note of warning is needed. The flights in the altitude range from 20,000 ft to the cruise altitudes of the U-2 airplane represent, to some extent, a vertical sounding during climb and descent over rather localized areas, and the data may not indicate average conditions at these altitudes over the northern hemisphere.

Frequency of Occurrence of Gust Velocities in Turbulence

As a means of assessing the relative intensity of the turbulence by altitude, the average number of gusts per mile of

Table 2 U-2 airplane data sample

Altitude, ft	Turbulence, miles	Total flight, miles
20,000–30,000	1,497	18,860
30,000–40,000	2,689	26,470
40,000–50,000	1,248	49,510
50,000–60,000	2,812	141,670
60,000–70,000	3,285	576,930
70,000–75,000	9	7,030
Totals	11,540	820,470

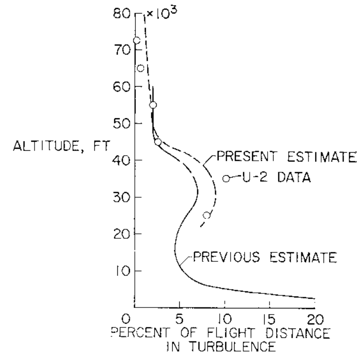

Fig. 1 Percent of flight distance in clear air turbulence as a function of altitude.

flight in turbulent air that exceeded given values of gust velocity are given in Fig. 2. The values of gust velocity given in Fig. 2 and subsequent figures are derived gust velocities U_{de}.[7] Two unique situations appeared to be present within the Japanese sample of data within the 50,000- to 60,000-ft-alt bracket. In order to examine the effect of these cases on the gust distributions, two distributions (curves) are shown in Fig. 2 for the 50,000- to 60,000-ft interval, one for the complete data within those altitudes and the other with the Japanese sample deleted.

The distributions in Fig. 2 which do not include the Japanese data fall into groups according to altitude above or below the approximate tropopause or jet-stream level. The three distributions for the higher altitudes, 40,000 to 70,000 ft, are of lower intensity than those below 40,000 ft. When the values are read at a frequency of 0.01, the curves indicate that a derived gust velocity of 6 and 8 fps or greater would be encountered on the average in 100 miles of flight in turbulence at altitudes of 40,000 to 70,000 and 20,000 to 40,000 ft, respectively. If the Japanese sample is included, the value would be 10 fps in the 50,000- to 60,000-ft-alt bracket. At low altitudes, say 2000 ft, other data indicate that a derived gust velocity of 20 fps would be encountered on the average in 100 miles of clear air turbulence.

Frequency of Occurrence of Gust Velocities per Flight Mile

If both the frequency of gusts per mile of turbulence from Fig. 2 and the percentage of turbulence in Fig. 1 are combined, the curves in Fig. 3 are obtained. These curves give the frequency of occurrence of gust velocities that exceed the given value, on the average, per mile of total flight in an altitude bracket. Again, the flagged symbols indicate that the Japanese data are included. These curves probably give the best indication of the reduction in the frequency of gust velocity with altitude.

In terms of the gust intensity, the results indicate that the maximum gust velocity experienced per mile of flight between 60,000 and 70,000 ft is on the order of $\frac{1}{3}$ or $\frac{1}{2}$ that experienced per mile of flight between 20,000 and 40,000 ft.

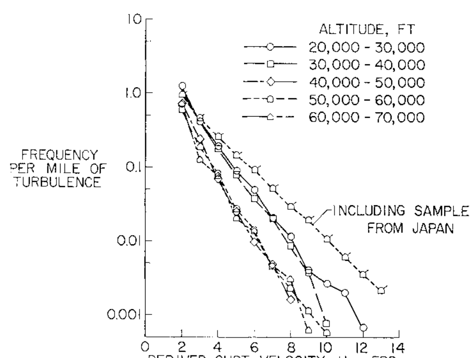

Fig. 2 Probability of exceeding a given derived gust velocity per mile of turbulence.

