NATIONAL ADVISORY COMMITTEE FOR AERONAUTICS

REPORT No. 387

THE VERTICAL WIND TUNNEL OF THE NATIONAL ADVISORY COMMITTEE FOR AERONAUTICS

By CARL J. WENZINGER and THOMAS A. HARRIS

1931

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AERONAUTICAL SYMBOLS

1. FUNDAMENTAL AND DERIVED UNITS

	Symbol	Metric		English	
		Unit	Symbol	Unit	Symbol
Length	l	meter	m	foot (or mile)	ft. (or mi.)
Time	t	second	s	second (or hour)	sec. (or hr.)
Force	F	weight of one kilogram	kg	weight of one pound	lb.
Power	P	kg/m/s		horsepower	hp
Speed		km/h	k. p. h.	mi./hr.	m. p. h.
		m/s	m. p. s.	ft./sec.	f. p. s.

2. GENERAL SYMBOLS, ETC.

W, Weight $=mg$

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

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

ρ, Density (mass per unit volume).

Standard density of dry air, 0.12497 (kg-m^{-4} s^2) at 15° C. and 750 mm $=0.002378$ (lb.-ft.$^{-4}$ sec.^{2}).

Specific weight of "standard" air, 1.2255 kg/m^3 $=0.07651$ lb./ft.^{3}.

mk^2, Moment of inertia (indicate axis of the radius of gyration k, by proper subscript).

S, Area.

S_w, Wing area, etc.

G, Gap.

b, Span.

c, Chord.

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

μ, Coefficient of viscosity.

3. AERODYNAMICAL SYMBOLS

V, True air speed.

q, Dynamic (or impact) 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 mi./hr. normal pressure, at 15° C., the corresponding number is 234,000;

or for a model of 10 cm chord 40 m/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.

REPORT No. 387

THE VERTICAL WIND TUNNEL OF THE NATIONAL ADVISORY COMMITTEE FOR AERONAUTICS

By CARL J. WENZINGER and THOMAS A. HARRIS
Langley Memorial Aeronautical Laboratory

NATIONAL ADVISORY COMMITTEE FOR AERONAUTICS

NAVY BUILDING, WASHINGTON, D. C.

(An independent Government establishment, created by act of Congress approved March 3, 1915, for the supervision and direction of the scientific study of the problems of flight. Its membership was increased to 15 by act approved March 2, 1929 (Public, No. 908, 70th Congress). It consists of members who are appointed by the President, all of whom serve as such without compensation.)

EXECUTIVE COMMITTEE

REPORT No. 387

THE VERTICAL WIND TUNNEL OF THE NATIONAL ADVISORY COMMITTEE FOR AERONAUTICS

By Carl J. Wenzinger and Thomas A. Harris

SUMMARY

The vertical open-throat wind tunnel of the National Advisory Committee for Aeronautics is described in this report. The tunnel was built mainly for studying the spinning characteristics of airplane models, but may be used as well for the usual types of wind-tunnel tests. A special spinning balance is being developed to measure the desired forces and moments with the model simulating the actual spin of an airplane.

Satisfactory air flow has been attained with a velocity that is uniform over the jet to within ±0.5 per cent. The turbulence present in the tunnel has been compared with that of several other tunnels by means of the results of sphere drag tests and was found to average well with the values of those tunnels. Included also in the report are comparisons of results of stable autorotation and of rolling-moment tests obtained both in the vertical tunnel and in the old horizontal 5-foot atmospheric tunnel.

INTRODUCTION

Some of the major problems under investigation by the National Advisory Committee for Aeronautics may be placed under the general heading of safety in flight. One of the most important of these problems is the study of spinning, both in the wind tunnel and in free flight. In the usual horizontal type of wind tunnel, however, considerable difficulty is encountered in making spinning tests of airplane models owing to the force of gravity acting with the rotation for part of a revolution and against the rotation for the remainder. This condition tends to give oscillating readings on the measuring apparatus and can be avoided only by very careful counterbalancing of the spinning model and balance parts. This undesirable feature can be overcome by locating the spin axis in the vertical rather than in the horizontal position, because the effect of gravity on the spin apparatus is then constant. In addition, a vertical type of tunnel requires much less floor space than the horizontal type of the same jet diameter.

The design of a vertical tunnel having a 5-foot diameter jet was accordingly started by the National Advisory Committee for Aeronautics in 1928. Actual construction of the new tunnel was completed in 1930, and the calibration tests were then made. The tunnel is now being used for autorotation and force tests pending the completion of a spinning balance.

DESCRIPTION OF TUNNEL

General.—The vertical tunnel is located in a portion of the building that formerly housed the old 5-foot Eiffel-type wind tunnel at the Langley Memorial Aeronautical Laboratory. Figure 1 is a diagrammatic sketch showing the general arrangement of the tunnel, and Figure 2 shows the appearance of the tunnel in the building.

The tunnel has an open jet, an open test chamber, and a closed return passage. As indicated on the drawing, the air passes through the test section in a downward direction, then enters the exit cone and passes through the first set of guide vanes to a propeller. From here it passes, by way of the return passage, through the successive sets of guide vanes at the corners, then through the honeycomb, and finally through the entrance cone.

In accordance with standard wind-tunnel practice, the air, in passing through the exit cone and return passage, is slowly decelerated by gradually increasing the cross-sectional area of the air passage. This change in area is accomplished by varying the diameter of the circular section and by changing from a circular to a square section in the return passage. After passing through the honeycomb, the air is rapidly accelerated in the entrance cone before passing into the test section. This acceleration of the air tends to produce a uniform velocity at the test section.

The tunnel passages are constructed of ⅛-inch sheet iron, stiffened with angle iron, and bolted together at the corners. The over-all dimensions are: Height, 31 feet 2 inches; length, 20 feet 3 inches; width, 10 feet 3 inches. There are four manholes for access to various parts of the tunnel passages. These are placed in the return passage, as shown in Figure 1.

