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RESEARCH MEMORANDUM

AN INVESTIGATION OF A METHOD TO INDICATE ATMOSPHERIC TURBULENCE FROM AN AIRPLANE IN FLIGHT

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AN INVESTIGATION OF A METHOD TO INDICATE ATMOSPHERIC TURBULENCE FROM AN AIRPLANE IN FLIGHT

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SUMMARY

An instrument to indicate atmospheric turbulence from an airplane in flight has been constructed and subjected to laboratory and flight tests. The design of the instrument was based on previous findings that the rapid fluctuations of the airspeed in gusty air constitute a measure of atmospheric turbulence. The instrument consists essentially of a vented airspeed diaphragm in a sealed case with the lag characteristics of the vent chosen so that the diaphragm responds to the rapid changes in dynamic pressure in gusty air but remains insensitive to gradual changes resulting from normal airspeed variations.

Flight and laboratory tests have shown that the instrument has satisfactory response to gusts, although errors in the measurements result from the changes in total pressure accompanying climbing or descending flight. Further design refinement to eliminate these errors is necessary before the instrument can be considered suitable for routine service use.

INTRODUCTION

Reports of the intensity of atmospheric turbulence encountered by airplanes in flight are of appreciable value not only for flight control and dispatching purposes but also in connection with airplane structural design problems and meteorological studies. Although current methods for estimating turbulence from the pilot's observations of the airplane behavior have been of value to operators for dispatching purposes, the subjective reports are not suited for analysis by the engineer and meteorologist. The difficulties experienced in past attempts to rationalize the pilot's reports of turbulence indicate that the reports should be in quantitative form and independent of the airplane and pilot response.

Previous work (reference 1) has indicated that measurements of the turbulence independent of the airplane and pilot may be obtained from rapid fluctuations in indicated airspeed readings. Such fluctuations are a measure of the horizontal components of gusts, and although equal horizontal and vertical gust intensities are not generally encountered simultaneously, reference 1 indicates that the fluctuations may be considered a measure of the vertical as well as the horizontal components of gusts. In an attempt to obtain an objective method for determining atmospheric turbulence, the development of an instrument for indicating horizontal gust velocities by measuring the rapid fluctuations in indicated airspeed was undertaken by the National Advisory Committee for Aeronautics. The operation of the instrument is described in this paper together with an analysis of limited test data obtained during its investigation.

PRINCIPLE OF OPERATION

The operation of the turbulence indicator is based on the fact that changes in impact pressure occurring at the pitot tube when horizontal gusts are encountered are rapid and of short duration as compared with the slow and long period changes for normal variations in flight speed. The formula that relates the change in impact pressure to the change in indicated airspeed at the pitot tube when a gust is encountered in steady flight can be readily derived from

$$\Delta q = \frac{1}{2}\rho_o(V_i + \Delta V_i)^2 - \frac{1}{2}\rho_o V_i^2 \tag{1}$$

which is equal to

$$\Delta q = \pm\rho_o V_i \, \Delta V_i + \frac{1}{2}\rho_o \, \Delta V_i^2 \tag{2}$$

where

Δq change in impact pressure, pounds per square foot

ρ_o sea-level air density, slugs per cubic foot

V_i indicated airspeed prior to encountering gust, feet per second

ΔV_i indicated gust velocity, feet per second

Since V_i is large compared to ΔV_i, errors generally less than 2 percent result from neglecting the second-order term of equation (2). The relation then becomes

$$\Delta q = \pm\rho_o V_i \, \Delta V_i \tag{3}$$

or

$$\Delta V_i = \frac{\pm \Delta q}{\rho_o V_i} \tag{4}$$

The indicated gust velocity is thus a linear function of the ratio of the change in impact pressure to indicated flight speed. The turbulence indicator described herein measures the ratio $\Delta q/V_i$ and, when properly calibrated, indicates the ratio in terms of gust velocity ΔV_i.

GENERAL DESCRIPTION

A photograph showing the external appearance of the gust detector, indicating unit, and power supply of the prototype of the turbulence indicator is given in figure 1. A drawing of the basic elements of the instrument is shown as figure 2.

As indicated in figure 2, the instrument consists of a sealed case containing two diaphragms which are connected by a linkage system. One diaphragm, referred to in the figure as the "gust diaphragm", has a high sensitivity and is vented to the interior of the case by a short length of capillary tubing. The interior of this diaphragm is vented to total pressure. The other diaphragm, referred to in the figure as the "airspeed diaphragm", has a lower sensitivity and is vented to static pressure. The ratio of the diaphragm deflections is determined by the linkage system. The resultant deflections of the linkage operate the brush-commutator assembly shown in figure 2 for actuating the electrical circuit of the gust indicating unit.

For the gradual variations in indicated airspeed that are normally experienced in flight, the pressures on either side of the gust diaphragm in figure 2 are equalized as a result of leakage through the capillary. When gusts are encountered, however, the capillary allows only small leakage of the sudden change in impact pressure from within the gust diaphragm to the case and a deflection occurs that corresponds to the pressure differential Δq across the diaphragm.

Since the average total pressure exists within the case because of leakage through the capillary, the differential pressure acting across the airspeed diaphragm is the average flight dynamic pressure. In order to obtain a deflection proportional to $\sqrt{q}$, and thereby proportional to V_i as required in equation (4), the airspeed diaphragm was connected to the cantilever spring system shown in figure 2. The spring constant of the system was varied by adjustable screws which shortened the effective cantilever length with increasing deflection. The screws were adjusted so that the airspeed diaphragm deflections were linear with indicated airspeed.

The movable arm connected to the airspeed diaphragm in figure 2 acts as a fulcrum between the gust diaphragm and the brush-commutator assembly and varies the magnification factor of the linkage with airspeed. Thus, for given values of Δq and V_i, the ratio $\Delta q/V_i$ is indicated by the position of the brush on the commutator. By proper calibration, the ratio $\Delta q/V_i$ is indicated in terms of gust velocity ΔV_i.

