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AIRSPEED FLUCTUATIONS AS A MEASURE OF ATMOSPHERIC TURBULENCE

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SUMMARY

Because of the need for a reliable quantitative method of reporting atmospheric turbulence from airplanes in flight, the rapid fluctuations in the pilot's indicated-airspeed readings in rough air were analyzed in relation to control difficulties experienced by the pilot and to structural loads. The data used for this purpose were obtained with the XC-35 airplane in flight through cumulus, cumulus-congestus, and cumulo-nimbus clouds.

The rapid fluctuations in the pilot's indicated-airspeed readings were found to apply with small error to the estimation of the structural loads resulting from flight in turbulent air. Data obtained from the airspeed meter, as in the case of acceleration data, however, do not permit accurate estimation of the control difficulties due to atmospheric turbulence that are experienced by the pilot.

INTRODUCTION

A reliable method by which pilots can make reports during flight of the intensity of atmospheric turbulence encountered has long been needed in order to provide quantitative data on the turbulence that would be of common significance to the meteorologist, the pilot, and the airplane designer. Various methods for reporting turbulence have been used, but the results obtained have been unsatisfactory because the reports are not standardized and cannot be converted to the desired form of data. For example, scales of turbulence based on the pilot's observations of the behavior and control response of the airplane in rough air (references 1 and 2) cannot be conveniently interpreted because the reactions of an airplane to atmospheric gusts, and consequently the pilot's opinion of the turbulence, depend upon the airplane characteristics and flight speed as well as upon the gust velocities. Attempts to utilize data obtained solely from the measured accelerations of an airplane have been unsuccessful for similar reasons.

Consideration of the difficulties which have been experienced indicates that, in order to obtain the desired results regardless of the type of airplane, the reports of atmospheric turbulence should be independent of the airplane characteristics, the flight speed, and the judgment of the pilot. A convenient method of obtaining such data on the turbulence is the use of the rapid fluctuations in the pilot's indicated-airspeed readings, which are a measure of the horizontal components of gusts that are encountered by the pitot-static head of the airplane. Unpublished data have shown that horizontal and vertical components of gusts of equal intensity occur with equal frequency in a given region of the atmosphere and, although equal horizontal and vertical intensities are not in general encountered simultaneously, the fluctuations in the airspeed indications may be considered a measure of the vertical as well as the horizontal components of the gusts. Control difficulties experienced by the pilot and gust loads imposed upon the structure during flight in turbulent air, however, result from the action of gusts over the entire airplane whereas fluctuations in the pilot's indicated-airspeed readings are point measurements of the gusts. The present work, therefore, was undertaken to determine whether the fluctuations in indicated airspeed are significant in relation to control problems and to structural loads.

During tests in which the XC-35 airplane was flown in turbulent air within clouds (reference 3), data on the fluctuations in the pilot's indicated-airspeed readings and on the disturbed angular motions of the airplane as indicated by the pertinent navigation instruments were obtained. Because control difficulties experienced by the pilot in maintaining the desired flight path are indicated by the amplitudes of the disturbed angular motions of the airplane, these data have been used to determine the significance of the fluctuations in the pilot's indicated-airspeed readings in relation to difficulty of control.

Increments in structural loads due to atmospheric turbulence can be accurately expressed in terms of flight speed and effective gust velocities (reference 4). Data from which the effective gust velocities could be computed were also obtained during the flights of the XC-35 airplane. These data have been used to determine the significance of the fluctuations in the pilot's indicated-airspeed readings in relation to structural loads due to atmospheric turbulence.

APPARATUS

The XC-35 airplane is a revised model of the Lockheed 10-E, and the two airplanes may be considered to have the same handling qualities. Pertinent dimensions of the XC-35 airplane are given in the following table:

Gross weight at take-off, pounds	11,139
Wing area, square feet	458.3
Wing loading at take-off, pounds per square foot	24.3
Mean aerodynamic chord, feet	9.23
Span, feet	55
Length, feet	39
Slope of lift curve, per radian	3.95

A sketch showing the arrangement and location of the pilot's airspeed installation in the airplane is given as figure 1.

The special instruments used in the airplane to obtain the desired data were:

(1) Ciné-Kodak Special 16-millimeter motion-picture camera

(2) NACA air-damped recording accelerometer

(3) NACA airspeed recorder

(4) NACA timer (1-sec interval)

The motion-picture camera was used to obtain records of the indications of the pilot's artificial horizon, directional gyro, and clock. The camera was operated at a film speed of 8 frames per second and was fitted with a magazine holding sufficient film for approximately 8 minutes of record. The airspeed recorder and accelerometer were operated at a film speed of 1/8 inch per second and carried sufficient film for 30 minutes of record. The timer was used to synchronize the records from the airspeed recorder and accelerometer. The switch controlling the instrument operation was arranged so that the motion-picture camera would operate concurrently with the acceleration and airspeed recorders.

