NATIONAL ADVISORY COMMITTEE FOR AERONAUTICS

REPORT No. 194

INVESTIGATION OF SLIPSTREAM VELOCITY

By J. W. CROWLEY, Jr.

WASHINGTON
GOVERNMENT PRINTING OFFICE
1924

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	sec.	second (or hour)	sec. (or hr.).
Force	F	weight of one kilogram	kg.	weight of one pound	lb.
Power	P	kg.m/sec		horsepower	HP
Speed		m/sec	m. p. s.	mi/hr	M. P. H.

2. GENERAL SYMBOLS, ETC.

Weight, $W = mg$.

Standard acceleration of gravity, $g = 9.806\text{m/sec.}^2 = 32.172\text{ft/sec.}^2$

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

Density (mass per unit volume), ρ

Standard density of dry air, 0.1247 (kg.-m.-sec.) at 15.6°C. and 760 mm. = 0.00237 (lb.-ft.-sec.)

Specific weight of "standard" air, 1.223 kg/m.^{3} = 0.07635 lb/ft.^{3}

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

Area, S; wing area, S_w, etc.

Gap, G

Span, b; chord length, c.

Aspect ratio $= b/c$

Distance from $c. g.$ to elevator hinge, f.

Coefficient of viscosity, μ.

3. AERODYNAMICAL SYMBOLS.

True airspeed, V

Dynamic (or impact) pressure, $q = \frac{1}{2} \rho V^2$

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

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

Cross-wind force, C; absolute coefficient

$C_c = \frac{C}{qS}$.

Resultant force, R

(Note that these coefficients are twice as large as the old coefficients L_c, D_c.)

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

Angle of stabilizer setting with reference to thrust line i_t

Dihedral angle, γ

Reynolds Number $= \rho \frac{Vl}{\mu}$, where l is a linear dimension.

e. g., for a model airfoil 3 in. chord, 100 mi/hr., normal pressure, 0°C: 255,000 and at 15.6°C, 230,000;

or for a model of 10 cm. chord, 40 m/sec., corresponding numbers are 299,000 and 270,000.

Center of pressure coefficient (ratio of distance of C. P. from leading edge to chord length), C_p.

Angle of stabilizer setting with reference to lower wing. $(i_t - i_w) = \beta$

Angle of attack, α

Angle of downwash, ϵ

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INVESTIGATION OF SLIPSTREAM VELOCITY.

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SUMMARY.

These experiments were made by the National Advisory Committee for Aeronautics at the request of the Bureau of Aeronautics, Navy Department, to investigate the velocity of the air in the slipstream in horizontal and climbing flight to determine the form of expression giving the slipstream velocity in terms of the airspeed of the airplane. The method used consisted in flying the airplane both on a level course and in climb at full throttle and measuring the slipstream velocity at seven points in the slipstream for the whole speed range of the airplane in both conditions. In general the results show that for both conditions—i. e., horizontal and climbing flights—the relation between the slipstream velocity V_s and airspeed V can be represented by straight lines and consequently the equations are of the form:

$$V_s = mV + b.$$

Where m and b are constants.

METHOD.

The investigation was made on a standard Vought (*VE-7*) training airplane with Navy propeller No. 047542. The velocity in the slipstream was measured by seven special Pitot static heads (Fig. 1) mounted on a streamline wooden spar which ran radially from the exhaust manifold to the leading edge of the top wing. The heads were distributed along this spar as shown in Figure 2, the inside one being 4 inches from the exhaust manifold and the others at 6-inch spaces, so that the region investigated extended well beyond the slipstream. The spar was mounted 0.32 diameter back of the propeller and as free as possible from any interference of bracing wires or other obstructions. However, it is felt that the reading of the innermost head may be somewhat erratic due to its proximity to the exhaust manifold. These heads and a universally mounted Pitot static head for measuring the airplane's airspeed (Fig. 3) were connected to the National Advisory Committee for Aeronautics multiple recording manometer[1] which recorded the eight readings simultaneously. The data were obtained as follows:

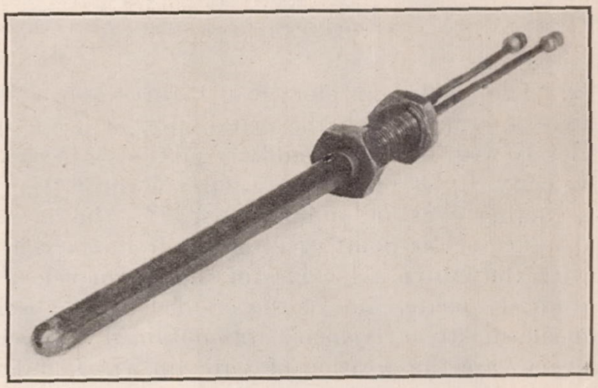

Fig. 1.—Pitot static head.