Test chamber.—The test chamber is of the open type and its floor is flush with the top of the exit cone. This floor is 10 feet square and has a central opening 6 feet in diameter around the exit cone, which leaves an annular space 5 inches wide between the floor and the exit cone. This space was left so that the spillage air would flow down past the exit cone. On one side the floor is extended as a working platform. On the 10-foot square part of the floor are the motor control, the starting switch, the dynamic pressure indicator, and receptacles for both a. c. and d. c. power connections.

The remainder of this floor space is used for installation of instruments used in the tests.

Entrance cone.—The entrance cone was made very short because of the limited height available for the wind tunnel. The section of the entrance cone changes from a 9-foot square to a 5-foot diameter circle in a length of 4 feet 2 inches. The entrance cone then flares out as a right circular cone with an included angle of 4° in the remaining 8 inches of its length. The entrance cone from the large end to the circular section is made of ⅛-inch welded sheet iron; the remaining part is made of laminated white pine turned to the proper shape.

Exit cone.—The exit cone is a right circular cone with an included angle of 7° 34′, the diameter of the small end being 5 feet 2 inches. No flare was used on the exit cone, because it was found in preliminary model-cone tests that satisfactory results could be obtained without it. A molding of ½-inch half-round iron is welded around the top to eliminate the sharp edge. The absence of a flare makes it possible, without putting in special platforms, to get much closer to the jet

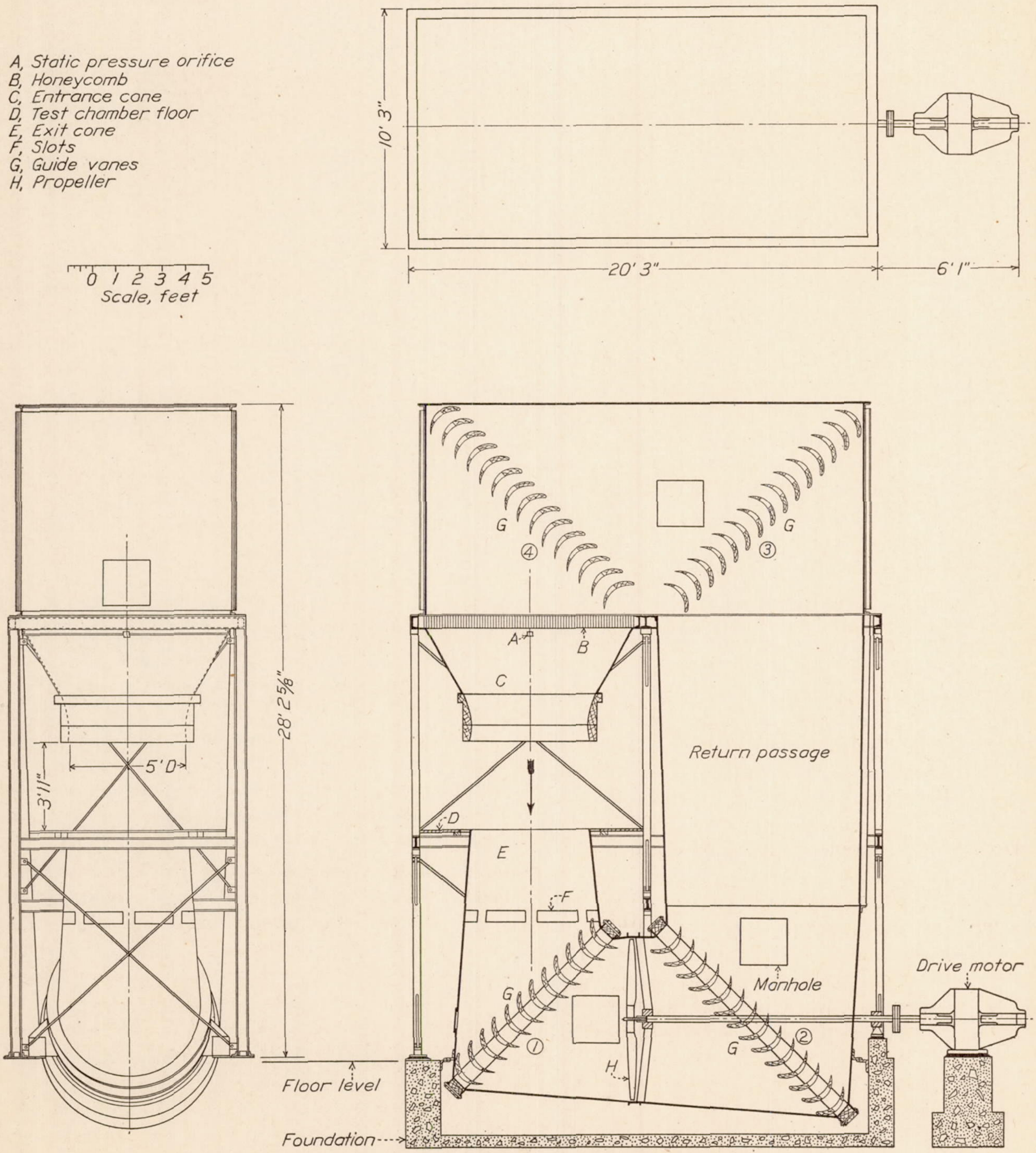

FIGURE 1.—Details—5-foot diameter jet vertical wind tunnel

while working on models. There are eight slots or openings about 6 by 20 inches in the exit cone. (Fig. 1.) These slots were necessary to eliminate pulsations. (Reference 1.)

Guide vanes.—The guide vanes are constructed of wood and metal. The leading and trailing edges are of wood connected with wooden ribs. To this framework a covering of 1/32-inch galvanized iron is nailed. The vanes are spaced one-third chord length apart in the corners of the tunnel passage.

