NATIONAL ADVISORY COMMITTEE FOR AERONAUTICS

REPORT No. 546

THE EFFECT OF TURBULENCE ON THE DRAG OF FLAT PLATES

By G. B. SCHUBAUER and H. L. DRYDEN

1935

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AERONAUTIC SYMBOLS

1. FUNDAMENTAL AND DERIVED UNITS

	Symbol	Metric		English	
		Unit	Abbreviation	Unit	Abbreviation
Length	l	meter	m	foot (or mile)	ft. (or mi.)
Time	t	second	s	second (or hour)	sec. (or hr.)
Force	F	weight of 1 kilogram	kg	weight of 1 pound	lb.
Power	P	horsepower (metric)		horsepower	hp.
Speed	V	kilometers per hour	k.p.h.	miles per hour	m.p.h.
		meters per second	m.p.s.	feet per second	f.p.s.

2. GENERAL SYMBOLS

W, Weight $= mg$

g, Standard acceleration of gravity $= 9.80665$ m/s^2 or 32.1740 ft./sec.^{2}

m, Mass $= \frac{W}{g}$

I, Moment of inertia $= mk^2$. (Indicate axis of radius of gyration k by proper subscript.)

μ, Coefficient of viscosity

ν, Kinematic viscosity

ρ, Density (mass per unit volume)

Standard density of dry air, 0.12497 kg-m^{-4}-s^2 at 15° C. and 760 mm; or 0.002378 lb.-ft.$^{-4}$ sec.^{2}

Specific weight of "standard" air, 1.2255 kg/m^3 or 0.07651 lb./cu.ft.

3. AERODYNAMIC SYMBOLS

S, Area

S_w, Area of wing

G, Gap

b, Span

c, Chord

$\frac{b^2}{S}$, Aspect ratio

V, True air speed

q, Dynamic pressure $= \frac{1}{2}\rho V^2$

L, Lift, absolute coefficient $C_L = \frac{L}{qS}$

D, Drag, absolute coefficient $C_D = \frac{D}{qS}$

D_o, Profile drag, absolute coefficient $C_{D_o} = \frac{D_o}{qS}$

D_i, Induced drag, absolute coefficient $C_{D_i} = \frac{D_i}{qS}$

D_p, Parasite drag, absolute coefficient $C_{D_p} = \frac{D_p}{qS}$

C, Cross-wind force, absolute coefficient $C_C = \frac{C}{qS}$

R, Resultant force

i_w, Angle of setting of wings (relative to thrust line)

i_t, Angle of stabilizer setting (relative to thrust line)

Q, Resultant moment

Ω, Resultant angular velocity

$\rho\frac{Vl}{\mu}$, Reynolds Number, where l is a linear dimension (e.g., for a model airfoil 3 in. chord, 100 m.p.h. normal pressure at 15° C., the corresponding number is 234,000; or for a model of 10 cm chord, 40 m.p.s. the corresponding number is 274,000)

C_p, Center-of-pressure coefficient (ratio of distance of $c.p.$ from leading edge to chord length)

α, Angle of attack

ϵ, Angle of downwash

α_o, Angle of attack, infinite aspect ratio

α_i, Angle of attack, induced

α_a, Angle of attack, absolute (measured from zero-lift position)

γ, Flight-path angle

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National Bureau of Standards

NATIONAL ADVISORY COMMITTEE FOR AERONAUTICS

HEADQUARTERS, NAVY BUILDING, WASHINGTON, D. C.

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SUMMARY

In determining the effect of turbulence on the forces exerted on bodies in the air stream of a wind tunnel, it is commonly assumed that the indications of the standard pitot-static tube used to determine the air speed are not dependent on the turbulence. To investigate the truth of this assumption, the drag of a normally exposed flat plate, the difference in pressure between the front and rear of a thin circular disk, the rate of rotation of a vane anemometer, and the pressure developed by a standard pitot-static tube were measured in an air stream for several conditions of turbulence. The results may be interpreted as indicating that there is no appreciable effect of turbulence on the vane anemometer and the standard pitot-static tube, but that there is a small effect on the drag of a flat plate and the pressure difference between front and rear of a disk. This drag was found to be independent of the speed or Reynolds Number and hence the observed turbulence effect is of a different nature from the effects observed on skin-friction plates and airship hulls or on spheres.