1. In horizontal flight the throttle was opened wide at maximum speed, gradually closed until the speed of minimum power was reached, and then opened wide at minimum speed. A level flight path was maintained by means of a statoscope and the readings recorded at airspeed increments of 10 M. P. H.

2. In climbing flight the throttle was opened wide for the whole run, beginning with high speed horizontal flight and pulling the airplane up through its entire range of climbing angle and ending with minimum speed in horizontal flight. As before, the readings were taken at airspeed increments of 10 M. P. H.

[1] National Advisory Committee for Aeronautics Report No. 148, or engineering division, McCook Field, Serial 1986.

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Four runs were made for each condition with the radial spar mounted on the right side. Then the installation of heads was changed to the corresponding position on the left side of the airplane and two additional runs made for both conditions.

All the flights were made at an altitude corresponding to a density of 88 per cent ($\pm$ 2 per cent) standard density and the speeds given are the indicated speeds for that density.

Before the flight tests the heads were tested in the Committee's wind tunnel for effects of misalignment with the relative wind. Also several flights were made with a yaw meter head mounted in place of the Pitot static heads to determine the amount of yaw of the slipstream.

PRECISION.

The capsules used on the multiple recording manometer were calibrated against a water column before and after the tests, and should be precise to ± 2 M. P. H. The yaw meter recorded a maximum yaw of 3.75° corresponding to an error of 0.6 per cent of the slipstream velocity, the velocity reading being too great.

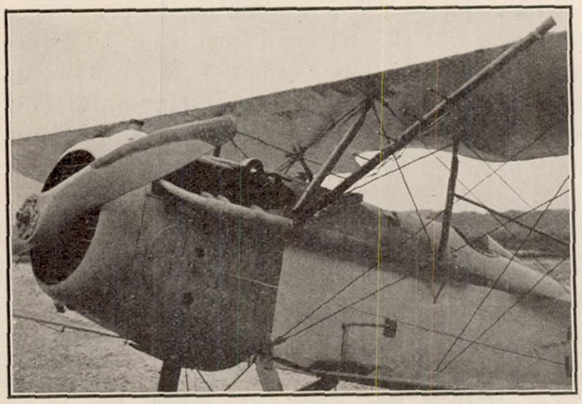

FIG. 2.—Mounting of Pitot static heads.

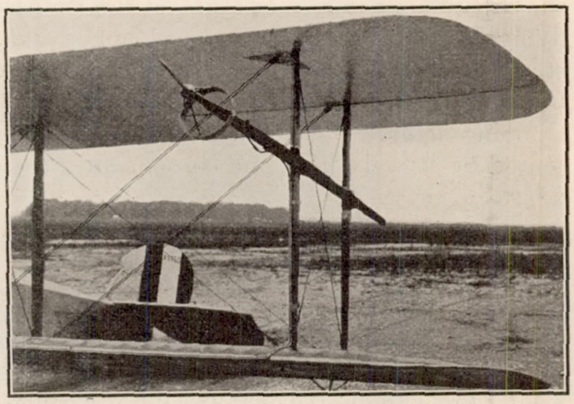

FIG. 3.—Universally mounted Pitot static airspeed head.

RESULTS.