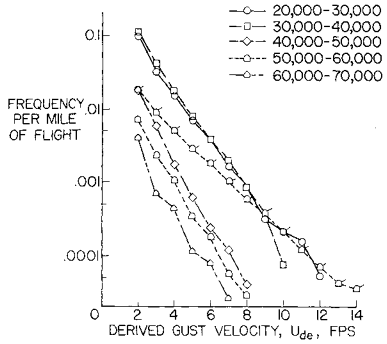

Fig. 3 Probability of exceeding a given derived gust velocity per mile of total flight distance.

This variation with altitude is illustrated by plotting the values of derived gust velocity at a frequency of 0.001 (the gust velocity exceeded in the average in 1000 miles) against altitude as shown in Fig. 4.

The values of derived gust velocities in Fig. 4 are relatively constant at the lower altitudes and drop off rapidly at the high altitudes. If a rough measure of the true gust velocities is desired, the derived gust velocities may be multiplied by the square root of the density ratio $(\rho_0/\rho)^{1/2}$. These values are also plotted in Fig. 4. The relatively small change in these values with altitude leads one to speculate that the true gust velocities may not decrease significantly at the higher altitudes.

The maximum value of U_{de} $(\rho_0/\rho)^{1/2}$ for the 800,000 miles of flight is approximately 58 fps. This value corresponds to a derived gust velocity of 20 fps encountered over Japan at an altitude of 55,000 ft.

Length of Turbulent Areas

The probability distribution of the lengths of the turbulent areas encountered in the different operations is given in Fig. 5 as the shaded area. The distribution for the jet-stream sample in Table 1 is shown as a dashed line. Inspection of the results shows that most of the patches of clear air turbulence are of relatively small horizontal extent. For example, less than 50% of the turbulent areas exceeded 10 miles in length. The jet-stream data indicate that relatively longer areas of turbulence may be found under some circumstances. In this case, lengths of 80 miles are exceeded about 10% of the time. Since turbulent areas sometimes occur in patches separated by only a few miles of smooth air, pilot reports tend to indicate much longer turbulent areas than indicated in Fig. 5. These turbulent areas are usually 2000 to 3000 ft in thickness.

The distribution of the length of the turbulent areas does not seem to vary significantly in the altitude range above 20,000 ft. The frequency of encountering the areas of turbulence, however, does vary considerably with altitude. A turbulent area would be encountered on the average of once every 55 miles at altitudes between 20,000 and 50,000 ft as compared to once in 1140 miles at the higher altitudes above 50,000 ft.

Unusual Turbulent Areas

The sample from Japan was included in Figs. 2 and 3 but was not completely discussed, partially because it was indicated that the data may be a unique case and would not fit what has been termed as average conditions. This leads to the question of possible extreme conditions that are not predictable by the average conditions of Fig. 2 and 3.

The high gust frequency indicated in Figs. 2 and 3 for the 50,000- to 60,000-ft altitude and attributed to the Japanese sample resulted predominantly from two areas of rough air that were encountered at an altitude of 52,000 ft on two separate flights over Honshu Island. Over one-half of the gusts for approximately 44,000 miles of flight were encountered in 151 miles of rough air on one flight over the eastern side of the mountains on the northern end of the island. A 195-mile area of less severe turbulence was encountered around the southern end of Honshu Island. In each case, the Japanese Islands were under the influence of moderately severe surface storms and well developed jet streams with peak wind velocities of about 200 knots at altitudes of 35,000 ft. At the flight altitude of 52,000 ft, the winds were between 100 and 150 knots. These weather conditions would be expected to produce turbulence.

Two large turbulence areas (approximately 80 miles in length) encountered in the U. S. were encountered during descent from approximately 50,000 ft. One case indicated a turbulent region approximately 30,000 ft in thickness extending from an altitude of 45,000 to 15,000 ft. This flight occurred during the season of rather severe convective activity over the flight area, and thunderstorms were observed in the general area of the base of operations.

The question of the frequency of occurrence of these phenomena and the possibility of moderately severe to severe turbulence in mountain waves, strong wind shears, jet streams, and clear air convection remains unanswered.