The shape of the under surface of each guide vane is a 90° arc of a circle. The upper surface is also shaped in an arc of a circle extending about 84° from the trailing edge toward the nose of the vane. An arc of a much smaller circle is then faired between this point and the rounded nose. The thickness is about 12.5 per cent of the chord at the 50 per cent chord point. The vanes are so placed in the tunnel that the under surface of the trailing edge of each vane is tangent to a line parallel to the center line of that part of the tunnel passage.

Honeycomb.—As mentioned before, there is a honeycomb ahead of the entrance cone. This honeycomb is made of galvanized iron bound around the outside with a steel channel. The cells are 1 inch square and 6 inches deep. To equalize the dynamic pressure in the test section, galvanized wire screen is secured to the honeycomb. This screen is fastened to the outer portion of the upper surface of the honeycomb, leaving a 5-foot circular section in the center uncovered.

Propeller and motor.—The fan is a 3-bladed, adjustable pitch, aluminum alloy propeller, 6 feet 11 inches in

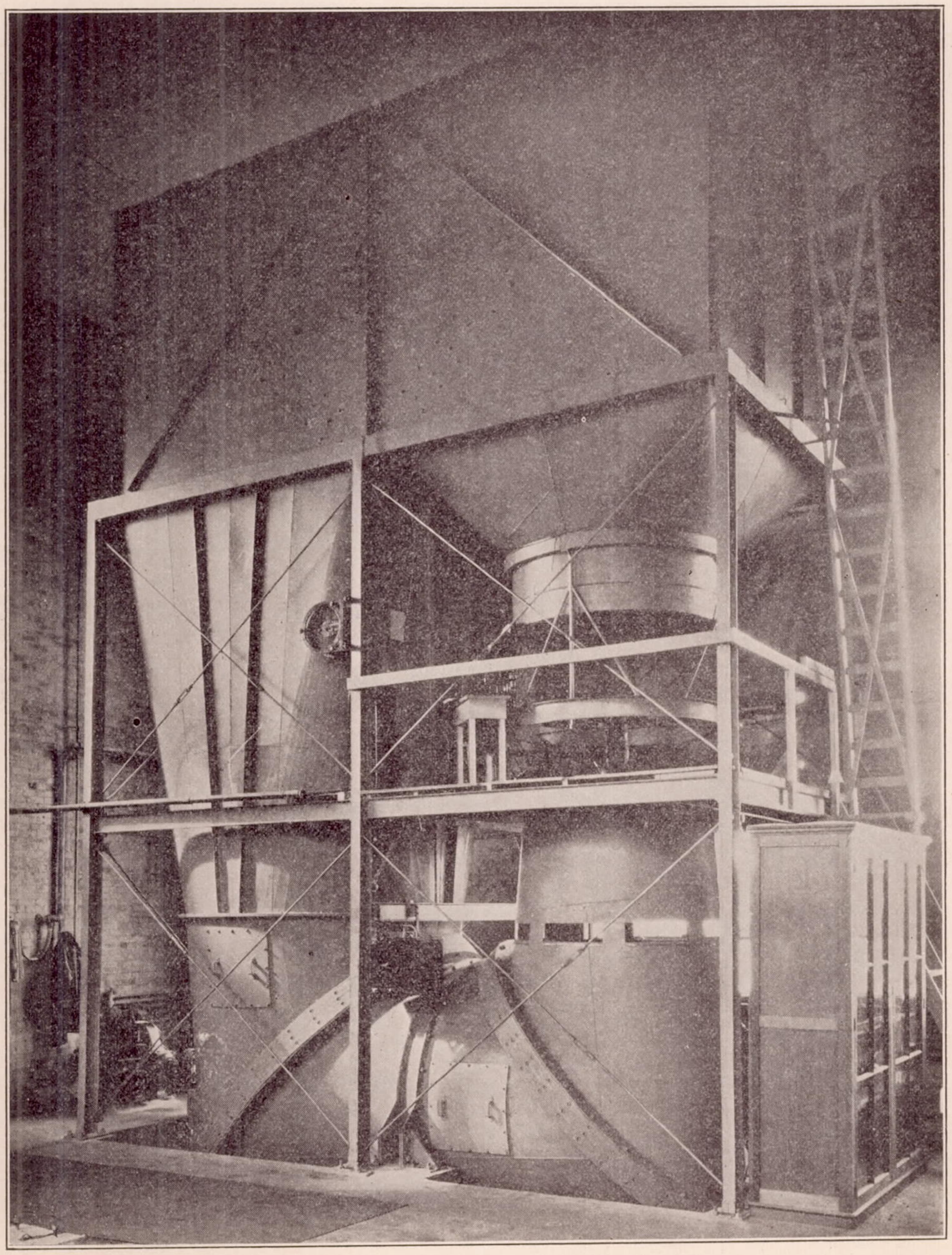

FIGURE 2.—Five-foot vertical wind tunnel

diameter, located as in Figure 1. It is driven by a 50-horsepower, 230-volt d. c. motor, to which it is directly coupled. Air speeds from 0 to 80 miles per hour can be obtained with this propeller-motor combination. The motor speed is changed by means of variable armature and field rheostats and by adjustable line voltage. The energy ratio of the tunnel was determined with the honeycomb and screen installed, and at 70 m. p. h. was found to be 1.22. In this case, energy ratio is defined as the ratio of kinetic energy of the air passing the test section to energy input to the drive motor for the same period of time.