The results are plotted in Figures 4, 5, and 6. The slipstream velocities obtained in the two runs made with the installation of heads on the opposite side of the airplane agree very closely with the others and are plotted with them in Figure 4. To obtain the mean slipstream velocity V_s, as plotted in Figures 5 and 6, the velocity at each airspeed head was considered as acting over an annular area. As this area is directly proportional to the square of the distance of the point investigated from the center line of the crankshaft, the data were plotted with the individual values of slipstream velocity as ordinates and the square of the distance from the center line of the crankshaft as abscissæ. The mean ordinate of this curve or the mean slipstream velocity was obtained between the fuselage and the place of zero slip. In every case the position of zero slip was found to be almost directly behind the propeller tip, so the distance to the propeller tip was used as the outside limit of the slipstream. For convenience, the data obtained at the same approximate airspeed (± 2 M. P. H.) were plotted together as in Figure 4. It should be noted, therefore, that each experimental point in Figures 5 and 6 represents data obtained from at least three runs. Two points computed on the basis of the momentum theory are also plotted in Figures 5 and 6 for comparison. [2]

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[2] Assuming the slipstream area to be 0.8 the propeller disc area, and that the velocity of the air is uniform over the slipstream, from the momentum theory of propulsion we have the following relation:

$$\begin{aligned} \text{Thrust} &= M\,(V_s - V) \\ &= \frac{\rho}{g} A_s\, V_s\,(V_s - V) \\ &= .0015\, D^2 V_s\,(V_s - V) \qquad (1) \\ \text{Thrust} &= \frac{550\, P\, \eta}{V} \qquad (2) \end{aligned}$$

Equating (1) and (2) and reducing

$$(V_s - V)\, V_s = \frac{367{,}000\ P\, \eta}{V D^2}$$

Where V_s = velocity of slipstream (ft./sec.).
V = airspeed (ft./sec.).
D = diameter of propeller (ft.).
A_s = slipstream area.
M = mass of air passing through propeller in 1 second.
P = horsepower.
η = propeller efficiency.