TEST METHODS

The method of conducting the flight tests consisted in making successive traverses through cumulus, cumulus-congestus, and cumulo-nimbus clouds with the airplane. Before the airplane entered a cloud it was trimmed for steady level flight, and during passage through the cloud the pilot attempted to use a minimum of control consistent with safety. Clouds were traversed at various altitudes ranging from approximately 5,000 to 34,000 feet, and traverses varied in length from about 1/2 to 15 miles.

The method of obtaining data consisted in taking continuous motion pictures of the pilot's airspeed meter, artificial horizon, directional gyro, and clock, and simultaneously taking records of acceleration and airspeed during each traverse through clouds.

RESULTS

The total amplitude (the difference between opposite extremes) of the indications of the artificial horizon and directional gyro were obtained from the motion-picture records of these instruments for each traverse through rough air. The maximum amplitude of the rapid fluctuations in the pilot's indicated-airspeed readings was also obtained from the motion-picture records for each traverse. Typical time histories of the pilot's airspeed indications and of the motions of the airplane in roll, heading, and pitch for a part of a traverse are shown in figure 2. This figure illustrates the method of obtaining the data from the motion-picture records.

The effective gust velocities evaluated from the airspeed and acceleration records by means of the sharp-edged-gust formula (equation (1) of reference 4) and summarized in figure 5 of reference 3 were used to obtain the maximum effective gust velocity $U_{e_{max}}$ for each traverse of the present analysis. All effective gust velocities evaluated for the part of the traverse indicated are also shown in figure 2.

The value of $U_{e_{max}}$ found for each traverse made during 12 flights picked at random from the data of reference 3 was plotted against the maximum value of the rapid fluctuation in the pilot's indicated-airspeed readings for the corresponding traverse (fig. 3). Figure 3 is used to determine the significance of the pilot's airspeed fluctuations as a measure of the effective gust velocities. The total amplitudes of the motions of the airplane in roll, heading, and pitch as obtained from the motion-picture records of the instrument panel were also plotted against the corresponding maximum rapid fluctuations in the pilot's indicated-airspeed readings in figures 4, 5, and 6, respectively, to determine the significance of the airspeed fluctuations as a measure of the disturbed angular motions of the airplane in rough air. Table I gives the coefficients of correlation (obtained by the methods of reference 5) for the data of figures 3 to 6.

PRECISION

The accuracy of the effective gust velocity depends upon the precision with which the indicated airspeed and the acceleration increment of the airplane can be measured. From a consideration of the precision of these measurements, the evaluated maximum effective gust velocities are estimated to be accurate within ±4 feet per second.

The accuracy to which the indications of the various flight instruments were read from the motion-picture records is estimated to be as follows:

Airspeed, miles per hour	±2
Angle of roll, degrees	±2
Angle of heading, degree	±1
Angle of pitch, degree	±1

DISCUSSION

Figure 3 indicates that the maximum rapid fluctuation in the pilot's indicated-airspeed readings $\Delta V_{i_{max}}$ which occurs over a period of flight in turbulent air is proportional to the maximum effective gust velocity $U_{e_{max}}$ computed from the acceleration and airspeed measurements over the same period. This result and the corresponding correlation coefficient between $\Delta V_{i_{max}}$ and $U_{e_{max}}$, (table I) indicate that the rapid fluctuations in indicated airspeed are significant in relation to the gust loads applied to the structure of an airplane in spite of the fact that values of $U_{e_{max}}$ represent an average vertical gust velocity along the span whereas the airspeed indications are point measurements of the gust velocity.

The experimental data plotted in figure 3 apply only to the XC-35 airplane because the effective gust velocities depend upon the airplane characteristics. For this reason a general expression for determining the effective gust velocities for conventional airplanes from the gust velocities indicated by the rapid fluctuations in the pilot's indicated-airspeed readings would be desirable. Such an expression, which should be reasonably satisfactory for conventional airplanes, may be obtained by using the relationship (theoretically and experimentally verified by references 4 and 6, respectively) that shows the acceleration increment of an airplane in traversing a constant-gradient gust to be a linear function of the gust velocity for any given set of conditions. The ratio of the actual acceleration increment Δn of an airplane in a gust of any gradient to the computed acceleration increment Δn_s obtained by using the actual gust velocity in the sharp-edged-gust formula may therefore be considered to be the ratio of the effective gust velocity to the actual gust velocity; that is.