The indicating unit (figs. 1 and 2) consists of a bank of neon lamps to indicate the maximum positive gust and a counter to indicate the number of positive gusts above a given threshold. This manner of presentation of the gust experience of the airplane was arrived at on the basis of past analysis of gust measurements (reference 2) which indicate a substantially fixed gust frequency distribution for different regions of turbulence. With knowledge of the shape of the frequency distribution, reasonable estimates of the total gust experience for a period of flight can therefore be obtained from the number of gusts and the maximum gust velocity encountered.

During flight in rough air, the electrical circuit to the individual neon lamps in the indicating unit is closed as the brush sweeps across the various segments of the commutator. The commutator segments are spaced at 5-foot-per-second gust-velocity intervals as determined from static calibrations, and the lamps therefore indicate the maximum gust intensity within intervals of 5 feet per second. The electrical circuit retains the maximum gust indication until the reset button is pushed. The counter is also connected to the commutator circuit and gives a count of all gusts greater than 10 feet per second. The counter is not reset by the reset button but continuously totalizes the gusts above the counting threshold.

LABORATORY TESTS

Static tests of the turbulence indicator were made by stopping the capillary within the instrument case. A suction was then applied to the static connection so that the airspeed diaphragm was subjected to a differential pressure within the airspeed range of the instrument. With the airspeed held constant, various pressures were applied to the pitot connection. These pressures corresponded to the dynamic pressures of gusts in increments of 5 feet per second at the given airspeed. The tests were repeated for different airspeeds from 150 to 200 miles per hour.

In order to obtain the dynamic response characteristics, the capillary was opened and various pressure waves were applied to the pitot connection of the intrument. The pressure waves were of the shape shown by the insert in figure 3 and corresponded to gusts with a peak velocity of 15, 30, and 45 feet per second. The time of rise of the pressure waves from zero to peak was 0.3, 0.5, 1.0, 2.0, and 3.0 seconds, which correspond to gradient distances of from 5 to 25 chords for a large modern airplane flying at 200 miles per hour. Time constants at sea level of 2 and 3 seconds were obtained with the capillaries used for the tests. These time constants are a measure of the speed of response of the instrument-tubing system and were obtained by subjecting the capillary to a suddenly applied pressure and noting the time required for the pressure to reach 63 percent of its final value. In order to simulate conditions in an airplane installation, 15 feet of $\frac{3}{16}$-inch inside-diameter tubing was connected to the pitot lead for the tests.

The results of the tests are shown by the response curves in figure 3. In obtaining these curves, the ratio of the gust velocity indicated by the instrument to the applied gust velocity for the pressure waves shown was plotted against the time of rise of the pressure wave for the two values of time constant. Since the time constant of a capillary varies inversely with pressure and directly with air viscosity (reference 3), the dynamic response of the instrument varies with altitude. An estimate of the response at an altitude of 18,000 feet (approx. 1/2 atmosphere) is shown by the dashed curve in figure 3(a). In estimating this curve, the relatively small variation in viscosity was neglected and the effect of the doubled time constant due to the lowered pressure was approximated by multiplying the abscissa for the sea-level curve by a factor of 2.

Inasmuch as a pressure differential is establised across the gust diaphragm in ascent or descent because of the varying total pressure at constant indicated speed, tests were conducted to determine the "rate-of-climb" effect on the gust indications. In the tests, increasing pressures corresponding to various rates of descent at an indicated airspeed of 200 miles per hour were applied to the total-pressure connection of the turbulence indicator. These tests indicated that with the time constants of 2 and 3 seconds, a 10-foot-per-second gust was indicated when the descent rates at sea level were 2000 and 1200 feet per minute, respectively.

FACTORS AFFECTING INSTRUMENT PERFORMANCE

UNDER FLIGHT CONDITIONS

The response of the turbulence indicator depends not only on its own internal construction and time constant but also upon the characteristics of the pitot-tubing-instrument volume systems to which it is attached. The dynamic response of the instrument must be evaluated, therefore, as a complete installation. In order to maintain given response characteristics, a separate tubing lead to the pitot head may be required for some installations.

The prototype of this instrument was designed to operate between indicated airspeeds of 150 and 200 miles per hour and all testing was done between these limits. These limits can be extended, however, by selecting pressure diaphragms of the proper range.

The brush used in the brush-commutator assembly is a very small wire. It is possible that oxidation on the brush and commutator bars over a period of several months will cause the resistance between the two to break the electrical circuit. Although failures of this nature were not evident in 120 hours of flight, the testing was done in a period of approximately 3 months so that no aging effects could be observed.

FLIGHT TESTS

In order to obtain test data on the operation of the prototype of the airplane turbulence indicator, the instrument was installed in a four-engine bomber-type airplane of the Air Weather Service. The pitot-static leads from the turbulence indicator were connected by means of 15 feet of $\frac{3}{16}$ -inch inside-diameter tubing to a spare service airspeed tube mounted on the airplane. A standard NACA airspeed-altitude recorder and an NACA recording accelerometer were also installed in the airplane to measure the airspeed fluctuations as a check on the turbulence indicator and to allow computation of effective gust velocities for gust loads determination.

Fourteen weather reconnaissance flights were made with the instruments installed in the airplane. During the flights, readings were taken of the turbulence indicator together with recordings of airspeed, altitude, and acceleration whenever rough air was encountered.

A preliminary comparison of the turbulence indicator readings with the airspeed-altitude records for the first 12 flights indicated that the 3-second time constant of the instrument was too great since response was obtained in some cases to normal airspeed changes as well as to the rapid fluctuations in indicated airspeed. It was also noted that the climb and descent rates of the airplane in rough air were sufficient to cause erroneous gust indications. The time constant of the instrument was therefore decreased to approximately 2 seconds. Two flights were made subsequently with the readjusted instrument.