U-2 Pilots' Reaction to Turbulence

A number of studies have been made to determine the tolerance levels of pilots to gust-induced accelerations. Much of this work has used sinusoidal accelerations and considered the frequency, the intensity, and the duration of the accelerations. An example of flight investigation of this problem is given in Ref. 8 in which the Cornell Aeronautical Laboratory established "tolerance" and "decreased-proficiency" boundaries as a function of exposure time. The Cornell study indicates that a rms acceleration of up to 0.20 to 0.25g could be tolerated for 2 to 5 min (the flight time through the majority of clear air turbulence areas) without an appreciable decrease in efficiency. In a flight of this length, one would expect to experience an acceleration approximately three times the magnitude of the measured rms acceleration.

The pilots on all of the U-2 flights submitted routine reports on the turbulence or other factors associated with each mission, but no case of discomfort or strain caused by turbulence was indicated. The turbulence encountered by the U-2 airplanes at altitudes above 20,000 ft was generally of such low rms acceleration and such short duration that it appears all of the incidents would be below the tolerable level. Although the coupling of the airplane-pilot system with the turbulence cannot be simply extrapolated from the U-2 airplane to the supersonic transport, current operating experience at 65,000-ft-alt levels points out no turbulence incidents of great concern. Additional investigations are being conducted on transport aircraft and in simulation studies that may lend more information on this subject.

Comparison of Turbulence for Different Weather Conditions

In addition to the description of turbulence intensities by the derived gust velocities, the turbulence may also be de-

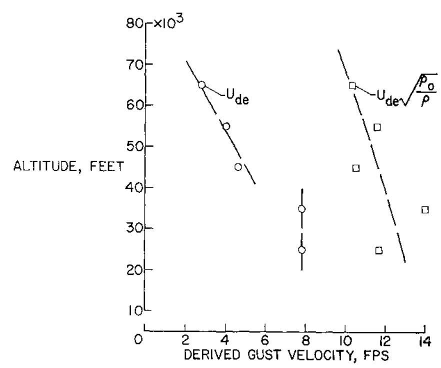

Fig. 4 Variation of intensity of turbulence with altitude.

scribed by the time history of the true gust velocities. These time histories are normally evaluated as power spectra[9] of atmospheric turbulence, and three typical spectra are presented in Fig. 6. The use of power spectra is a convenient way to study the frequency content of the turbulence or the relative power at the various wavelengths. The three atmospheric conditions represented are clear air, cumulus clouds, and thunderstorms. The clear air turbulence represented is for a low-altitude condition of 5000 ft, inasmuch as no high-altitude spectra are yet available.

These spectra cover a range of wavelengths from about 50 4000 or 5000 ft, the range of interest to present-day aircraft. As can be seen, all three spectra have about the same general slope. The scale on the left should be thought of as being "power" with larger numbers representing increasing levels of turbulence intensity. The abscissa scale is in terms of reduced frequency, radians per feet, in order to remove effects of the flight or traverse speed. A wavelength scale has also been superimposed on the abscissa. The rms gust velocity σ_1 is simply the square root of the area underneath the spectrum. Using the rms value as a measure of the intensity of the turbulence, the relative intensity of the turbulence in the three weather conditions is readily apparent.

The wavelengths of interest for present subsonic jet airplanes ($M = 0.8$) are indicated by the shaded area for the short-period frequencies. The range of wavelengths expected to be of primary importance to the rigid-body response of the Mach 3 transport extends to about 14,000 ft (corresponding to about 0.2 cps) as indicated in the figure. The severe storm spectra have been measured in a few cases to wavelengths of 14,000 ft where it appears that the spectrum is extended as a straight line. Although the clear air spectrum is lower in "intensity" or "power" than the other spectra, there would still be considerable power if the clear air turbulence spectrum also continues as a straight line to wavelengths of 14,000 ft. The shape of the clear air turbulence spectra at the long wavelengths must still be defined. Effort is being made to extend clear air turbulence data in this form to longer wavelengths and higher altitudes.