This work was conducted by the National Bureau of Standards with the cooperation and financial assistance of the National Advisory Committee for Aeronautics.

INTRODUCTION

It is now well known that all aerodynamic measurements are to some extent dependent on the magnitude of the small fluctuations of speed, collectively called turbulence, which are present in the air stream. The effects of turbulence are supposed to be related to the effects of Reynolds Number in that both are the expression of the same basic phenomenon. A brief summary of the status of knowledge in April 1934 is given in reference 1.

In determining the effect of turbulence and Reynolds Number on aerodynamic force coefficients for various body forms, it is assumed that the force on the body is affected by turbulence and Reynolds Number, but that the pressure developed by the standard pitot-static tube, from which the dynamic pressure q $(=\frac{1}{2}\rho V^2$ where ρ is the density and V the speed of the air stream) is computed, is not. In support of this assumption it is often possible to point to changes in pressure and velocity distribution about the body, indicating with little doubt that the force on the body also changes. While it has been possible to show, by means of whirling arm tests, that the pressure difference obtained from the standard pitot-static tube is equal to the dynamic pressure q over the usual range of Reynolds Number (reference 2), no such fundamental test has been devised to show that this pressure difference is the same as q when the air is turbulent. It is generally assumed that turbulence can have little or no effect on the readings as long as the direction changes introduced by the turbulent motions are not over 3° (turbulence about 5 percent). The effect on the boundary layer about the static orifices in the wall of the tube is certainly negligible.

The drag coefficient [1] for a flat disc normal to the wind is constant over part of the range of Reynolds Numbers.[2] The explanation of this fact is simply that the separation lines must lie at the edges of the plate and consequently cannot shift as the Reynolds Number changes. The same kind of reasoning would deny the possibility of a turbulence effect, and indeed the argument appears to be as strong as that advanced in the case of the pitot-static tube.

In the course of some investigations at the National Bureau of Standards in 1932, an attempt was made to test the correctness of a calibration for the wall orifice of the 4½-foot wind tunnel, used to indicate the speed of the air stream, by measuring the drag coefficient for a 2- by 12-inch rectangular flat plate placed normal to the wind. The stream had been previously made very turbulent by placing a screen with loosely attached aluminum tags across the upstream section of the tunnel. The drag coefficient was found to be higher than that obtained in some earlier work. A check calibration of the wall orifice against the standard

[1] The drag coefficient is equal to the drag divided by q and by the area of the plate.

[2] In the early experiments of Eiffel and others, various sources of error, such as tunnel wall effects, spindle interference, and lack of geometrical similarity, were not recognized and an apparent variation with Reynolds Number was found. The careful experiments of C. Wieselsberger described in Ergebnisse Aerodyn. Versuchsanstalt, Göttingen, II, p. 25, show that there is no variation as great as 1 percent between a Reynolds Number of 10,000 and 1,000,000 for the circular disks tested. In other experiments, some variation is found. It is the opinion of the authors that all of the published data considered together supports the conclusion that the drag of a given thin flat plate with sharp square edges is independent of Reynolds Number in the range 10^4 to 10^6.

pitot-static tube showed that the calibration was not at fault. Later when the screen was removed and the turbulence was much lower, the drag determination was repeated. In this case the drag coefficient was lower and agreed well with earlier values. The difference in the two results appeared to be an effect of turbulence, but whether on the plate or the pitot-static tube was not known. Since the speed was not equally uniform over the area occupied by the plate in the two cases, and accordingly the difference in results might have been due to the failure to get a correct average calibration for the region occupied by the plate, the data were not considered to be conclusive.

For this reason it was decided to investigate the turbulence effect more fully before reporting it. The object of the present investigation was to repeat the earlier work under a greater variety of conditions, paying close attention to speed distribution in every case, and to obtain data which would show whether the effect was on the flat plate or the standard pitot-static tube.

METHOD OF PRODUCING TURBULENCE

Before the present investigation was begun, considerable attention had been given to methods of varying the turbulence of the 4½-foot wind tunnel of the National Bureau of Standards. The placing of square-mesh screens, made from cylindrical wires or rods, over the entire cross section of the tunnel at some upstream position, was found to be satisfactory both from the standpoint of turbulence production and uniformity of speed (reference 3). In order to avoid a regular pattern in the speed distribution from the individual wires, it was necessary to work at distances greater than 65 wire diameters from the screens. These screens were installed one at a time and the turbulence measured at several distances back of each of them by the "hot-wire" method (reference 4).