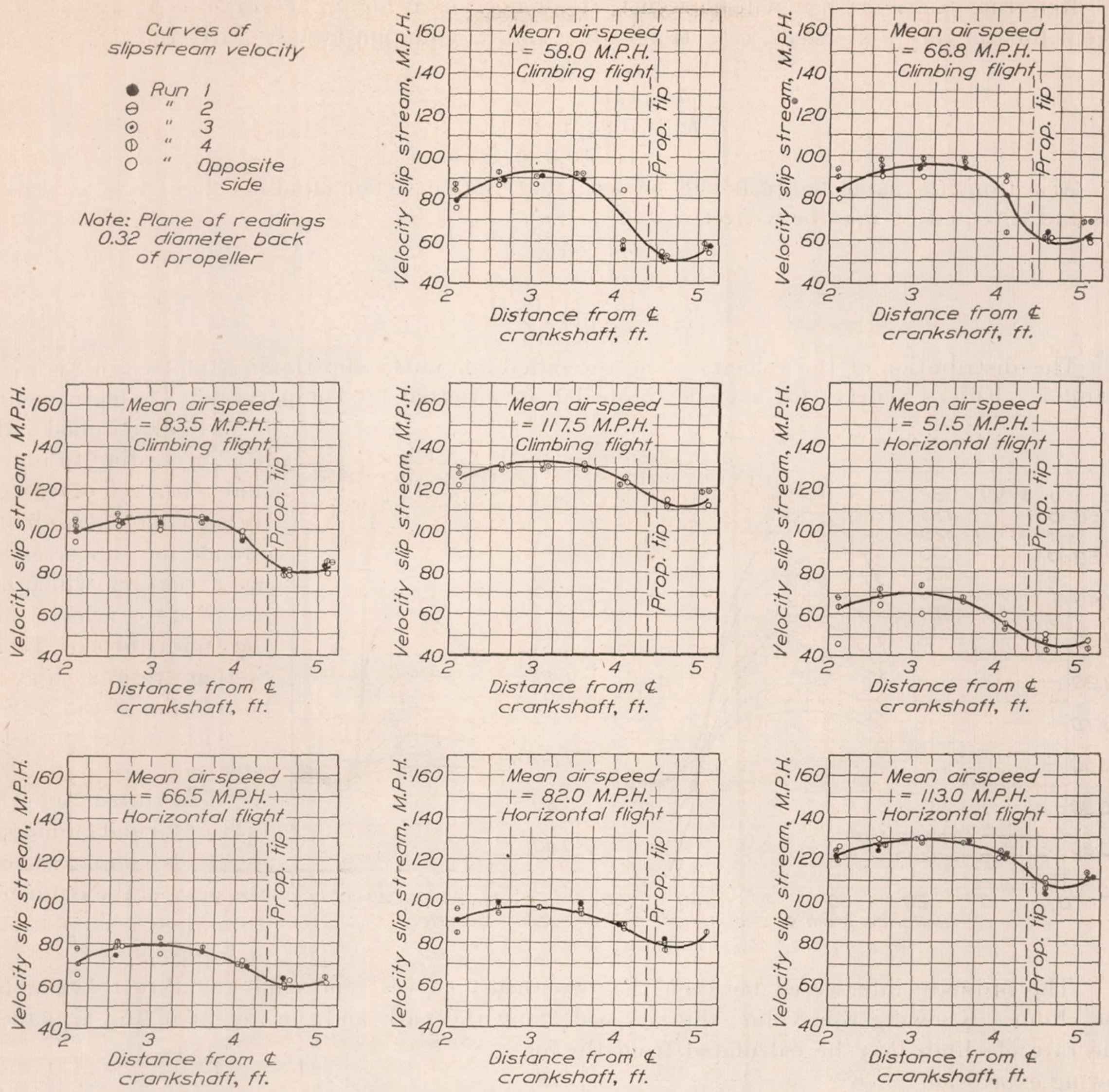

FIG. 4.—Slipstream velocity curves for VE-7.

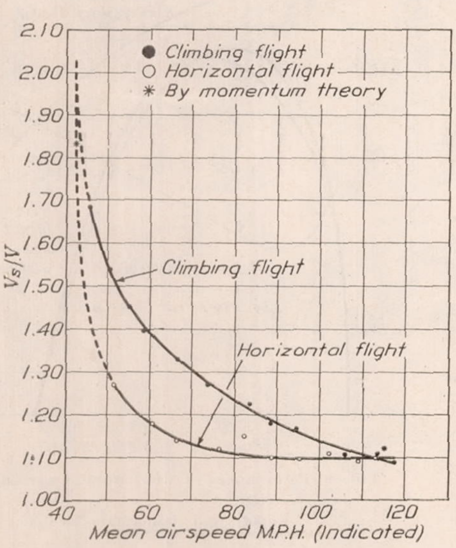

FIG. 5.—Slipstream velocity, VE-7.

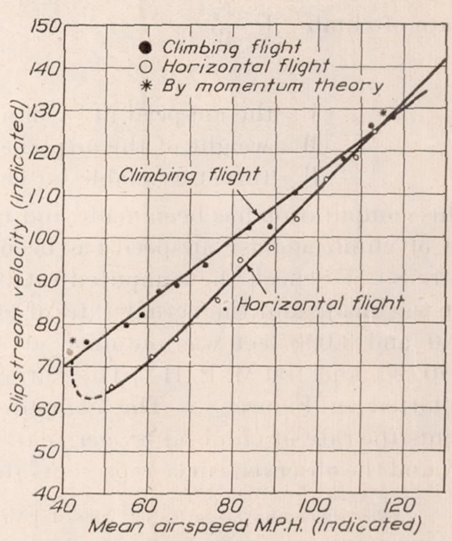

FIG. 6.—Slipstream velocity, VE-7.

Referring to Figure 6 it will be seen that for horizontal flight the curve of V_s against V, except for the very low speeds, is a straight line and its equation may be written:

$$V_s = mV + b.$$
$$m = 1.0$$
$$b = 10.0 \text{ M. P. H.}$$
$$V_s = V + 10.0 \text{ M. P. H.}$$

Also from the same figure it will be seen that the curve for climbing flight is a straight line and its equation may be written:

$$V_s = mV + b$$
$$m = .75$$
$$b = 40.5 \text{ M. P. H.}$$
$$V_s = .75\ V + 40.5$$

The distribution of the velocity along the radial line in the slipstream is plotted in Figures 4 and 7. Eiffel's [3] curves for a model propeller are inserted for comparison. The agreement is particularly good and it is interesting to note that with reference to the airplane, the air just outside the slip stream has a velocity which is less than the velocity of the undisturbed air. Similar results have been found at the N. P. L. with model propellers.[4]