A summary is given in table I of the number of gusts greater than 10 feet per second and the maximum gust velocity within the 5-foot-per-second indicating intervals of the turbulence indicator from each run through rough air. The number of fluctuations in indicated airspeed greater than the instrument threshold of 10 feet per second and the maximum fluctuation as read from the airspeed records for each run are also summarized in the table. The fluctuations are defined as the changes in indicated airspeed that occur in an interval of 2 seconds or less. Check readings of the records indicated that the airspeed fluctuations in table I were read to an accuracy of ±1 foot per second.

The records of airspeed, altitude, and acceleration for each run were also evaluated to obtain the effective gust velocities above a threshold of 7 feet per second by the sharp-edge-gust formula (reference 2)

$$U_e = \frac{2 \Delta n \frac{W}{S}}{\rho_o V_e K \frac{dC_L}{d\alpha}}$$

where

U_e	effective gust velocity, feet per second
Δn	acceleration increment in gust, g units
$\frac{W}{S}$	airplane wing loading, pounds per square foot
V_e	equivalent airspeed, feet per second
K	gust alleviation factor
$\frac{dC_L}{d\alpha}$	slope of lift curve, radians

The 7-foot-per-second threshold of effective gust velocity corresponded to the counting threshold of a 10-foot-per-second indicated gust velocity for the turbulence indicator. This effective-gust-velocity threshold was approximated from the relation between effective and indicated gust velocities given in reference 1 as

$$\frac{\Delta n}{\Delta n_s} = \frac{U_e}{U_i}$$

where

Δn_s	acceleration increment obtained by using the actual gust velocity in the sharp-edge-gust formula, g units
U_i	indicated gust velocity, feet per second

For the test airplane, $\Delta n/\Delta n_s$ is equal to 0.7 for the most probable gust of about 10 chords.

The number of effective gust velocities greater than 7 feet per second and the maximum effective gust velocity for each run are shown in table I. Consideration of the accuracy of the airspeed-acceleration measurements would indicate that the effective gust velocities are accurate to within ±2 feet per second.

For ease of comparison, the number of gusts in table I for the turbulence indicator is shown plotted against the number of airspeed fluctuations greater than 10 feet per second in figure 4 and against the number of effective gust velocities greater than 7 feet per second in figure 5. Similarly, the maximum gust velocity from the turbulence indicator is plotted against the maximum airspeed fluctuation and the maximum effective gust velocity in figures 6 and 7, respectively. Parallel lines are shown in figures 6 and 7 spaced at an interval of 5 feet per second to show the indicating interval of the turbulence indicator. The parallel lines have a slope of 1.0 in figure 6 because of the one-to-one relation between the indicated gust velocities of both ordinate and abscissa. The parallel lines in figure 7, however, have a slope of 0.7 because of the relation between effective and indicated gust velocities discussed in the preceding paragraph.

DISCUSSION

Inspection of figure 3(a) indicates that with the 3-second capillary the gust velocities obtained from the turbulence indicator in level flight at sea level would be less than 10 percent in error for gusts with a time from zero to peak velocity of about 0.3 to 1.0 second. As altitude increases, this figure indicates that errors would decrease to 5 percent for gusts with a time from zero to peak velocity of 0.3 to 1.0 second and not be greater than 10 percent for gusts up to 2 seconds. With the 2-second capillary, figure 3(b) indicates that the errors tend to increase over those shown in figure 3(a) with increasing gust length. The time from zero to peak gust velocity of 0.3 to 1.0 second corresponds to gust gradient distances of about 5 to 25 chords for a large modern airplane flying at about 200 miles per hour. Since this range of gradient distance includes most of the significant gusts, the response of the turbulence indicator with a 3-second time constant appeared satisfactory in the laboratory tests.

Although the time constants shown in figure 3 were considered sufficiently small to cause the slow and long period changes in total pressure accompanying normal variations in flight speed to have little effect on the turbulence indicator, the total-pressure variations due to altitude changes in rough air were more serious. As has been indicated, laboratory tests showed that with the 3-second time constant, a descent velocity of 1200 feet per minute would cause a 10-foot-per-second gust to be indicated at the test speed. For smaller descent velocities and for climbing flight, the changing total pressure would affect the instrument as a zero shift. Errors in gust velocity measurement therefore result from the rate-of-climb effect on the present instrument.

The comparison of the gust counts and maximum gust velocity from the turbulence indicator with the airspeed fluctuations in figures 4 and 6 indicates an appreciable scatter in the data for the flights with the 3-second time constant. This result reflects the rate-of-climb effect on the instrument since an examination of the altitude records for these flights indicated ascent and descent velocities from about 500 to 2000 feet per minute. Although the scatter noted in figures 4 and 6 would indicate poor accuracy, the tendency for the points to spread along the one-to-one relation given by the dashed lines indicates that the basic operations of the instrument in measuring the airspeed fluctuations are being performed. The data from the flights after the capillary time constant was changed from 3 to 2 seconds might indicate some improvement, especially in the maximum indications of figure 6, but the number of points obtained were insufficient to determine whether the modification is adequate for routine operations.

Inspection of figures 5 and 7 indicates that the number of gusts obtained from the turbulence indicator are predominately higher than the number of effective gust velocities above 7 feet per second for the flights with the 3-second capillary in the instrument. This result might be due to a predominance of triangular-shaped gust-velocity distributions across the span (reference 4) or to the use of an effective-gust-velocity threshold that was slightly high. From the general scatter in these figures, it would appear that further experience under a variety of operating conditions would be required to determine the inherent errors of the instrument.

CONCLUDING REMARKS

On the basis of laboratory and flight tests of an instrument to indicate atmospheric turbulence from an airplane in flight, it is concluded that the basic operating principles of the prototype are satisfactory for obtaining in-flight reports of turbulence. Further refinements to the design are needed, however, to decrease errors resulting from rates of climb or descent of the airplane and to obtain the reliability required of a service instrument.