Other Research Programs

NASA has formulated an inter-center program intended to provide a more basic understanding of problems associated with the flight of large flexible aircraft in severe turbulence. The program is divided into four studies: analysis, wind-tunnel tests, flight tests, and piloted-simulator tests. Although the program is slanted toward severe turbulence, the results from the study of airplane handling qualities, control systems, autopilots, and structural flexibility in turbulence will be equally beneficial for flight in less severe turbulence.

The analysis program has, as its primary objectives, 1) to arrive at a preliminary assessment of the significance of factors such as handling quality and pitch-up characteristics and flexible aircraft response to gust and control inputs, 2) to determine the effectiveness of simple control system and autopilot modifications in reducing gust-induced accelerations and in minimizing or eliminating aircraft upset, and 3) to help orient the wind-tunnel, flight, and simulation programs.

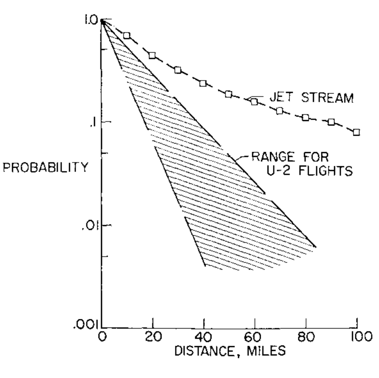

Fig. 5 Distribution of lengths of clear air turbulence areas.

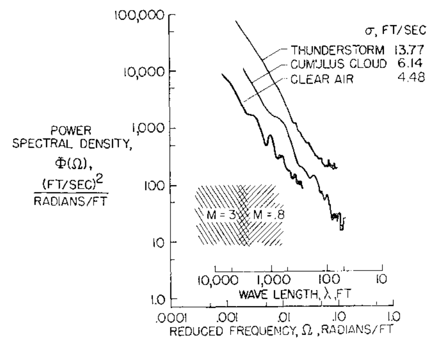

Fig. 6 Comparison of power spectra of turbulence for three weather conditions.

The objective of the wind-tunnel tests is to provide basic aerodynamic data over a wide range of Mach numbers and angle of attack to fill in gaps in available data. The objectives of the flight program are to study such items as pilot environment and control activities in rough air for use in simulator inputs, to provide NASA pilot experience for simulator validation, to obtain basic handling-qualities characteristics over a wide range of flight conditions, and to investigate turbulence penetration characteristics for several flight and control configurations and for different types of turbulence.

The NASA piloted-simulator program includes most of the factors that might contribute to airplane control problems in rough air. If certain factors, singly or in combination, prove significant, the simulation will be used to develop procedures or instrumentation to ease the pilot's control task during encounters with turbulence.

Conclusions

In summary, the NASA programs have indicated that:

1) For the higher flight altitudes (40,000 to 75,000 ft) turbulence is both less frequent and less severe than for the lower altitudes (20,000 to 40,000 ft). Turbulence appears to be present at the high altitudes less than 1% of the time. The frequency of occurrence of given values of gust velocity for the high altitudes is roughly $\frac{1}{10}$ of that for the lower altitudes.

2) In general, the intensity of the turbulence decreases in an orderly pattern with increasing altitude throughout the altitude range (20,000 to 75,000 ft) covered by the data. A notable exception to this orderly pattern is present in the data for the operations over Japan in that the altitude interval of 50,000 to 60,000 ft appears more turbulent than the lower altitude interval (20,000 to 40,000 ft). Moderately heavy turbulence appears to exist on occasion at altitudes of about 50,000 ft over Japan.

3) The results indicate that for altitudes of 20,000 to 75,000 ft, less than 50% of the turbulent areas exceeded 10 miles in length. For operations over three of the geographical areas, only about 1% of the turbulent areas exceeded 30 miles in length. For the operations over Japan and the southern U. S., however, approximately 10% of the turbulent areas exceeded 30 miles in length.

4) The maximum value of $U_{de}(\rho_0/\rho)^{1/2}$ (a rough approximation of the intensity of the true gust velocity) measured is approximately 58 fps encountered at an altitude of 52,000 ft.