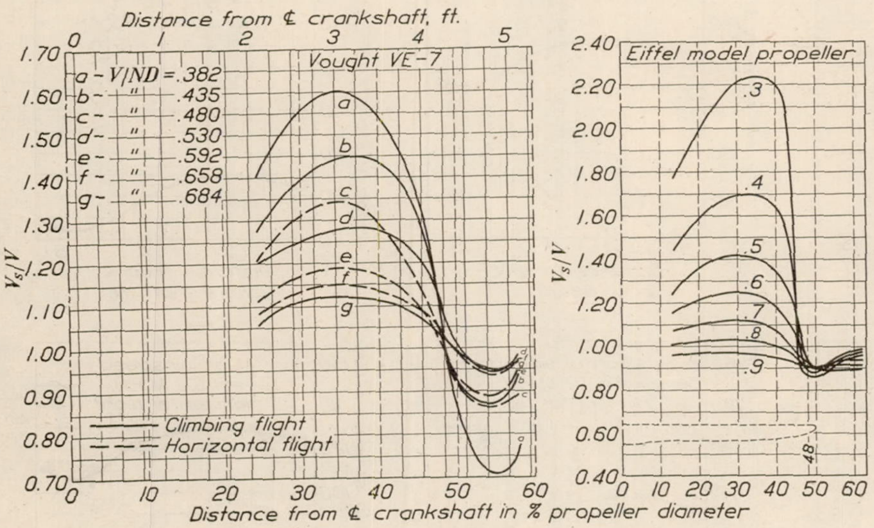

FIG. 7.—Slipstream velocity curves.

The thrust for both horizontal and climbing flights as computed on the basis of the momentum theory is plotted in Figure 8.

The ordinate intersected between the two thrust curves represents the thrust available for climb. Knowing this value, the airspeed along the path and the weight of the airplane, the rate of climb may be calculated from the following expression:

$$\text{Rate of climb} = V\ \frac{T_a}{W}$$

Where

V = the airspeed in ft./min.
W = weight of the airplane.
T_a = thrust available for climb.

This computation has been made and the curve of rate of climb against airspeed has been plotted in Figure 8. To check the computed rate of climb a flight was made and the actual rate of climb between 0 and 3,000 feet was obtained at airspeeds of 70, 80, 90, and 100 M. P. H. This curve has also been plotted in Figure 8. The computed curve represents the rate of climb at 88 per cent standard density and the observed curve represents the rate of

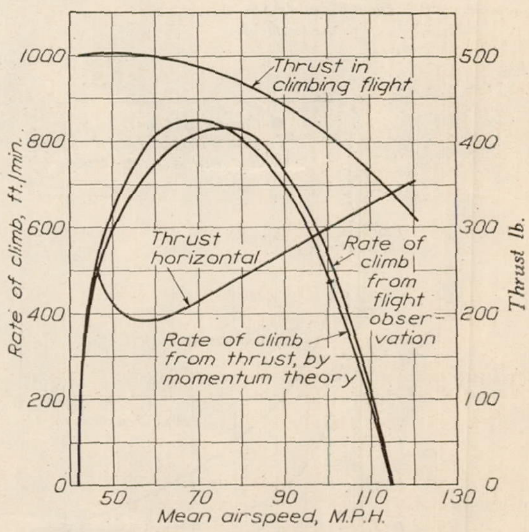

FIG. 8—Performance of VE-7 from slipstream data.

[3] Nouvelles Recherches sur La Resistance de l'Air et Aviation.

[4] Reports and Memoranda No. 371.

climb at 91 per cent standard density. The conditions are sufficiently close for comparative purposes. The maximum rate of climb is the same by both methods and although the actual performance curve indicates the maximum value of rate of climb at a higher airspeed than does the computed curve, the discrepancy is slight and probably within the accuracy of the measurements.

Value of R. P. M. was observed in all these tests and a curve of R. P. M. against airspeed has been inserted for reference (Fig. 9).