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TABLE I

SUMMARY OF GUST DATA OBTAINED FROM AIR WEATHER SERVICE AIRPLANE

Flight date	Run	Turbulence indicator		Recording instruments			
		Number of gusts greater than 5 fps	Maximum gust velocity (fps)	Number of effective gust velocities greater than 7 fps	Maximum effective gust velocity (fps)	Number of air-speed fluctuations greater than 10 fps	Maximum air-speed fluctuation (fps)
7-27-48	1	4	10 - 15	2	7.8	5	17.6
	2	0	0 - 10	1	8.1	1	14.0
	3	1	10 - 15	0	5.7	2	11.0
	4	3	10 - 15	0	6.9	1	10.3
	5	2	10 - 15	1	10.9	1	8.8
	6	0	10 - 15	1	8.6	0	9.8
7-30-48	1	1	10 - 15	1	7.2	2	13.9
	2	3	10 - 15	1	9.8	7	13.9
	3	2	10 - 15	0	6.4	2	10.9
8-7-48	1	1	10 - 15	0	6.2	2	13.1
8-11-48	1	8	10 - 15	5	10.8	9	19.8
	2	18	25 - 30	14	18.9	14	40.3
	3	9	10 - 15	7	11.3	12	27.8
	4	1	15 - 20	2	7.8	1	11.7
	5	7	15 - 20	3	17.1	8	22.7
	6	12	10 - 15	5	10.7	9	19.8
8-12-48	1	16	15 - 20	7	12.0	6	13.9
8-17-48	1	5	15 - 20	1	7.4	2	11.7
	2	5	10 - 15	2	7.5	0	9.5
	3	8	15 - 20	1	8.4	5	13.6
	4	10	15 - 20	9	9.4	7	13.9
8-19-48	1	8	20 - 25	4	12.0	7	20.8
	2	9	15 - 20	4	13.3	16	15.4
	3	11	25 - 30	5	12.0	14	19.8
	4	2	10 - 15	1	7.0	2	16.1
8-20-48	1	1	10 - 15	0	5.8	1	10.2
	2	2	10 - 15	1	7.9	0	----
	3	1	10 - 15	3	12.6	1	12.5
	4	6	15 - 20	7	15.1	14	21.0
8-21-48	1	1	10 - 15	2	10.3	3	11.0
	2	1	10 - 15	0	5.1	1	11.0
	3	1	10 - 15	0	4.6	0	----
10-9-48	1	3	10 - 15	3	9.2	3	16.0
12-9-48	1	14	10 - 15	14	8.8	10	13.2
	2	6	10 - 15	6	9.1	3	12.5

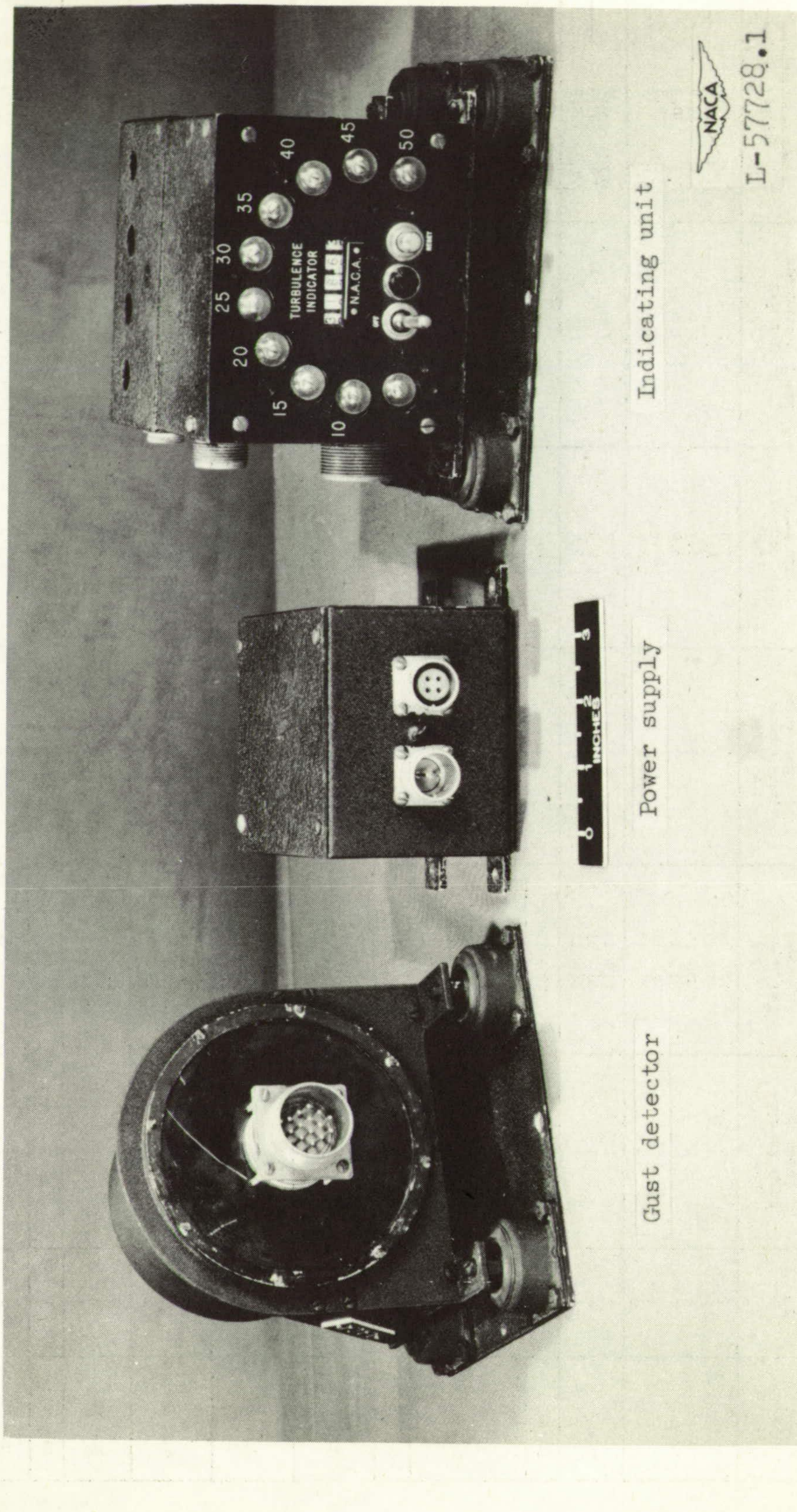


Figure 1.- Photograph of turbulence indicator.