Turbulence measured by this method is expressed as the ratio of the root-mean-square of the speed fluctuation at a point to the average speed. This quotient times 100 is termed the percentage turbulence. Values of the turbulence back of the two screens used in the present investigation are shown in figure 1.

TEST EQUIPMENT AND PROCEDURE

Since the aerodynamic balance used in the 4½-foot tunnel was fixed in position, and it was not practicable to change the position of the screens, measurements of the drag coefficient for the 2-by 12-inch flat plate could be made only at 2.7 and 1.1 percent turbulence with the screens and 0.7 percent for the free tunnel condition.

In order to get a device to indicate the presence or absence of the effect over a wider range of turbulence, the so-called "pressure disk" shown in figure 2 was devised. This is simply a 3-inch disk with one orifice at the center of the front face and four others at the back where the supporting spindle is connected to the plate. By means of these orifices, the pressure difference across the plate can be determined. This difference, denoted by Δp, when divided by q yields a pressure coefficient, which should vary with turbulence somewhat like the drag coefficient. It was not intended that the drag coefficient be determined from the pressure coefficient. This would be a very doubtful procedure. The work on the disk was intended to bring out independent evidence of the effect on drag coefficients by another method. Both the 2- by 12-inch plate and the 3-inch disk had sharp square edges. The thickness of the plate was 0.046 inch and that of the disk 0.043 inch.

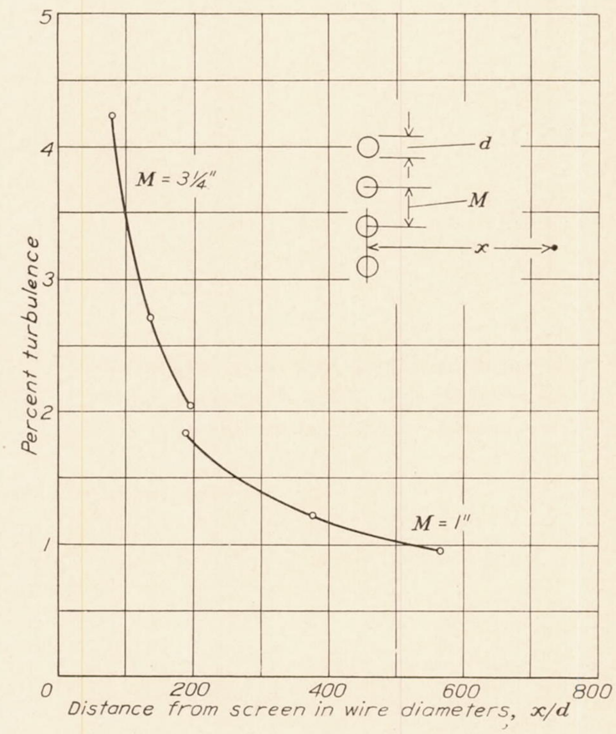

FIGURE 1.—Variation of percentage turbulence with distance from screens. Distance expressed in wire diameters.
d=0.625 inch for 3¼-inch mesh
d=0.192 inch for 1-inch mesh

Being faced with the problem of deciding whether to place the effect of turbulence on the flat plate or the pitot-static tube, it was desirable to obtain an entirely independent indication of the speed at the position where the pitot-static tube and the flat plates were run. A vane anemometer [3] (shown in fig. 2) having about the same diameter as the pressure disk was used for this purpose. The anemometer was not to be used to measure the air speed, but rather the speed indicated by it was to be compared with that indicated by the pitot-static tube, as in a calibration of the instrument.

[3] Vane anemometer built by Davis Instrument Co. Eight-blade, low-speed type, rated at 3,000 feet per minute maximum speed.

Working positions back of the two screens were selected according to the amount of turbulence desired. At any given position the procedure consisted of making three separate sets of runs covering a given speed range, one on the pressure disk, another on the vane anemometer, and still another on the standard pitot-static tube. Taking the pitot-static tube as an example, a run consisted of reading the manometer to which the pitot-static tube was connected simultaneously with another manometer connected to the tunnel wall orifice. The factor obtained from the ratio of the two readings amounted to a calibration factor for the wall orifice, to be used to obtain the value of q and hence of the air speed when the pitot-static tube was removed. Having calibrated the wall orifice, readings from it, taken simultaneously with those from the pressure disk, allowed $\Delta p/q$ to be calculated. Similarly, in calibrating the vane anemometer, readings from the wall orifice were used to indicate the air speed. Hence the results are expressed in terms of the speed indicated by the pitot-static tube, assuming no effect of turbulence.