$$\frac{\Delta n}{\Delta n_s} = \frac{U_e}{U_i} \qquad (1)$$

where

U_e effective gust velocity, feet per second

U_i actual indicated gust velocity, feet per second

According to unpublished data for conventional airplanes, the gust velocity for the most probable gust increases from zero to its maximum value in about 9 chords. For this gust, the acceleration ratio was found from equation (4) of reference 4 to be 0.65 ± 0.1 for conventional airplanes. As has been noted, the horizontal gusts indicated by the rapid airspeed fluctuations ΔV_i are a measure of the actual vertical gusts U_i. When U_i in feet per second is replaced by $\Delta V_{i_{max}}$ in miles per hour, $U_{e_{max}}$ is written instead of U_e since only maximum values are involved, and 0.65 is substituted for $\Delta n/\Delta n_s$, equation (1) becomes

$$0.65 = \frac{U_{e_{max}}}{1.47\Delta V_{i_{max}}}$$

or

$$U_{e_{max}} = 0.95\Delta V_{i_{max}} \qquad (2)$$

Equation (2) is plotted in figure 3 and the curve shows good agreement with the experimental data for the XC-35 airplane.

It is apparent from figures 4 to 6 and the corresponding correlation coefficients (table I) that the correlation between the maximum rapid fluctuations in the pilot's indicated-airspeed readings in turbulent air and the disturbed angular motions of the airplane in roll, heading, and pitch are not sufficiently high to permit accurate prediction of these motions of the airplane from the airspeed data. This result is evidently due to the fact that the disturbed angular motions of the airplane in turbulent air, even with fixed stability and piloting technique, are dependent not so much upon the maximum intensity of a single gust as upon the sequence, spacing, and intensity of all the gusts encountered. Other factors affecting the angular motions of the airplane are the spatial extent and unsymmetrical components of the gusts in both the horizontal and vertical directions. Measurements of all these quantities cannot be obtained from the pilot's airspeed fluctuations, and for this reason the airspeed data are not readily adapted to the study of control problems arising during flight in turbulent air.

The indicated gust velocities obtained from the rapid fluctuations in the pilot's indicated-airspeed readings may be converted to true gust velocities, the form of data used by meteorologists, by correcting for altitude.

Additional attention of the pilot to the airspeed meter would be required in order to note the fluctuations in the readings for the turbulence reports. If experience shows that the pilot cannot note these fluctuations, an instrument for holding the visual indications for short time intervals or a recording instrument would be required. An instrument of this type might consist basically of a total-pressure capsule in a sealed case with a capillary leak in the capsule that will bypass slow changes in total pressure but remain sensitive to rapid changes like those indicated by the rapid fluctuations in the airspeed readings in figure 2. Such an instrument could be either an indicating or a recording type.

CONCLUSIONS

From an analysis of the rapid fluctuations in the pilot's indicated-airspeed readings in turbulent air in relation to the disturbed angular motions of the XC-35 airplane and to effective gust velocities, the following conclusions are made:

1. The maximum rapid fluctuations that occur in the pilot's indicated-airspeed readings are proportional to the maximum effective gust velocities.

2. For computing structural loads for conventional airplanes, the maximum rapid fluctuations in the pilot's indicated-airspeed readings $\Delta V_{i_{max}}$ in miles per hour may be converted to maximum effective gust velocities $U_{e_{max}}$ in feet per second by the relation $U_{e_{max}} = 0.95\Delta V_{i_{max}}$.

3. Data obtained from the rapid fluctuations in the pilot's indicated-airspeed readings cannot readily be adapted to the study of control problems resulting from atmospheric turbulence.

4. Data on the gust velocities obtained from the rapid fluctuations in the pilot's indicated-airspeed readings may be readily converted to true gust velocities, which is the form used by meteorologists.

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REFERENCES

1. Kaul, Hans W.: Statistical Analysis of the Time and Fatigue Strength of Aircraft Wing Structures. NACA TM No. 992, 1941, p. 22.

2. Harrison, L. P.: Atmospheric Turbulence. Pt. III. Soaring, May-June 1942, p. 9.

3. Moskovitz, A. I.: XC-35 Gust Research Project Bulletin No. 8 - Analysis of Gust Measurements. NACA RB No. L4D22, 1944.

4. Rhode, Richard V.: Gust Loads on Airplanes. SAE Jour., vol. 40, no. 3, March 1937, pp. 81-88.

5. Kenny, John F.: Mathematics of Statistics. Pt. I. D. Van Nostrand Co., Inc., 1939, pp. 183-186.

6. Donely, Philip: An Experimental Investigation of the Normal Acceleration of an Airplane Model in a Gust. NACA TN No. 706, 1939, p. 10 and figs. 11-16.