Air-speed indicator.—An N. A. C. A. micromanometer is used to indicate the air speed. One side of this manometer is connected through copper tubing to four static pressure orifices equally spaced around the large end of the entrance cone. The other side of the manometer is open to the atmospheric pressure. The

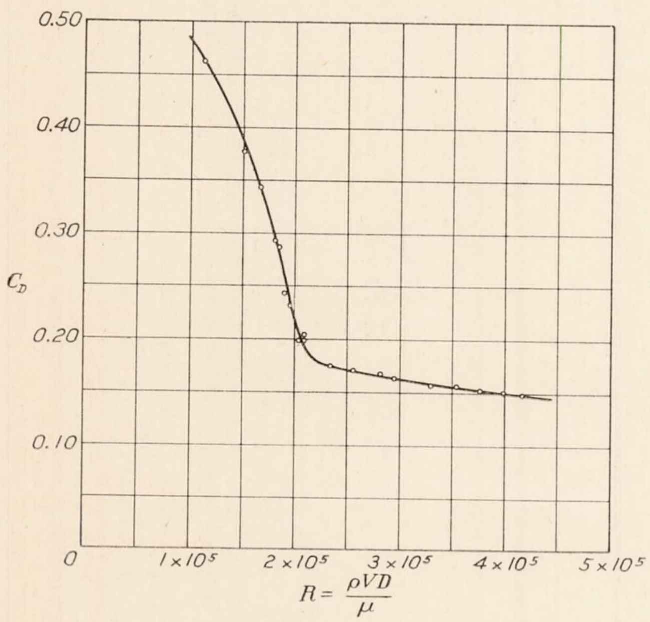

FIGURE 3.—Sphere drag coefficient vs. Reynolds number

$C_D = \frac{\text{force}}{\frac{1}{2}\rho A V^2}$ where A=cross section of sphere$=\frac{\pi D^2}{4}$.

pressure head of this manometer is calibrated against the dynamic pressure in the test section.

SPIN TESTING APPARATUS

A small electric dynamometer, known as the "autorotation dynamometer," was mounted in the vertical tunnel for the first series of tests on airfoil models. A detailed description of the dynamometer and associated apparatus may be found in Reference 2. The dynamometer was modified for vertical operation, as it had previously been used in the horizontal position in the old 5-foot atmospheric tunnel. This apparatus is capable of measuring the rolling moments of airfoil models that are being rotated at desired rates about the tunnel axis.

A spinning balance is now being developed which, when completed, will replace the dynamometer in the vertical tunnel. The airplane models to be tested on this balance will have a span of about 30 inches and will be roughly balanced about their center of gravity. These models will be mounted and rotated in the tunnel so as to simulate the actual steady spin of an airplane with respect to the relative wind. The balance will make possible a study of the effects of variations in the radius of the path of the center of gravity about the spin axis, the attitude and angle of attack of the airplane, and the rate of spin.

CALIBRATION OF TUNNEL

The calibration tests consisted mainly of determinations of the dynamic pressure distribution over the jet and of the angularity of the air stream. Drag tests of a 20-centimeter sphere also were made at several air speeds to obtain a measure of the turbulence in the new tunnel.

The dynamic pressure distribution over the working section of the jet (36 inches) is uniform to within about ±1.0 per cent, corresponding to the small change in velocity of about ±0.5 per cent. Over the same section of the jet the direction of flow is parallel to the tunnel axis to within about 1°, and no definite direction of twist was indicated.

The 20-centimeter sphere was supported by a fine steel wire attached to a balance on the roof of the tunnel. A counterweight, shielded from the air stream, was fastened also by a fine steel wire to a sting extending from the lower side of the sphere. The drag of the sphere was measured for a range of Reynolds Numbers extending from about 100,000 to 400,000. The measured drag was then corrected for the static pressure gradient along the sphere. This gradient amounts to about 0.98 per cent of the dynamic pressure for a distance of 5 inches along the tunnel center line. The 5-inch length was given because it specifies the chord length of most of the models tested in the tunnel.

Figure 3 shows the sphere drag coefficient plotted against Reynolds Number. According to the definition given by Dryden and Kuethe (Reference 3), the characteristic number of a tunnel corresponding to the turbulence present is the Reynolds Number at which the sphere drag coefficient is 0.3. Tunnels having the same characteristic number should then give comparable results. This number, determined as above for the vertical tunnel, is 180,000. It is of interest to note that the characteristic number of the 5-foot horizontal tunnel was about 170,000. In this connection some values of other tunnels may also be noted:

Original variable density wind tunnel, 92,000. (Reference 4.)

Open-throat variable density wind tunnel, 156,000.

Bureau of Standards 3-foot wind tunnel, 270,000. (Reference 3.)

Bureau of Standards 4½-foot wind tunnel, 164,000.

Bureau of Standards 10-foot wind tunnel, 232,000.

COMPARATIVE AUTOROTATION AND ROLLING-MOMENT TESTS

The first series of tests in the vertical tunnel was made to obtain a comparison of the results of stable autorotation tests and rolling-moment tests obtained in it, with the results from the 5-foot closed-throat horizontal tunnel. Tests were also made to show the effect of changes in the tunnel air speed on the results.

A 5 by 30 inch model of the N. A. C. A. 84 airfoil, which had been tested previously (Reference 2) in the horizontal tunnel (Reference 5), was mounted on the remodeled autorotation dynamometer in the vertical tunnel. Figure 4 shows the set-up of apparatus including an airfoil, the dynamometer and controls, the angle of attack changing device, and the torque-measuring balance.

Stable autorotation tests were made at air speeds of 20, 40, and 60 miles per hour, and rates and ranges of stable autorotation were determined for angles of yaw of 0° and 10°. The angle of attack range was from 0° to about 35°.