5) Clear air turbulence spectra are still to be defined to wavelengths of possibly 14,000 ft and for the higher altitudes.

References

[1] Coleman, T. L. and Steiner, R., "Atmospheric turbulence measurements obtained from airplane operations at altitudes be-

tween 20,000 and 75,000 ft for several areas in the northern hemisphere," NASA TN D-548 (1960).

[2] Taback, I., "The NACA oil-damped V-G recorder," NACA TN 2194 (1950).

[3] Richardson, N. R., "NACA VGH recorder," NACA TN 2265 (1951).

[4] "The thunderstorm: report of the thunderstorm project," Weather Bureau, U. S. Dept. of Commerce, Washington, D. C. (June 1949).

[5] Staff, "National severe storms project objectives and basic design," Rept. 1, National Severe Storms Project, Weather Bureau, U. S. Dept. of Commerce, Washington, D. C. (March 1961).

[6] Press, H. and Steiner, R., "An approach to the problem of estimating severe and repeated gust loads for missile operations," NACA TN 4332 (1958).

[7] Pratt, K. G. and Walker, W. G., "A revised gust-load formula and a re-evaluation of V-G data taken on civil transport airplanes from 1933 to 1950," NACA Rept. 1206 (1954).

[8] Notess, C. B., "The effects of atmospheric turbulence upon flight at low altitude and high speed," Frequency Div. Multiplex 325, Cornell Aeronautical Lab., Inc. (October 31, 1961).

[9] Rhyne, R. H. and Steiner, R., "Power spectral measurement of atmospheric turbulence in severe storms and cumulus clouds," NASA TN D-2469 (1964).

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Parachute Stress Analysis during Inflation and at Steady State

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The stresses occurring in the cloth of a parachute during the period of inflation and at steady state are calculated for a number of instantaneous shapes that are characteristic of the opening process and the steady state. The method is general and may be applied to any type of parachute built out of solid cloth, concentric rings, or ribbons. The presented analysis is related to canopies consisting of triangular gores but can be extended to other gore patterns. A numerical calculation is made for a solid flat circular parachute during the period of opening and at steady state.

Nomenclature

b_0 = a length (Figs. 4 and 5)
C_p = pressure coefficient
D = projected diameter
D_0 = canopy nominal diameter
D_v = vent diameter
d_0 = a length (Fig. 5)
E = cloth modulus of elasticity, lb/ft
f_1 = circumferential stress (Fig. 2), lb/ft
f_2 = meridional stress (Fig. 2), lb/ft
F = force between canopy and store (Fig. 4)
F_{max} = opening force or opening shock
N = number of gores
plane Q = illustrated in Fig. 4
Δp = pressure differential across cloth (Fig. 5)
q = dynamic pressure $\equiv \frac{1}{2}\rho V^2$
r_b = bulge radius (Figs. 2 and 5)
S = area
S_0 = canopy nominal area
s = a length (Figs. 2 and 6)
t = time
t_f = filling time
V = velocity
V_0 = initial velocity
W_s = store weight
x = a length (Figs. 2 and 4)
y = a length (Fig. 5)
z = a length (Fig. 4)
α = gore half-angle (Fig. 5)
ϵ = strain
θ = angle between suspension lines and canopy centerline (Fig. 4)
λ^* = a dimensionless parameter [Eq. (23)]
ρ = radius of curvature (Fig. 2)
ϕ = an angle (Fig. 4)

Superscript

$*$ = a dimensionless quantity

Subscripts

0 = initial or unstretched condition
c = referred to cord line
g = referred to gore centerline
∞ = freestream conditions

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I. Introduction

THE known analytical studies of parachute stresses are primarily concerned with the steady-state phase, during which the drag of the parachute equals the suspended weight. The earliest studies of the canopy stresses have been summarized by Jones in 1923,[1] and they consider the canopy shapes and stresses under the assumption of an infinite number of gores.

In 1942, Stevens and Johns[2] introduced into the basic analysis the concept of a finite number of gores and also