TABLE I

CORRELATION COEFFICIENTS BETWEEN MAXIMUM RAPID AIRSPEED FLUCTUATIONS AND PARAMETERS OF MOTION OF XC-35 AIRPLANE IN TURBULENT AIR

Quantities correlated with maximum rapid airspeed fluctuation $\Delta V_{i_{max}}$	Coefficient of correlation
Maximum effective gust velocity $U_{e_{max}}$	0.928
Maximum total angle of roll	.557
Maximum total angle of heading	.180
Maximum total angle of pitch	.180

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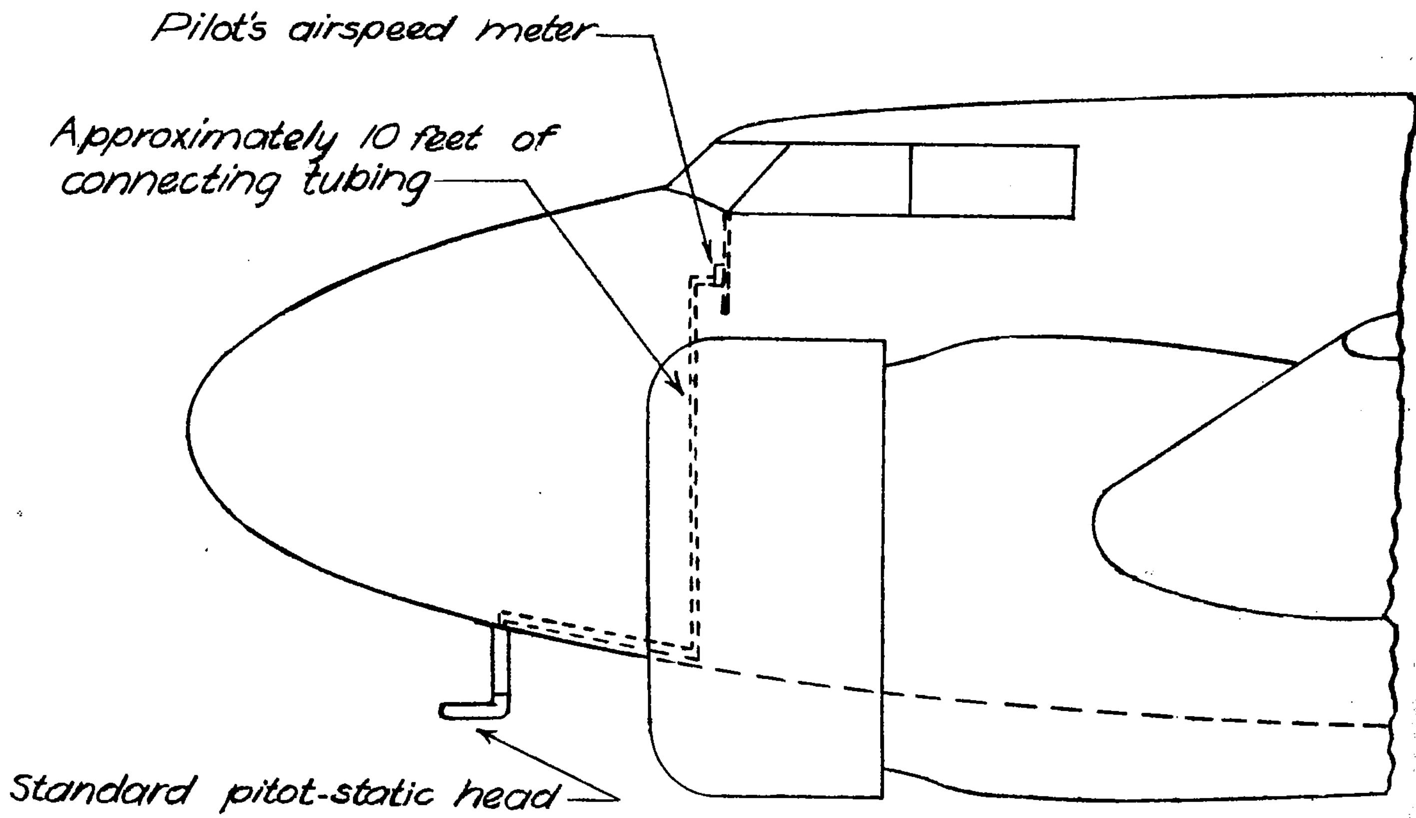

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Figure 1.- Arrangement and location of pilot's airspeed installation in XC-35 airplane.