The results are given in the form of graphs of $\frac{pb}{2V}$ and C, where

$\frac{pb}{2V}$ = ratio of wing tip speed to forward speed,

p = angular velocity at tip, radians per second,

b = span of the wing, feet,

V = wind velocity, feet per second,

C_λ = coefficient of rolling moment due to roll, $= \frac{\lambda}{qbS}$

where λ = rolling moment about dynamometer axis,

q = dynamic pressure,

b = span of the wing,

S = area of the wing,

all in a consistent system of units. Curves of $\frac{pb}{2V}$ versus angle of attack are given in Figures 5, 6, 7, and 8. For the zero yaw condition (fig. 5) it may be seen that the agreement is good between the rates of stable autorotation as obtained both in the vertical and in the horizontal tunnels. The upper limit of the angular range of stable autorotation of the model in the vertical tunnel, however, is not very definite. This difference

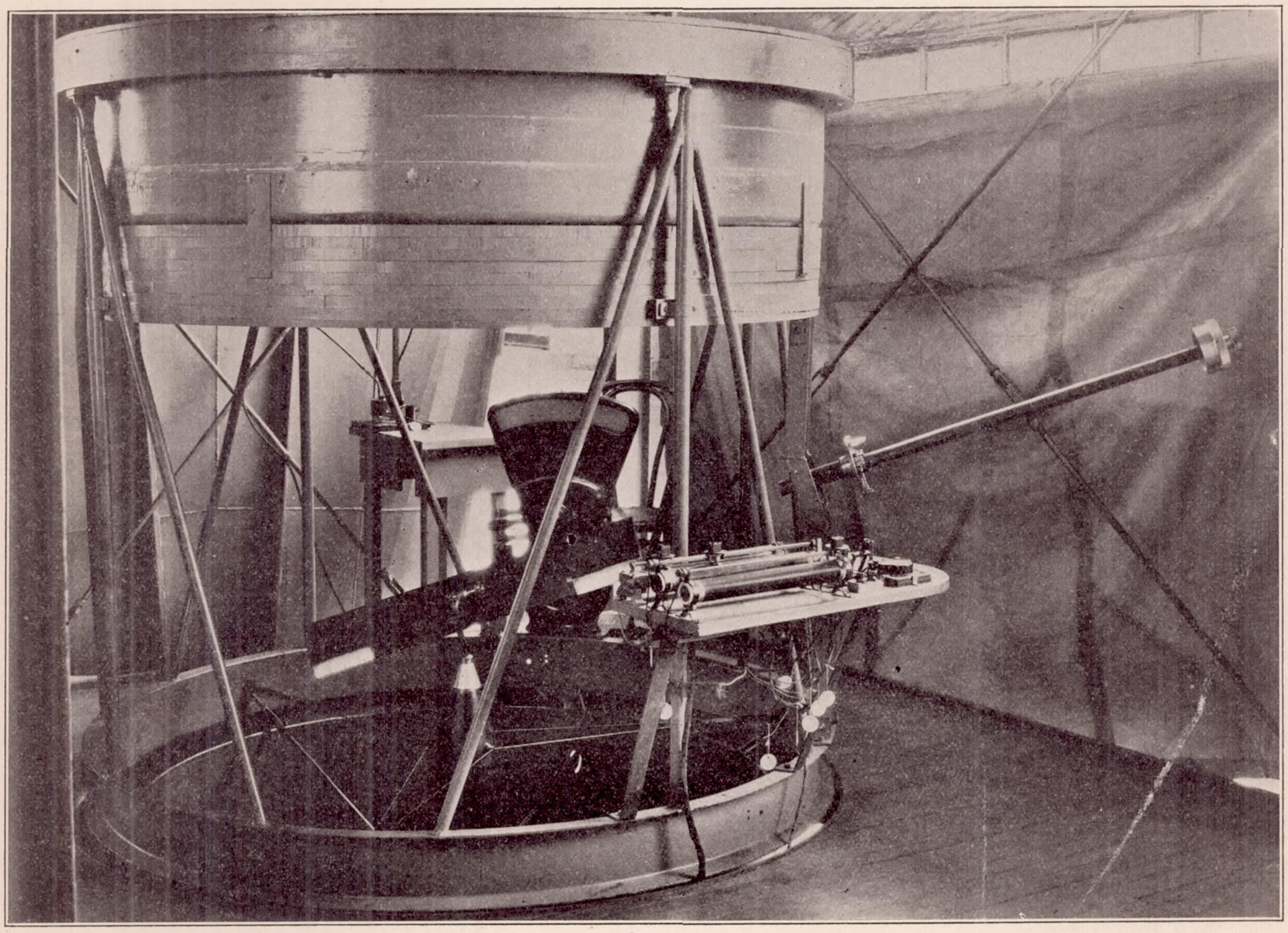

FIGURE 4.—Autorotation and rolling moment apparatus set up in vertical wind tunnel

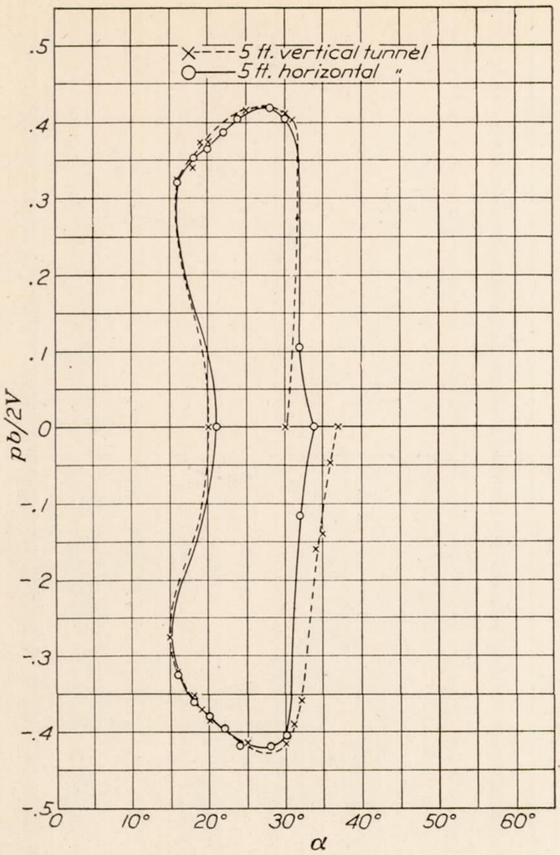

FIGURE 5.—Comparative results—$\frac{pb}{2V}$ vs. angle of attack. Yaw=0°; zero torque