The disk and vane anemometer responded to the average conditions over an area, presumably over their frontal area. The indications of the pitot-static tube were obtained therefore at a number of points over the area swept out by the disk and the anemometer in order to obtain a similar integrated effect. Measurements were made at the center of this area and at several points on a 1- and 2-inch radius.

In connection with the force measurements a similar procedure was followed at the position determined by the balance. The pitot-static tube runs in this case were distributed over the area occupied by the 2- by 12-inch plate, and the vane anemometer was calibrated at the position later occupied by the center of the plate. Both were run with the shielded balance arm protruding into the stream.

The force measurements were made on a balance of the N. P. L. type. The plate was attached to the shielded balance arm by a spindle 9 inches long fastened rigidly to one end of the plate. The drag of this spindle was determined by making a separate run with a dummy spindle attached to the balance and with the plate mounted separately above it. By deducting the spindle drag from the drag of the plate and spindle combined, the drag of the plate alone was obtained. The interference of the spindle on the plate drag was not corrected for by this procedure, but a preliminary investigation showed that this interference was too small to be detected.

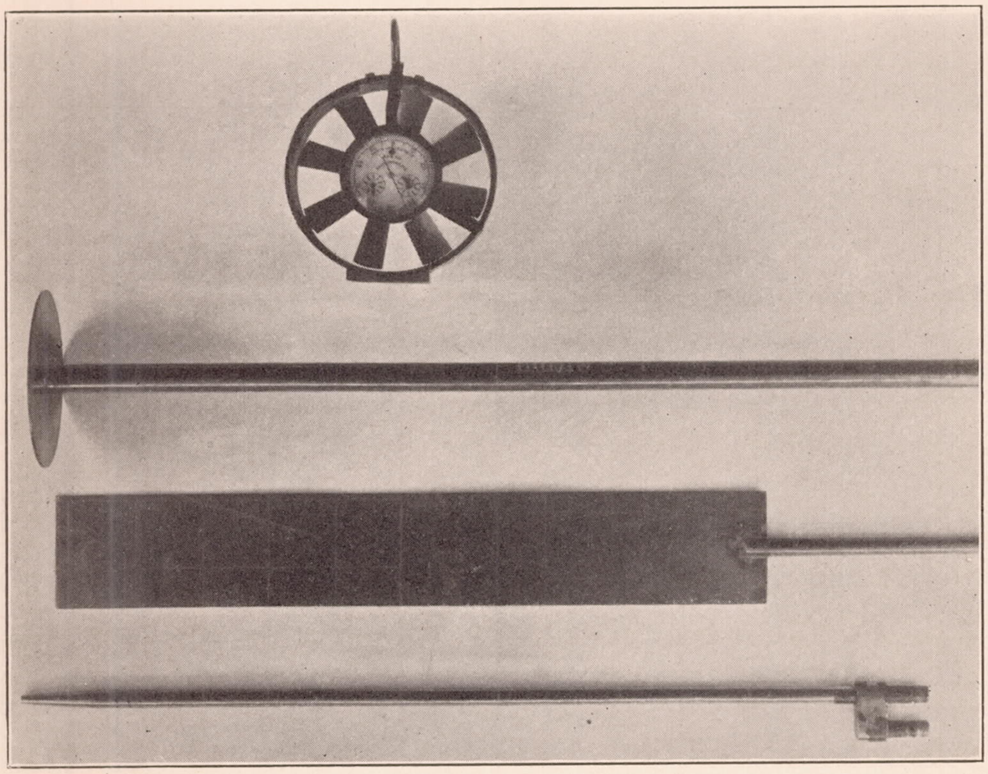

FIGURE 2.—Vane anemometer, 3-inch pressure disk and spindle, 2- by 12-inch flatplate and spindle, and standard pitot-static tube.