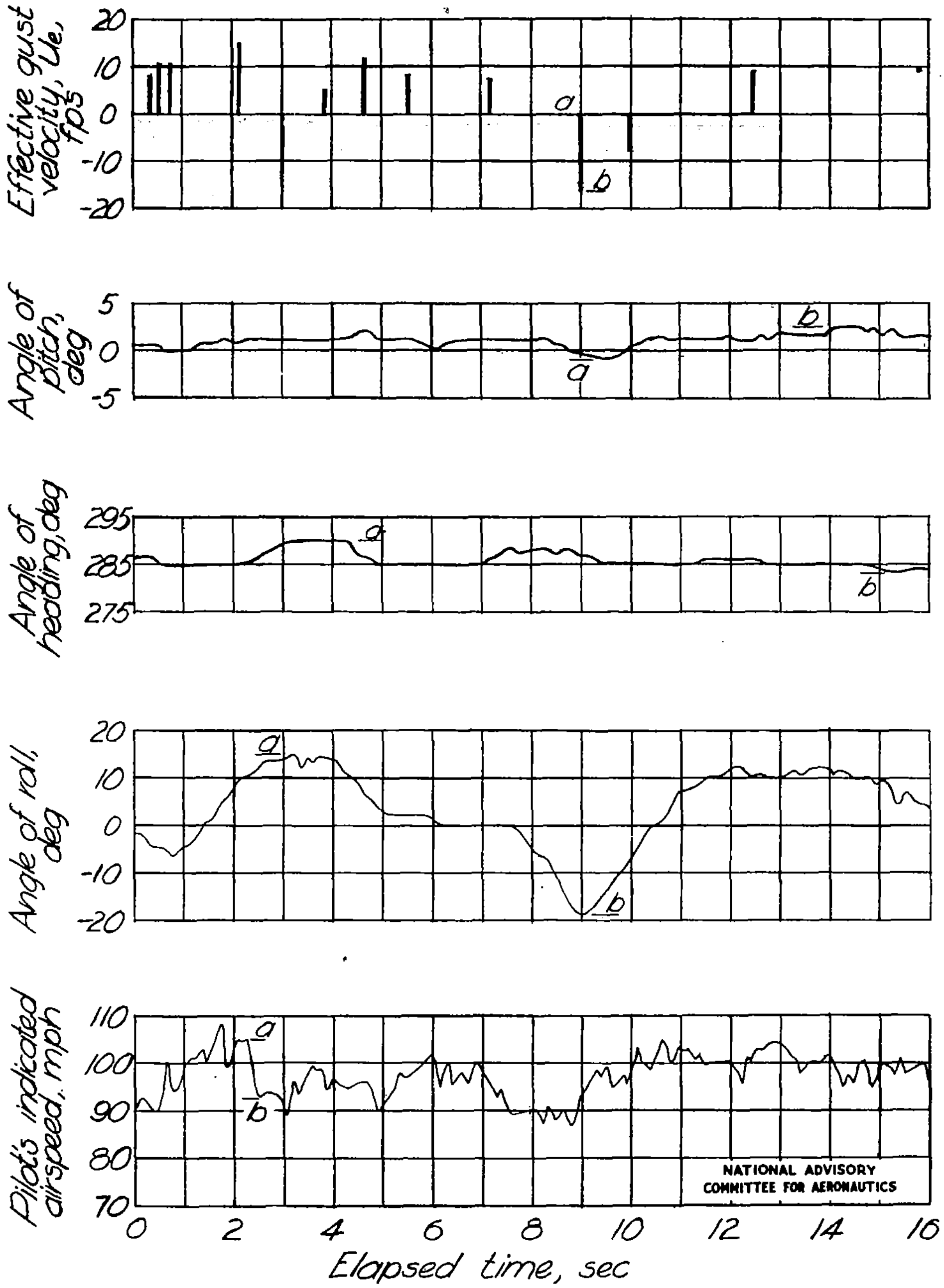

Figure 2.- Typical time histories of pilot's indicated airspeed and angular motions of XC-35 airplane for a part of a traverse in rough air, together with evaluated effective gust velocities. Increments indicated by intervals a-b represent values read.