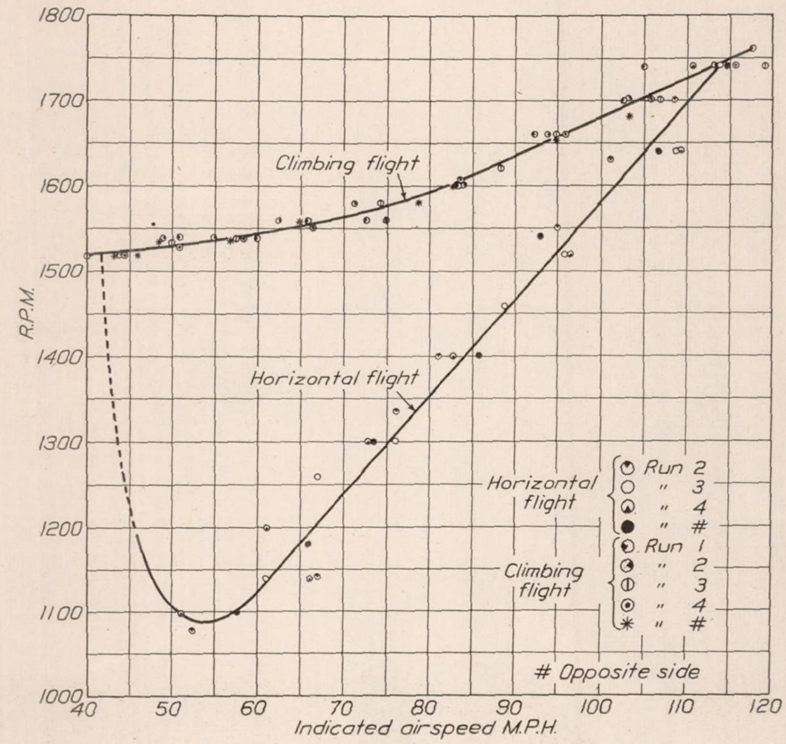

FIG. 9.—Revolutions per minute vs. airspeed, VE-7.

CONCLUSIONS.

Besides the fact that the expression for the value of the slipstream velocity may be represented by a straight line, the most noteworthy fact brought out by this report is the good comparison between wind tunnel and free flight results and the results obtained by the computations based upon the momentum theory. A series of tests on a single airplane of one type may not produce any conclusive evidence but it does point strongly to the conclusion that for the usual uses to which a knowledge of the slipstream velocity is applied, namely, slipstream corrections in preliminary performance calculations and design, the momentum theory is sufficiently accurate.

REFERENCES.

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An Investigation into the Nature of the Flow in the Neighborhood of an Airscrew. R. and M. 371.

Experimental Determination of the Slipstream Behind the Airscrew of a Pusher. R. and M. 382.

Exploration of the Air Speed in the Airscrew Slipstream of a Tractor Machine. R. and M. 438.

Exploration of the Slipstream Velocity in a Pusher Machine. R. and M. 444.

On a Method of Estimating, from Observations on the Slipstream of an Airscrew, the Performance of the Elements of the Blades and the Total Thrust of the Air Screw. R. and M. 460.

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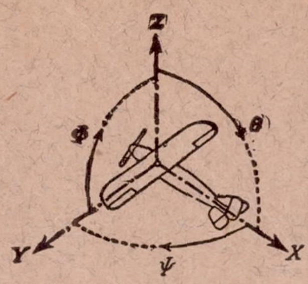

Positive directions of axes and angles (forces and moments) are shown by arrows.

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

$$C_l = \frac{L}{q\,b\,S} \quad C_m = \frac{M}{q\,c\,S} \quad C_n = \frac{N}{q\,f\,S}$$

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

4. PROPELLER SYMBOLS.

Diameter, D
Pitch (a) Aerodynamic pitch, p_a
(b) Effective pitch, p_e
(c) Mean geometric pitch, p_g
(d) Virtual pitch, p_v
(e) Standard pitch, p_s
Pitch ratio, p/D
Inflow velocity, V'
Slipstream velocity, V_s

Thrust, T
Torque, Q
Power, P
(If "coefficients" are introduced all units used must be consistent.)
Efficiency $\eta = T\,V/P$
Revolutions per sec., n; per min., N
Effective helix angle $\Phi = \tan^{-1}\left(\frac{V}{2\pi r n}\right)$

5. NUMERICAL RELATIONS.

1 HP = 76.04 kg. m/sec. = 550 lb. ft/sec.
1 kg. m/sec. = 0.01315 HP
1 mi/hr. = 0.44704 m/sec.
1 m/sec. = 2.23693 mi/hr.

1 lb. = 0.45359 kg.
1 kg. = 2.20462 lb.
1 mi. = 1609.35 m. = 5280 ft.
1 m. = 3.28083 ft.