RESULTS

Great care was taken to secure accurate values of the mean velocity pressure over the area to be occupied by the plate or anemometer at a given reading of the manometer connected to the wall orifice. Thus, for the 2- by 12-inch plate, readings were taken at 7 points for 6 speeds. Considering the results obtained with the 3¼-inch screen, the average deviation of a single observation from the mean at any one point was about 0.5 percent, the maximum deviation 1 percent. For all points considered together, the average deviation was 1 percent, the maximum 2 percent. It seems

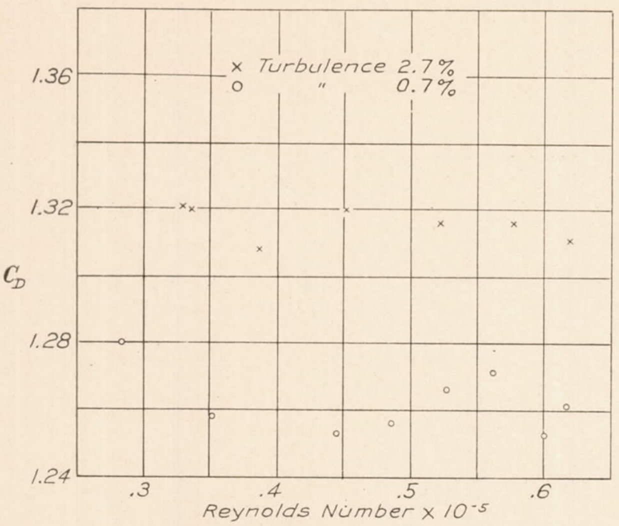

FIGURE 3.—Drag coefficients for 2- by 12-inch flat plate for various Reynolds Numbers. The length term in the expression for Reynolds Number is the width of the plate, i. e., 2 inches.

conservative, taking account of "sampling" errors, to assume that the mean value for the 42 points is equal to the correct average over the area of the plate within 0.5 percent. The probable error computed by considering the 42 observations as being made on the same quantity is only 0.1 percent.

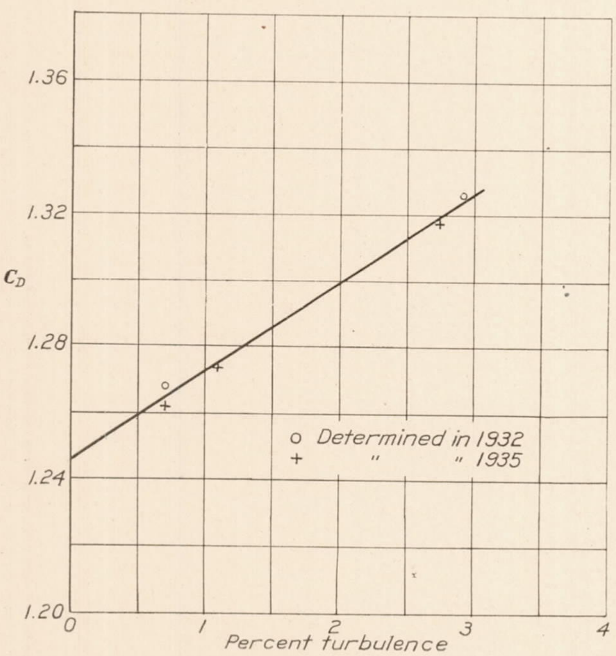

FIGURE 4.—Relation between percentage turbulence and drag coefficient for 2- by 12-inch flat plate. $C_D=\frac{D}{qS}$, where S=area of plate, q=dynamic pressure, and D=drag.

The deviations which have been given for the 3¼-inch screen represent the worst condition. Over smaller areas and with the 1-inch screen or with no screen, the deviations were much smaller, and a fair average value of the mean deviation for those conditions would be about 0.3 percent.

Two series of determinations of the drag coefficient of the rectangular plate are shown in figure 3. Whereas there is no definite variation of the drag coefficient with Reynolds Number over the range from 30,000 to 60,000, there is a marked change in the coefficient with turbulence. This variation with turbulence is shown more clearly in figure 4 where the coefficients have been averaged over the Reynolds Number range and plotted against turbulence. Determinations made in 1932, shown on the same figure, agree well with those