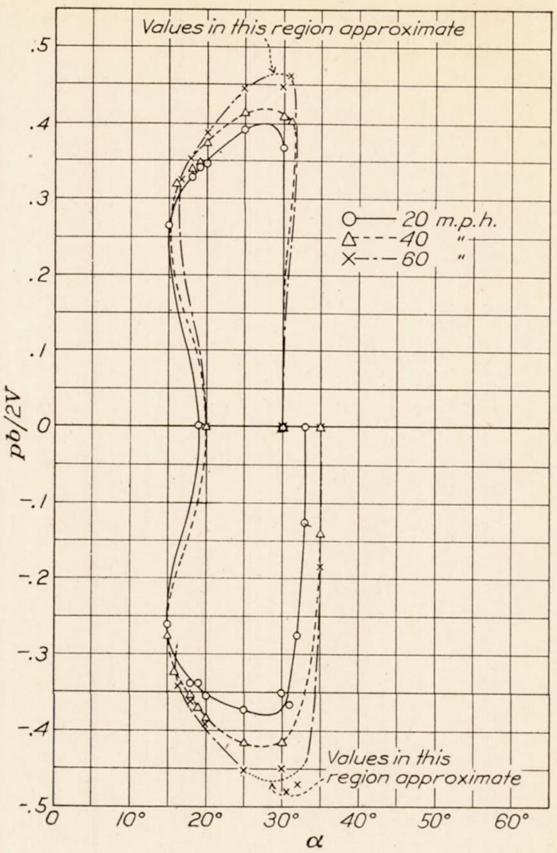

FIGURE 7.—Effect of changes in air speed—$\frac{pb}{2V}$ vs. angle of attack. Yaw=0°; zero torque. Five-foot vertical tunnel

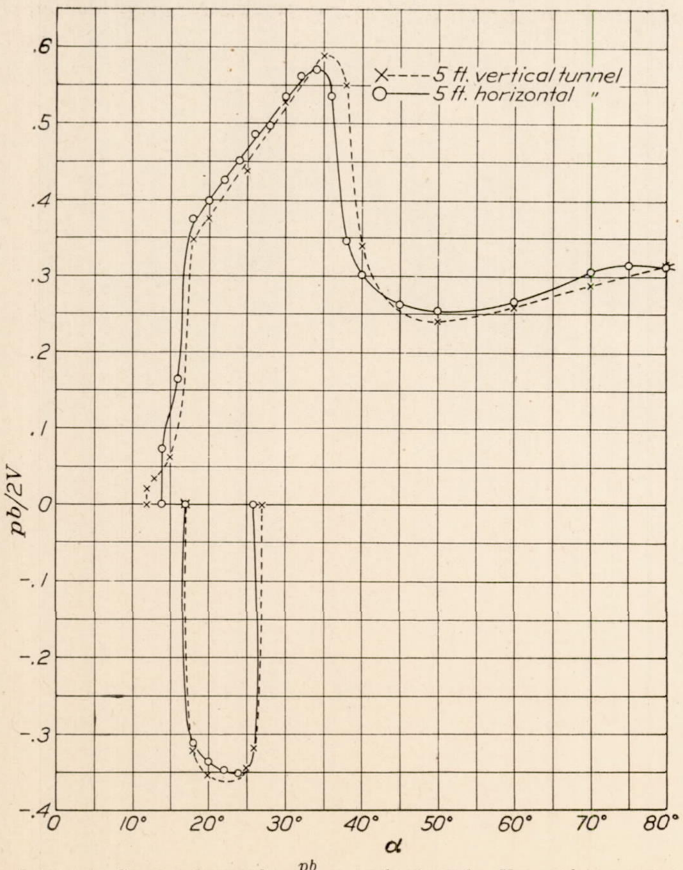

FIGURE 6.—Comparative results—$\frac{pb}{2V}$ vs. angle of attack. Yaw=10°; zero torque

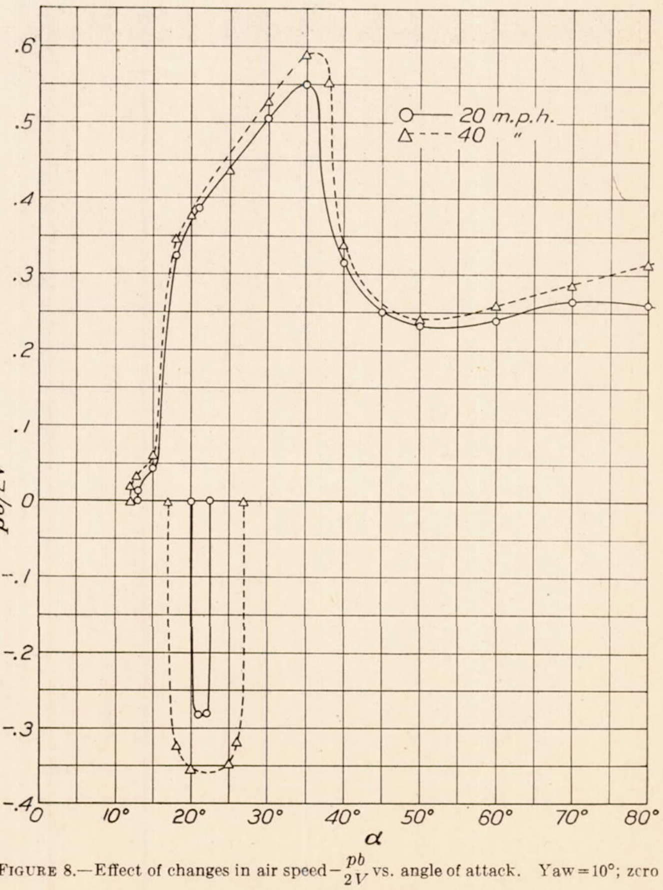

FIGURE 8.—Effect of changes in air speed—$\frac{pb}{2V}$ vs. angle of attack. Yaw=10°; zero torque. Five-foot vertical tunnel