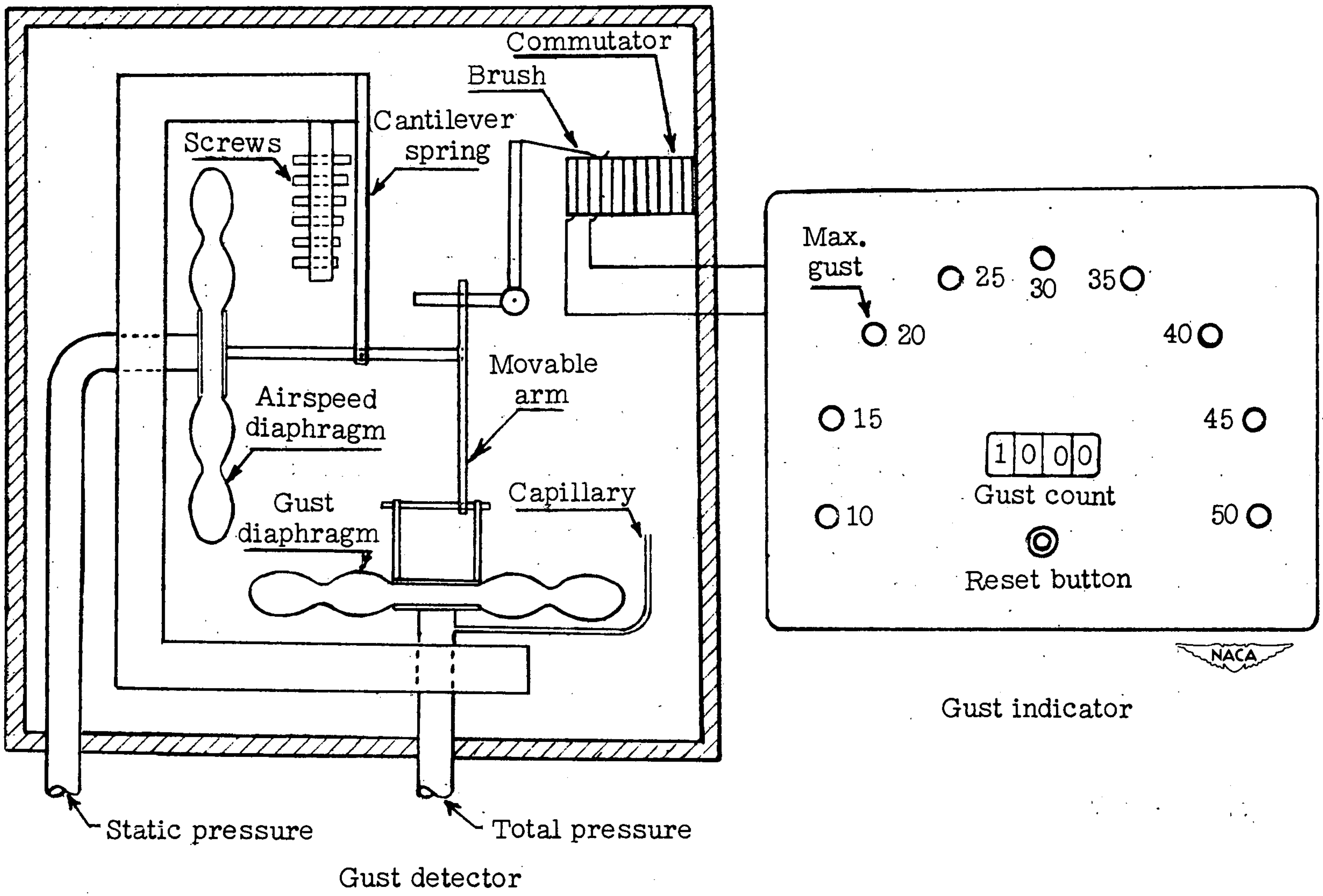
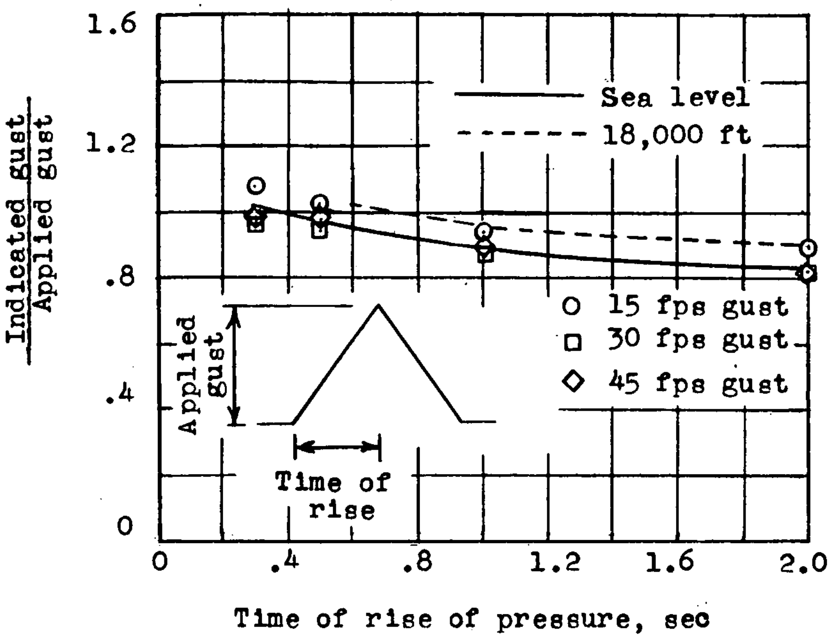
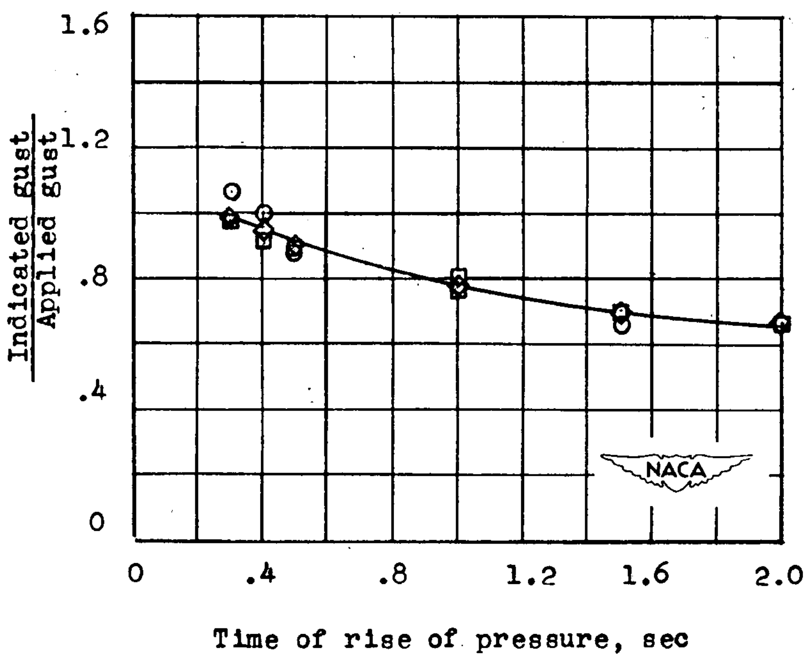