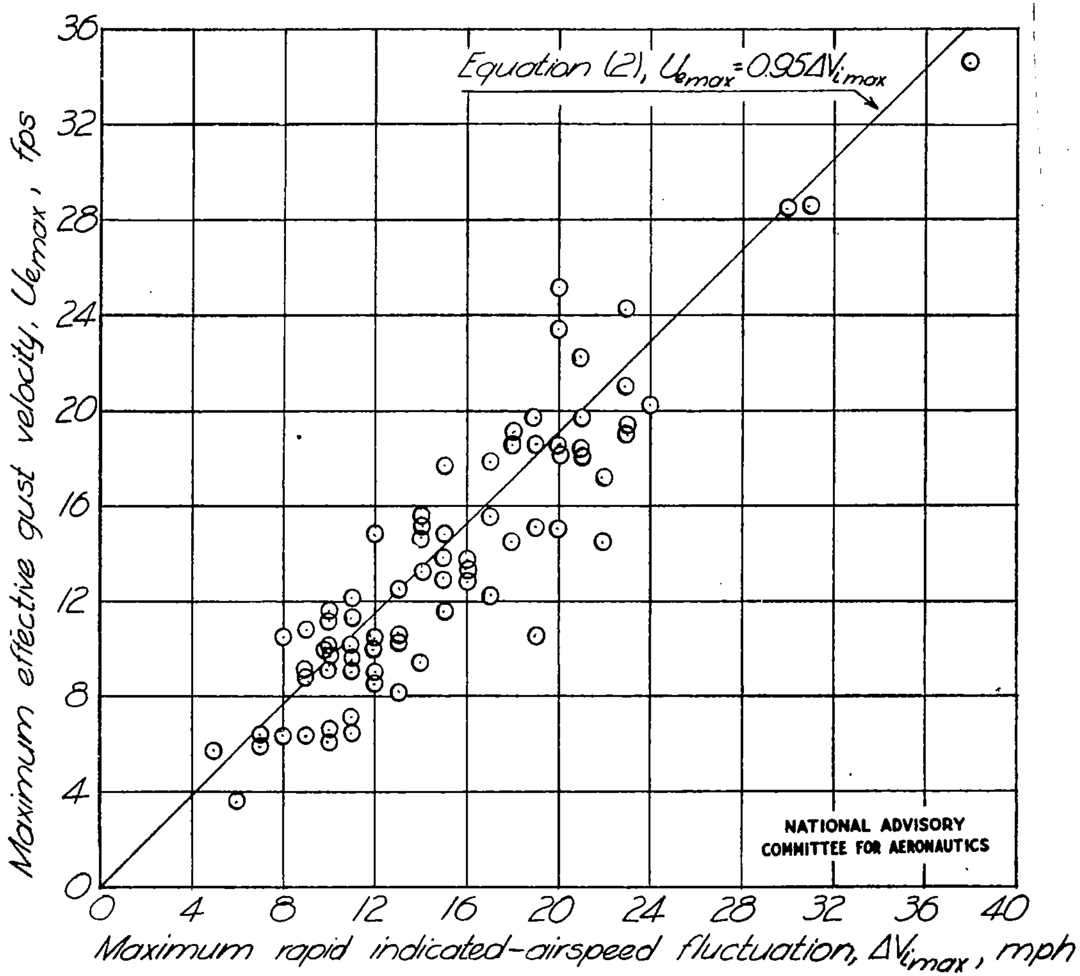

Figure 3.- Comparison of maximum effective gust velocity for XC-35 airplane with maximum rapid indicated-airspeed fluctuation for separate troverses in rough air. (Values of $U_{e_{max}}$ taken from reference 3.)