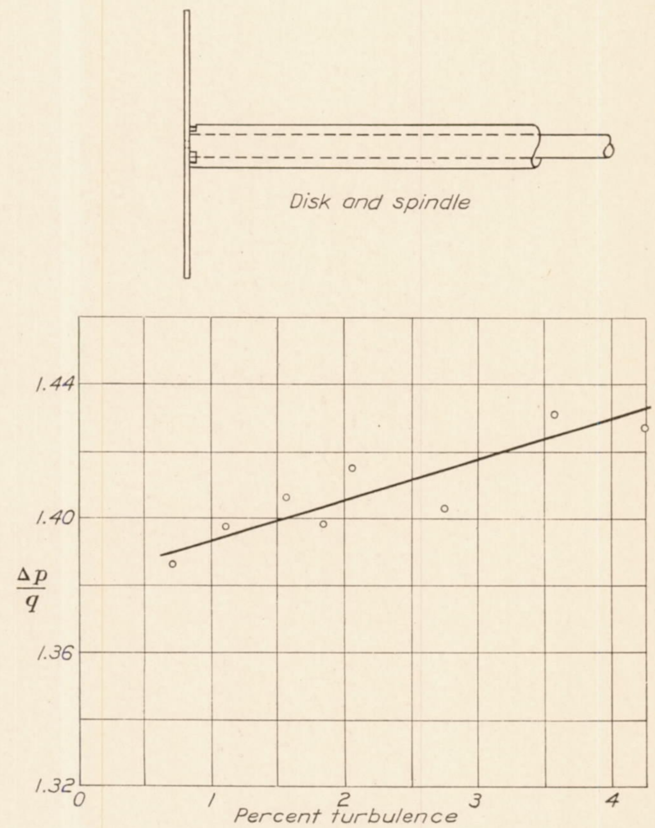

FIGURE 5.—Relation between percentage turbulence and pressure coefficient for 3-inch diameter disk.

of 1935. Extrapolating to zero turbulence, we find a drag coefficient of 1.246. Since wind tunnels may vary in turbulence from near zero to 2 percent or possibly more, a dispersion among results in various tunnels of perhaps 4 percent may be expected. This is nothing like the disagreement found in sphere drag results; nevertheless it is enough to be of importance in precise work.

Figure 5 shows the variation of the pressure coefficient of the pressure disk with turbulence. While the scatter in this diagram is considerable, there is a definite upward trend to the coefficient with increasing turbulence. Here again the coefficient was independent of the speed.

We may contrast the results for the plates with those shown in figure 6 for the vane anemometer. Here there is no evidence of any dependence of the

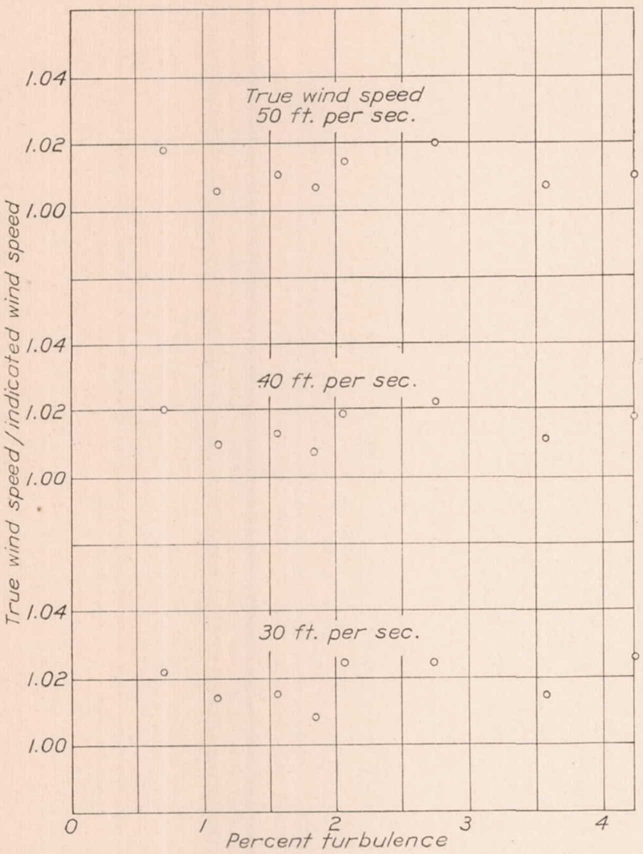

FIGURE 6.—Calibration of vane anemometer for various amounts of turbulence.

calibration factor on turbulence. This means either that the indications of the anemometer and the pitot-static tube both vary with the turbulence in such a way as to mask any effect, or that there is no turbulence effect on either instrument. Since the two are radically different both in construction and principle of operation, it seems very unlikely that turbulence should affect the two alike. Hence the conclusion: Both the pitot-static tube and the vane anemometer are free from any effect of turbulence. The dynamic pressure q is therefore determined correctly by the pitot-static tube, and the variation of the flat plate coefficient is due to the effect of turbulence on the plate itself.