Figure 2.- Schematic diagram of turbulence indicator.



(a) 3-second capillary.



(b) 2-second capillary.

Figure 3.- Dynamic response characteristics of turbulence indicator with two values of capillary time constant and 15 feet of $\frac{3}{16}$-inch inside-diameter tubing connected to pitot lead.

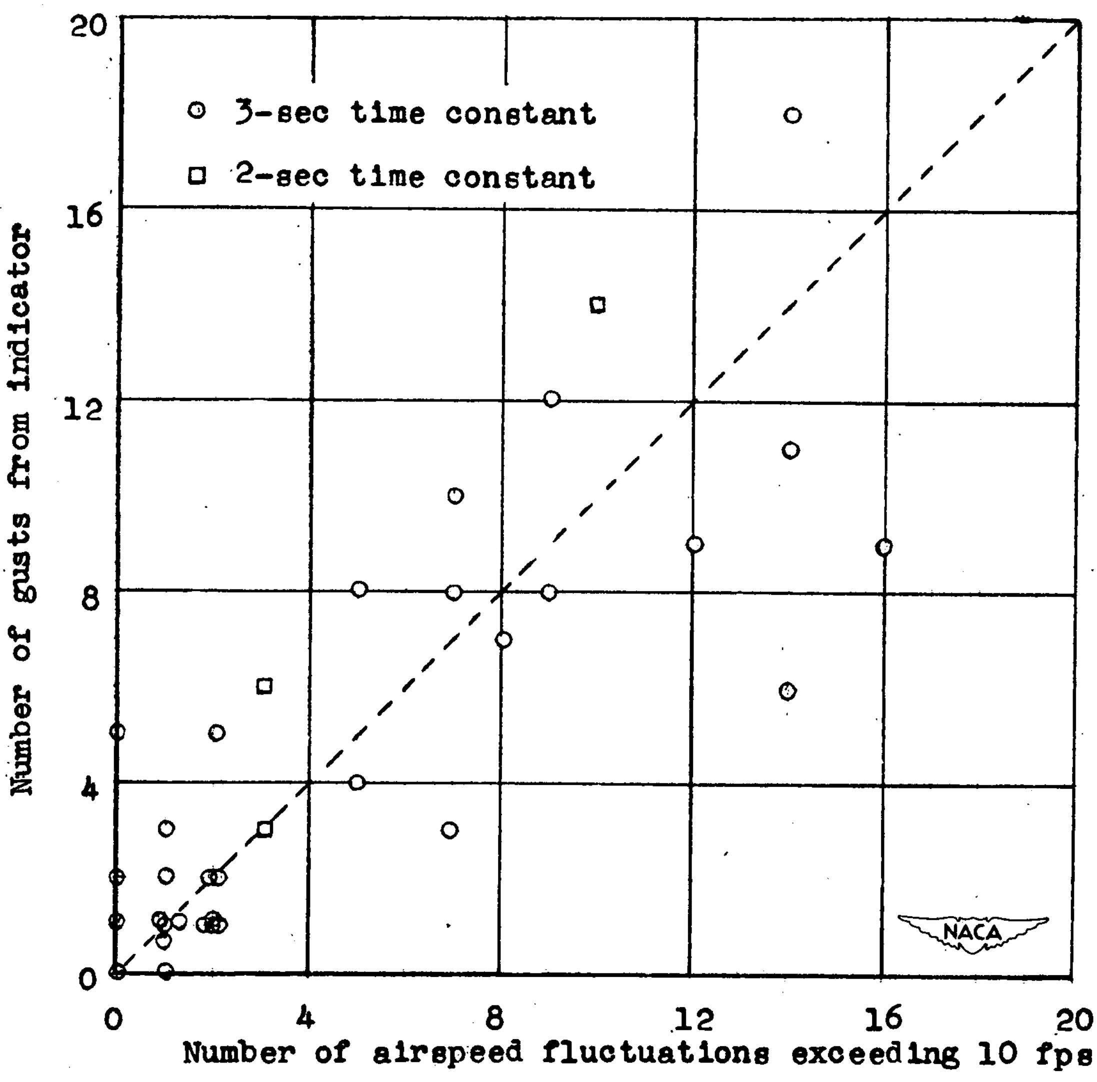


Figure 4.- Comparison of number of gusts from turbulence indicator with number of airspeed fluctuations greater than 10 feet per second for separate traverses in rough air.