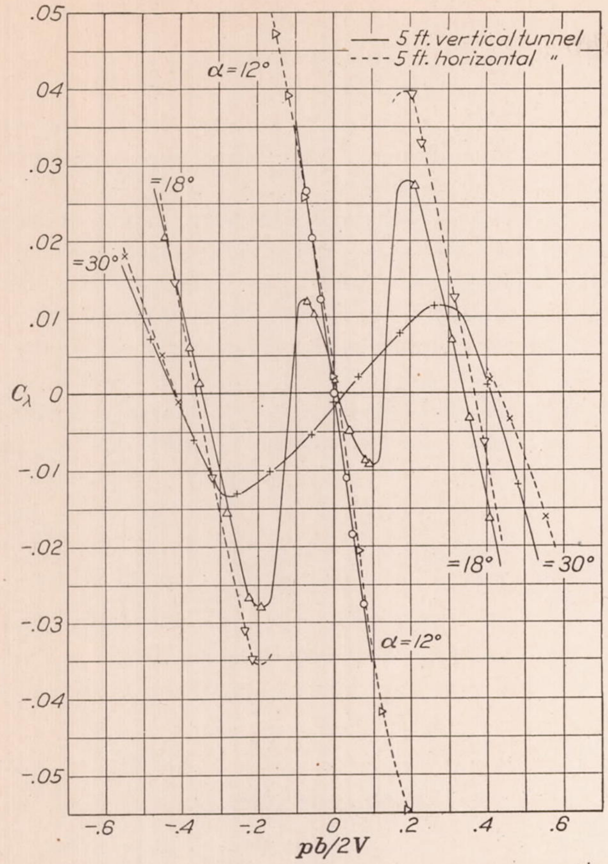

FIGURE 9-a.—Comparative results—rolling moment coefficient vs. $\frac{pb}{2V}$. Yaw=0°; 44 m. p. h.

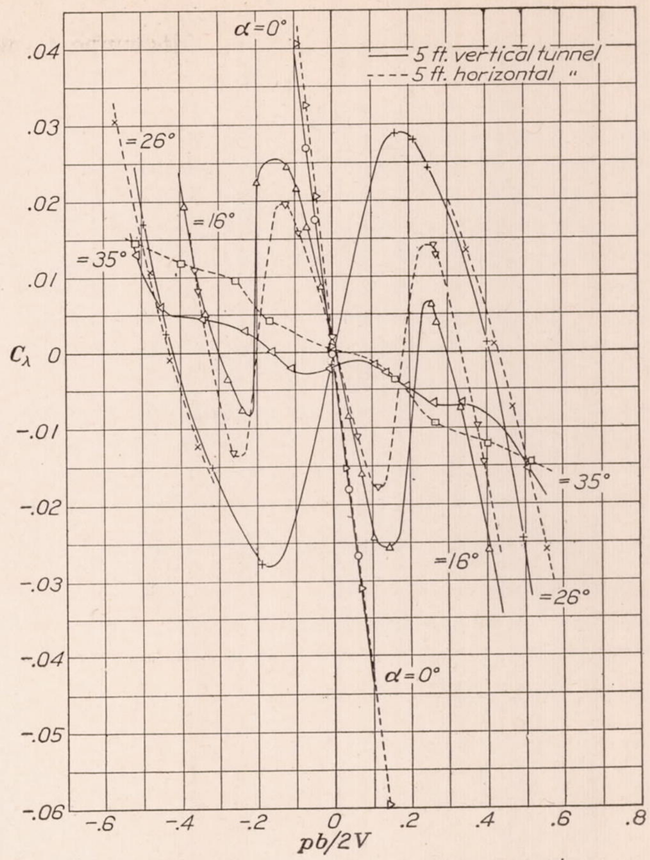

FIGURE 9-b.—Comparative results—rolling moment coefficient vs. $\frac{pb}{2V}$. Yaw=0°; 44 m. p. h.

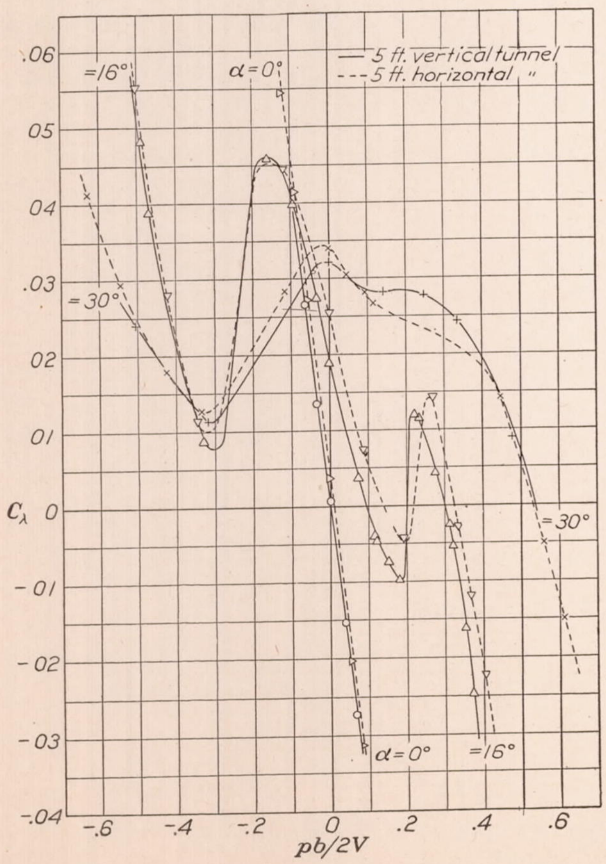

FIGURE 10-a.—Comparative results—rolling moment coefficient vs. $\frac{pb}{2V}$. Yaw=10°; 44 m. p. h.