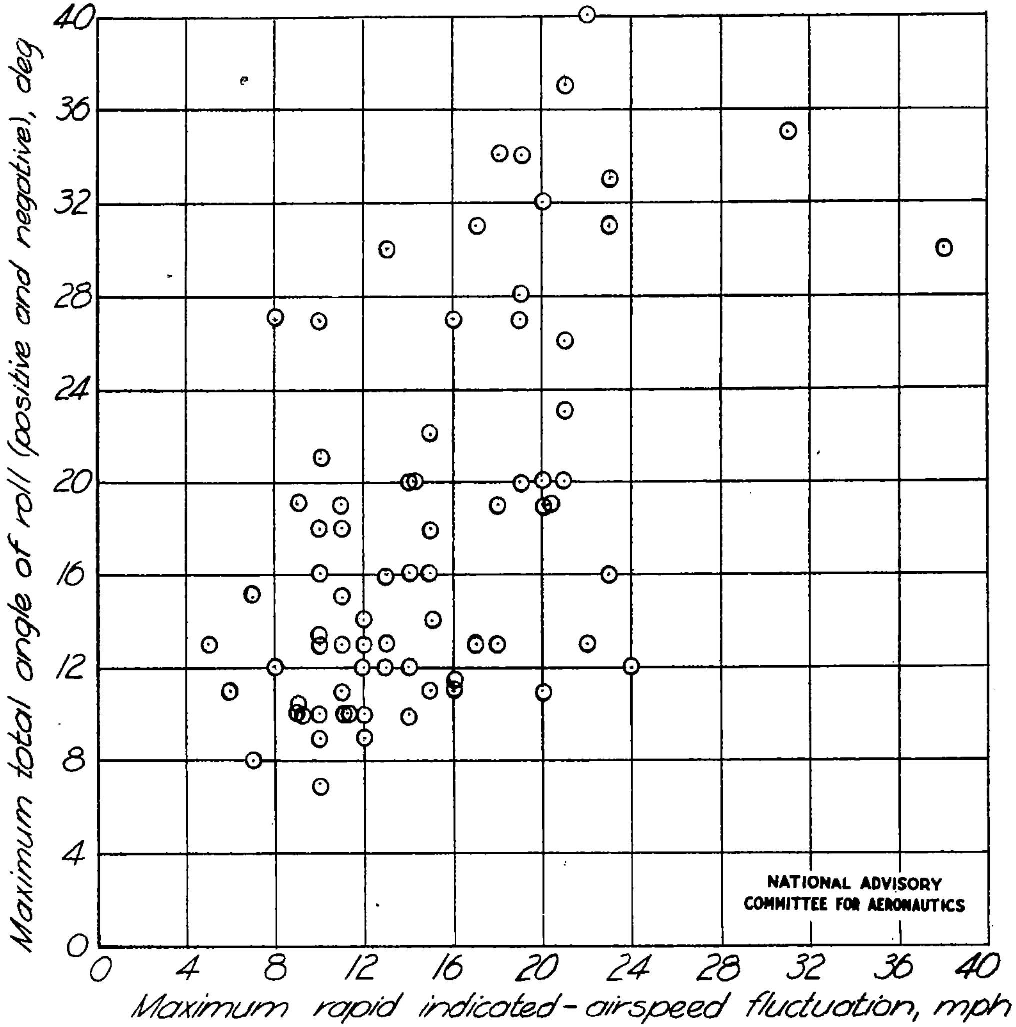

Figure 4.- Comparison of maximum total angle of roll of XC-35 airplane with maximum rapid indicated-airspeed fluctuation for separate traverses in rough air.

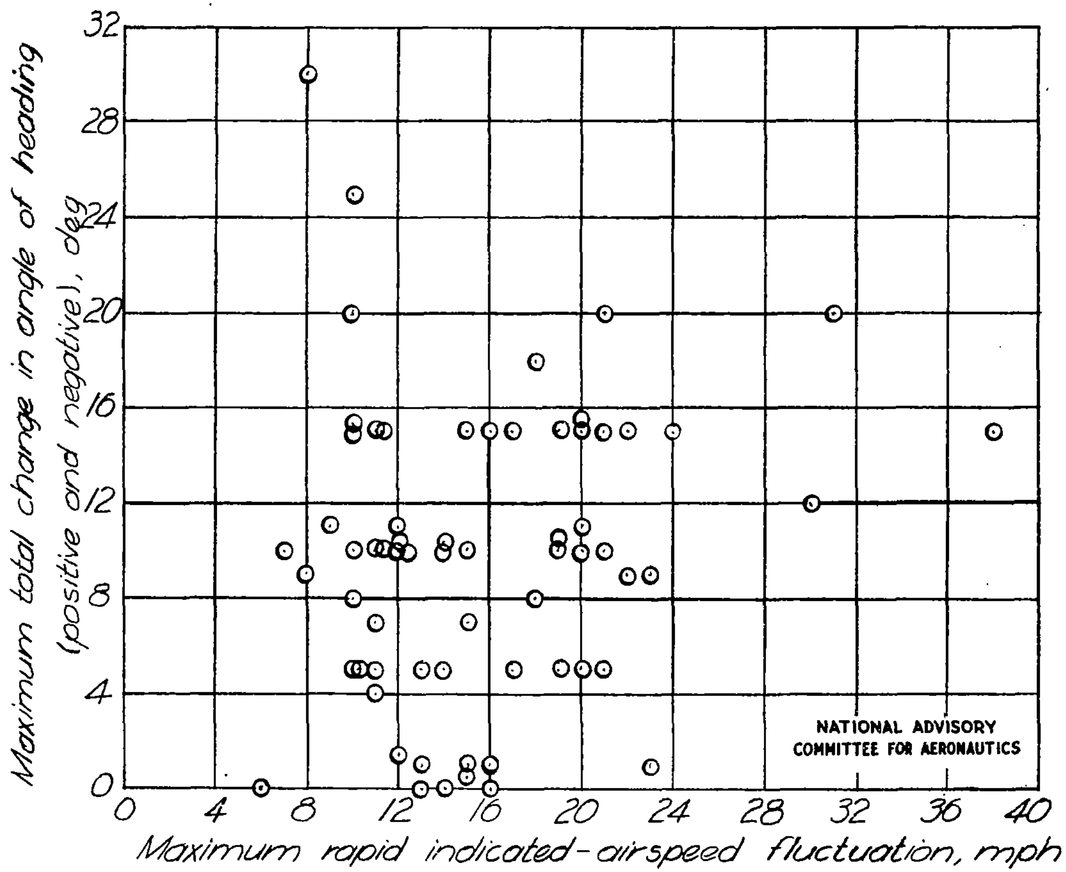

Figure 5.- Comparison of maximum total change in angle of heading of XC-35 airplane with maximum rapid indicated-airspeed fluctuation for separate traverses in rough air.