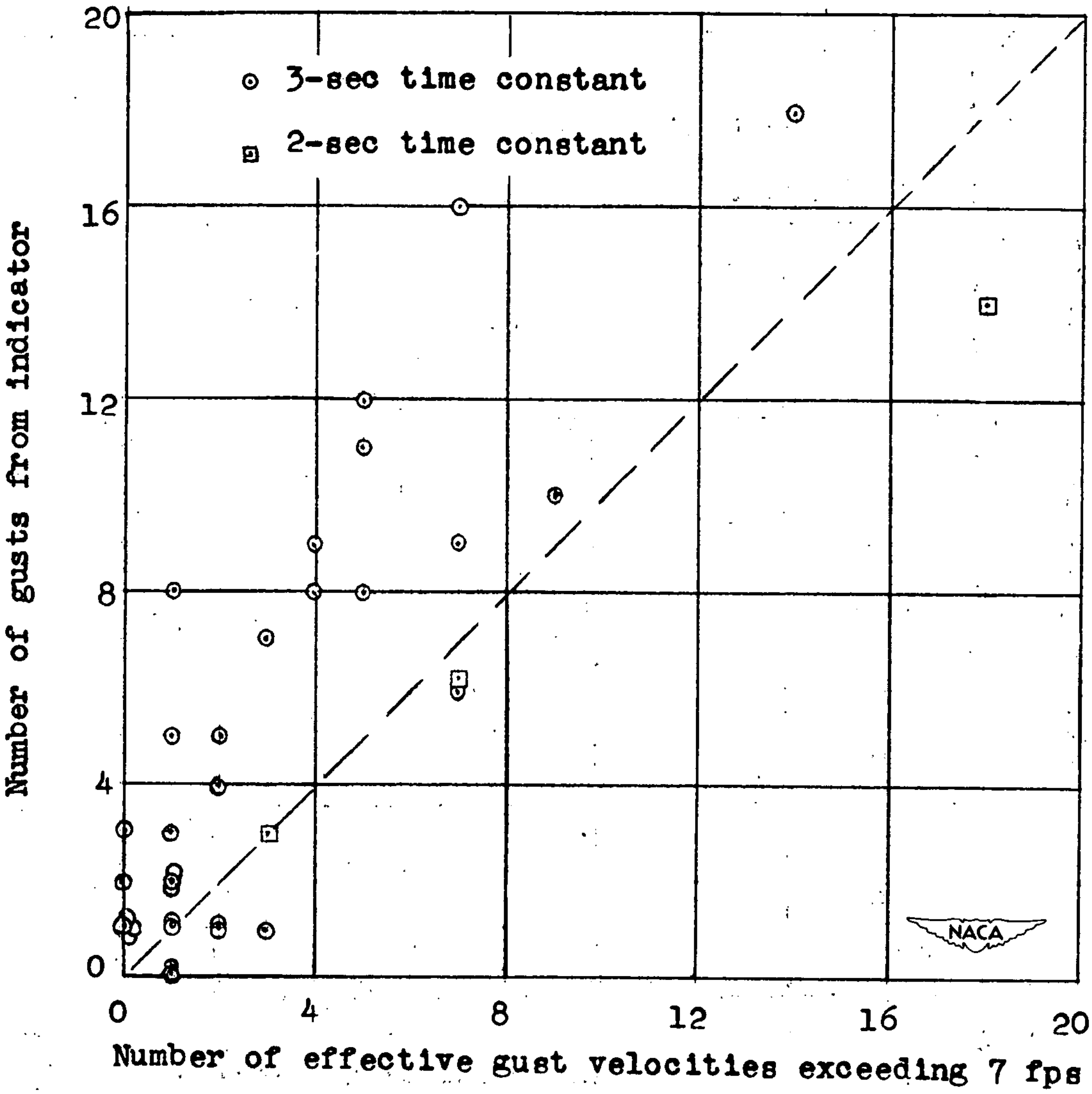


Figure 5.- Comparison of number of gusts from turbulence indicator with number of effective gust velocities greater than 7 feet per second for separate traverses in rough air.