It is usual to attribute the effect of wind-tunnel turbulence on aerodynamic forces to a shift in the point of transition from laminar to turbulent boundary-layer flow. The result is a different skin friction and a different separation point. It is difficult to see how this explanation can be applied in the case of the flat plate. We have here a case where the turbulence apparently affects the wake of the plate; or, if we wish to imagine a separated boundary layer enveloping the wake, perhaps the exterior turbulence affects the stability of this layer. Whatever the explanation, the work with the pressure disk indicates that turbulence does lower the pressure in the wake.

NATIONAL BUREAU OF STANDARDS,
WASHINGTON, D. C., *June 22, 1935*.

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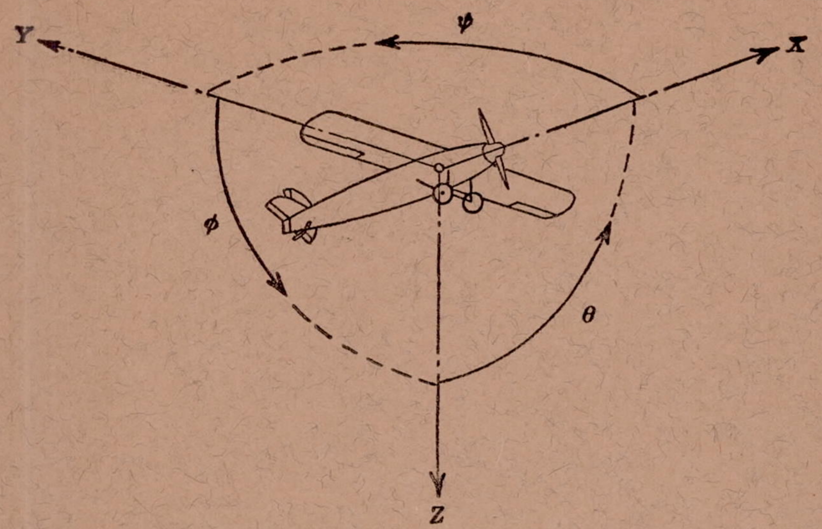

Positive directions of axes and angles (forces and moments) are shown by arrows

Axis		Force (parallel to axis) symbol	Moment about axis			Angle		Velocities	
Designation	Symbol		Designation	Symbol	Positive direction	Designation	Symbol	Linear (component along axis)	Angular
Longitudinal	X	X	Rolling	L	$Y \longrightarrow Z$	Roll	ϕ	u	p
Lateral	Y	Y	Pitching	M	$Z \longrightarrow X$	Pitch	θ	v	q
Normal	Z	Z	Yawing	N	$X \longrightarrow Y$	Yaw	ψ	w	r

Absolute coefficients of moment

$C_l=\frac{L}{qbS}$ (rolling) $\quad C_m=\frac{M}{qcS}$ (pitching) $\quad C_n=\frac{N}{qbS}$ (yawing)

Angle of set of control surface (relative to neutral position), δ. (Indicate surface by proper subscript.)

4. PROPELLER SYMBOLS

D, Diameter
p, Geometric pitch
p/D, Pitch ratio
V', Inflow velocity
V_s, Slipstream velocity
T, Thrust, absolute coefficient $C_T=\frac{T}{\rho n^2 D^4}$
Q, Torque, absolute coefficient $C_Q=\frac{Q}{\rho n^2 D^5}$

P, Power, absolute coefficient $C_P=\frac{P}{\rho n^3 D^5}$
C_s, Speed-power coefficient $=\sqrt[5]{\frac{\rho V^5}{P n^2}}$
η, Efficiency
n, Revolutions per second, r.p.s.
Φ, Effective helix angle $=\tan^{-1}\left(\frac{V}{2\pi r n}\right)$

5. NUMERICAL RELATIONS

1 hp. = 76.04 kg-m/s = 550 ft-lb./sec.
1 metric horsepower = 1.0132 hp.
1 m.p.h. = 0.4470 m.p.s.
1 m.p.s. = 2.2369 m.p.h

1 lb. = 0.4536 kg.
1 kg = 2.2046 lb.
1 mi. = 1,609.35 m = 5,280 ft.
1 m = 3.2808 ft.