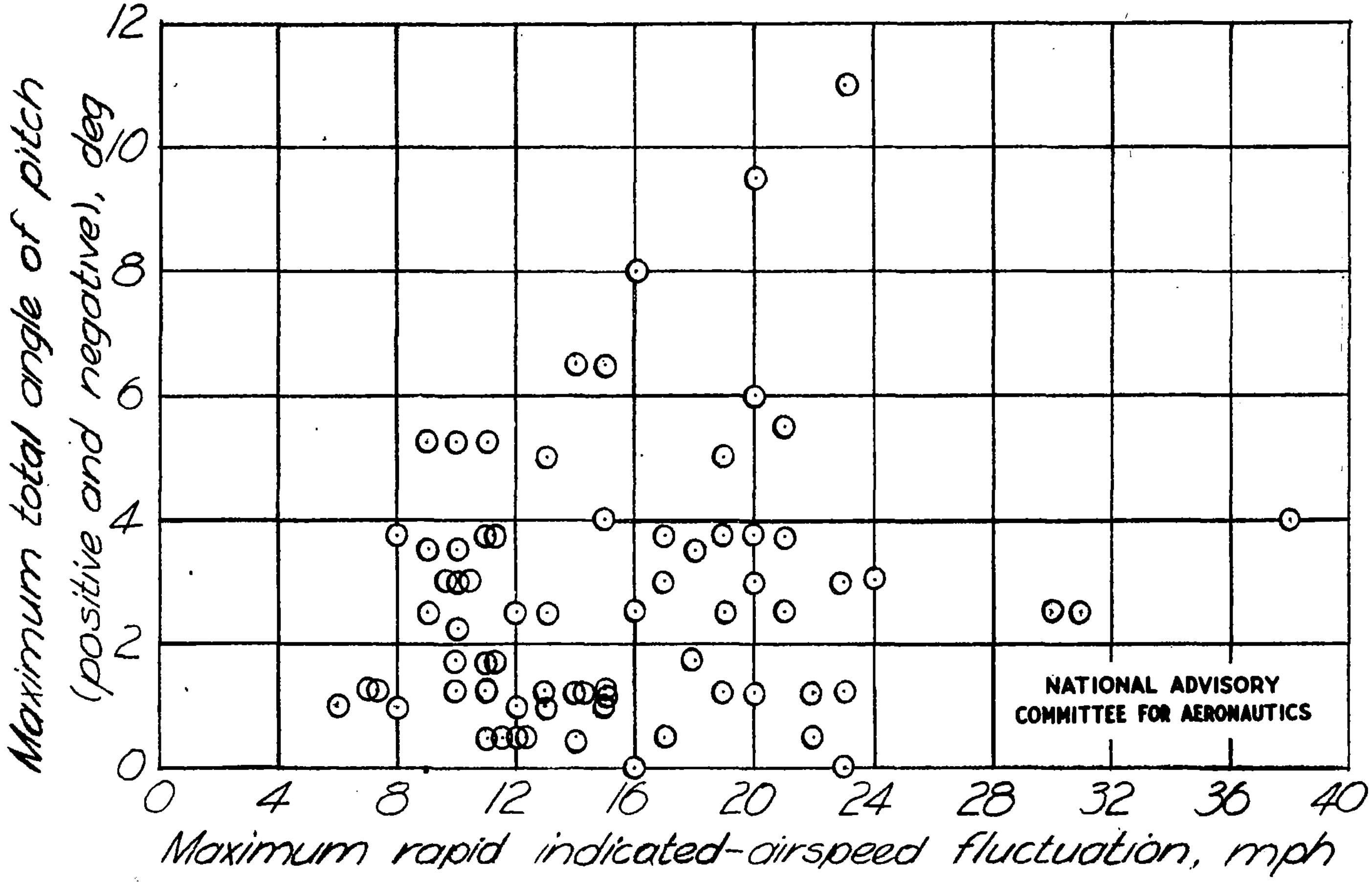

Figure 6.- Comparison of maximum total angle of pitch of XC-35 airplane with maximum rapid indicated-airspeed fluctuation for separate traverses in rough air.