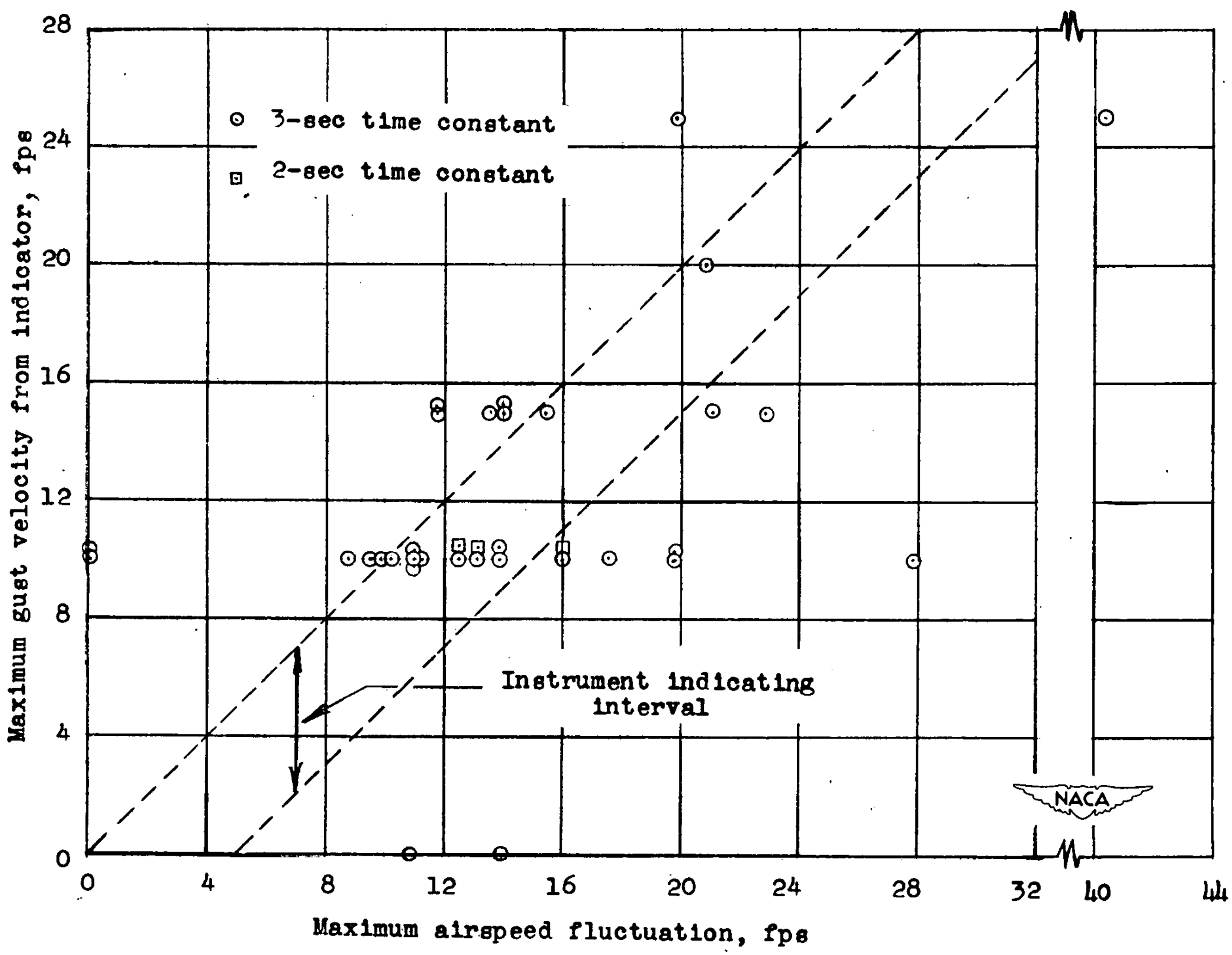


Figure 6.- Comparison of maximum gust velocity from the turbulence indicator with maximum airspeed fluctuation for separate traverses in rough air.

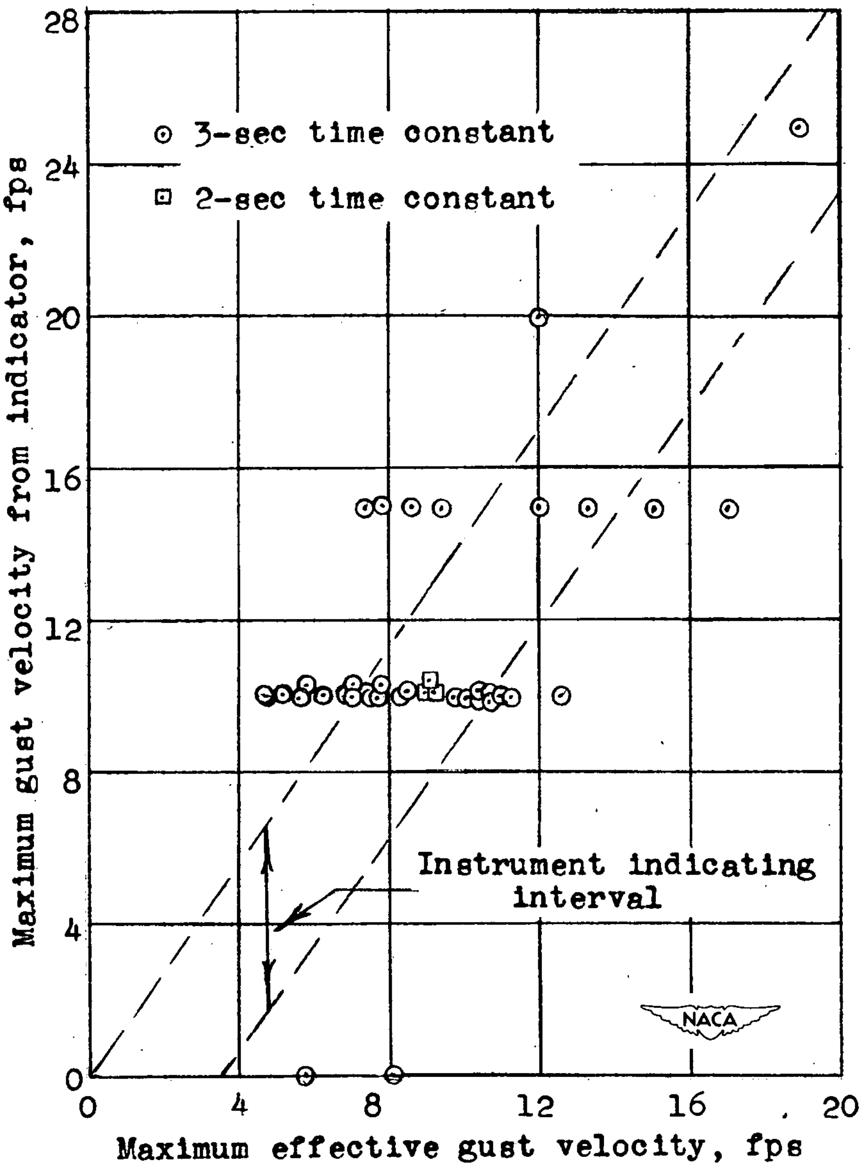


Figure 7.- Comparison of maximum gust velocity from turbulence indicator with maximum effective gust velocity for separate traverses in rough air.