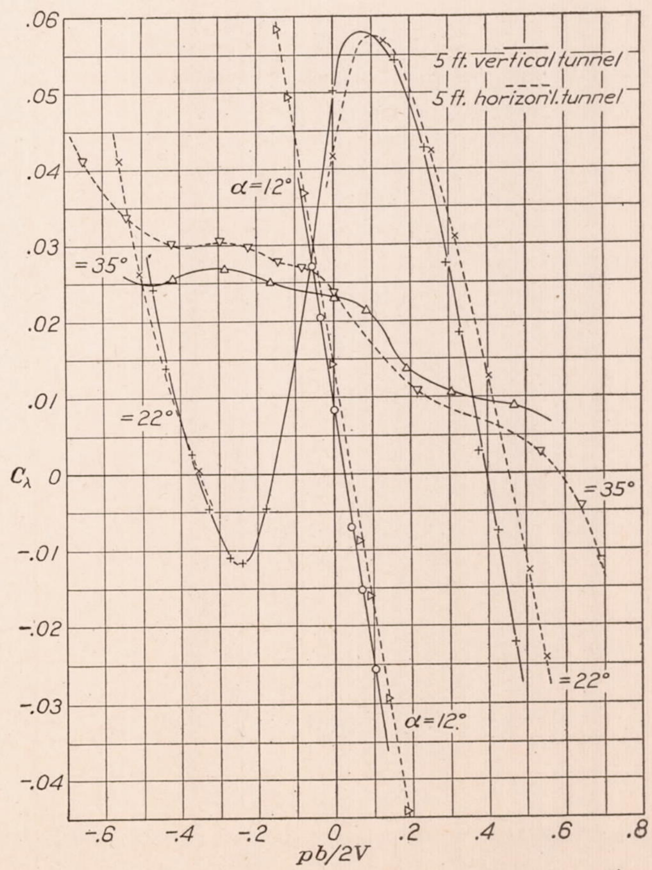

FIGURE 10-b.—Comparative results—rolling moment coefficient vs. $\frac{pb}{2V}$. Yaw=10°; 44 m. p. h.

was probably caused by a small angle of yaw of the model owing to a slight misalignment of its supporting arm. The average range of stable autorotation is in good agreement, falling within 1° of the test results from the horizontal tunnel.

Figure 6 shows the relation of the results when the wing was yawed 10°. The rates and ranges of stable autorotation are again found to be in good agreement, although the angle of self-starting autorotation is about 2° lower for the tests in the vertical tunnel. This discrepancy, however, may have been due to the method of determining the point at which autorotation became self-starting in the tests made in the horizontal tunnel.

Figure 7 shows the effect of changing the air speed, or Reynolds Number, on the rates and ranges of stable autorotation for the zero yaw condition. It is found that the curves are similar in shape, but that maximum values of $\frac{pb}{2V}$ increase with increasing tunnel air speed. Ranges of stable autorotation are also affected somewhat, but not in a clearly defined manner. For a yaw of 10° (fig. 8), it can be seen that, as the air speed is increased, the values of $\frac{pb}{2V}$ and also the ranges of stable autorotation are increased.

Curves of rolling moment coefficient C_λ versus $\frac{pb}{2V}$ are given in Figures 9a, 9b, 10a, and 10b for several angles of attack. The results of tests in both tunnels are plotted. Figures 9a and 9b are for the zero yaw condition. The agreement is fairly good except for angles in the vicinity of maximum lift, i. e., 16° and 18°. Some of the curves obtained in the horizontal tunnel are not shown in their entirety, as the apparatus at that time did not permit of stable operation at the omitted portions. Figures 10a and 10b show the comparisons of the results from both tunnels when the model was yawed 10°. Here the agreement is found to be good throughout the range covered by the tests in both tunnels.

CONCLUSIONS

1. The vertical type of tunnel is well adapted to making all ordinary wind-tunnel tests, but is especially useful for studying the factors affecting the spinning of airplanes, owing to the ease of mounting models and measuring apparatus.

2. Satisfactory air flow has been attained in the new tunnel with a velocity over the jet uniform to within ±0.5 per cent, and a flow parallel to the center line to within about 1°. The turbulence present in the air stream as determined by sphere drag tests may be denoted by the characteristic number 180,000.

3. The results of stable autorotation and of rolling-moment tests from the vertical tunnel are in good agreement with the results of similar tests from the 5-foot horizontal tunnel.

LANGLEY MEMORIAL AERONAUTICAL LABORATORY,
NATIONAL ADVISORY COMMITTEE FOR AERONAUTICS,
LANGLEY FIELD, VA., *February 9, 1931.*

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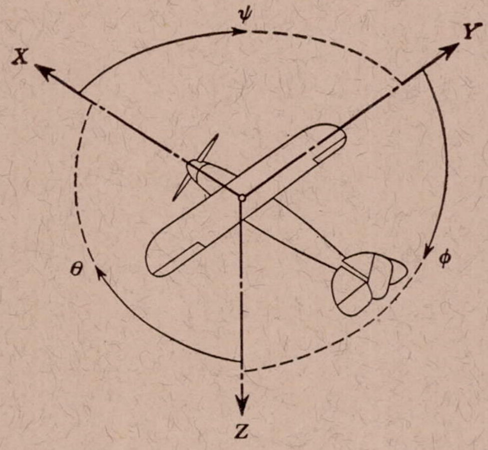

Positive directions of axes and angles (forces and moments) are shown by arrows

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

$$C_l=\frac{L}{qbS} \qquad C_m=\frac{M}{qcS} \qquad C_n=\frac{N}{qbS}$$

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 $=\tan^{-1}\left(\frac{V}{2\pi rn}\right)$

5. NUMERICAL RELATIONS

1 hp = 76.04 kg/m/s = 550 lb./ft./sec.
1 kg/m/s = 0.01315 hp
1 mi./hr. = 0.44704 m/s
1 m/s = 2.23693 mi./hr.
1 lb. = 0.4535924277 kg
1 kg = 2.2046224 lb.
1 mi. = 1609.35 m = 5280 ft.
1 m = 3.2808333 ft.