REPORT No. 323

FLOW AND FORCE EQUATIONS FOR A BODY REVOLVING IN A FLUID

By A. F. ZAHM
Aerodynamical Laboratory
Bureau of Construction and Repair, U. S. Navy
CONTENTS

Summary ........................................ 411
Part I. Introduction .......................... 412
  Steady-flow method ......................... 412
  General formulas for velocity com-
  ponents ...................................... 413
  Surface velocity ................................ 413
  Zonal forces and moments .................... 413
  Geometrical formulas ......................... 414
  Conventions .................................. 415
Part II. Velocity and Pressure ............... 416
  (A) Bodies in Simple Rotation .............. 416
    Elliptic cylinder .......................... 416
    Prolate spheroid ........................... 418
    Ellipsoid ................................... 422
  (B) Bodies in Combined Translation  and Rotation .... 422
    Most general motion ........................ 422
    Yawing flight ............................... 422
    Flow inside ellipsoid ....................... 424
    Potential coefficients ...................... 426
    Relative velocity and kinetic pres-
    sure ........................................ 426
Part III. Zonal Force and Moment on Hull Forms .... 427
  Pressure loading ................................ 427
  Zonal force .................................. 428
  Zonal moment .................................. 428
  Correction factors ............................ 428
Part IV. Resultant Force and Mo-
  ment ......................................... 429
  Body in free space ............................ 429
  Reactions of fluid ............................. 429
  Combination of applied forces .............. 431
  Hydrokinetically symmetric forms .......... 432
  Examples ..................................... 432
  Theory vs. experiment ......................... 433
  Correction factors ............................ 435
Part V. Potential Coefficients—In-
 ertia Coefficients ......................... 436
  Green's integrals ............................. 436
  Potential coefficients ....................... 436
  Inertia coefficients .......................... 436
  Limiting conditions ........................... 437
  Physical meaning of the coefficients ....... 437
Symbols Used in the Text .................... 438
References .................................... 439
Tables and Diagrams ........................... 439
REPORT No. 323

FLOW AND FORCE EQUATIONS FOR A BODY REVOLVING IN A FLUID

IN FIVE PARTS

By A. F. Zahm

SUMMARY

This report, submitted to the National Advisory Committee for Aeronautics for publication, is a slightly revised form of U. S. Navy Aerodynamical Laboratory Report No. 380, completed for the Bureau of Aeronautics in November, 1928. The diagrams and tables were prepared by Mr. F. A. Louden; the measurements given in Tables 9 to 11 were made for this paper by Mr. R. H. Smith, both members of the Aeronautics Staff.

Part I gives a general method for finding the steady-flow velocity relative to a body in plane curvilinear motion, whence the pressure is found by Bernoulli's energy principle. Integration of the pressure supplies basic formulas for the zonal forces and moments on the revolving body.

Part II, applying this steady-flow method, finds the velocity and pressure at all points of the flow inside and outside an ellipsoid and some of its limiting forms, and graphs those quantities for the latter forms. In some useful cases experimental pressures are plotted for comparison with theoretical.

Part III finds the pressure, and thence the zonal force and moment, on hulls in plane curvilinear flight.

Part IV derives general equations for the resultant fluid forces and moments on trisymmetrical bodies moving through a perfect fluid, and in some cases compares the moment values with those found for bodies moving in air.

Part V furnishes ready formulas for potential coefficients and inertia coefficients for an ellipsoid and its limiting forms. Thence are derived tables giving numerical values of those coefficients for a comprehensive range of shapes.
REPORT No. 323

FLOW AND FORCE EQUATIONS FOR A BODY REVOLVING IN A FLUID

PART I

INTRODUCTION

STEADY-FLOW METHOD.—In some few known cases one can compute the absolute particle velocity \( q' \) at any point \( (x, y, z) \) of the flow caused by the rotation of a body, say with uniform angular speed \( \Omega \), in an infinite inviscid liquid otherwise still. Thence, since \( q' \) is unsteady at \( (x, y, z) \), the instantaneous pressure there is found by Kelvin’s formula

\[
p_{\psi}/\rho = -\partial \psi/\partial t - q'^2/2,
\]

\( \psi \) being the supervacuo pressure there, and \( \partial \psi/\partial t \) the velocity potential.

Otherwise superposing upon said body and flow field the reverse speed \(-\Omega\), about the same axis, gives the same relative velocity \( q \) but which now is everywhere a steady space velocity. In the body’s absence the circular flow speed at the radial distance \( R \) would be \( q_0 = -\Omega R \).

If the fixed body’s presence lowers the speed at \( (x, y, z) \) from \( q_0 \) to \( q \), it obviously begets there the superstream pressure

\[
p = \frac{1}{2} \rho (q_0^2 - q^2)
\]

or in dimensionless form, \( a \) being some fixed length in the body,

\[
\frac{p}{\frac{1}{2} \rho a^2} = \frac{R^2}{a^2} (1 - q^2/q_0^2)
\]

The present text finds \( p \) by this steady-flow method only, and applies it to streams about various forms of the ellipsoid and its derivatives.

The superposed circular flow, \( q_0 = -\Omega R = -\partial \psi/\partial R \), has the stream-function

\[
\psi = \frac{1}{2} \Omega R^2
\]

which, for rotation about the \( z \) axis, plots as in Figure 4. This flow has no velocity potential, since \( \partial \psi/\partial R \neq 0 \).

GENERAL FORMULAS FOR VELOCITY COMPONENTS.—In plane flow,\(^1\) as is known, a particle at any point \( (x, y) \) of a line \( s \) drawn in the fluid has the tangential and normal velocity components

\[
q_t = \frac{\partial \psi}{\partial y} = \frac{\partial \psi}{\partial n}, \quad q_n = \frac{\partial \psi}{\partial n} = \frac{\partial \psi}{\partial n}
\]

\(^1\) This velocity entails the centrifugal pressure \( p_c = \rho \Omega^2 R^2/2 \) at all distances, \( R = \sqrt{x^2 + y^2} \) from the rotation axis of the circular stream, here assumed to be constrained by a coaxial closed cylinder infinitely large. To the dynamic pressure \( p_d \) may also be added any arbitrary static pressure such as that due to weight or other impressed force.

\(^2\) At any surface point of the body \( q \) is the velocity of wash or slip, whether the body moves or not, it is \( q'_t - q'_n \), the difference of the tangential space velocities of the fluid and surface point. If the body is fixed \( q'_t = 0, q = q'_n \).

\(^3\) Plane flow, i.e., two-dimensional flow, literally means flow in a plane; the term applies also to space flow that is the same in all parallel planes.
FLOWS AND FORCE EQUATIONS FOR A BODY REVOlVING IN A FLUID

where \( \delta s, \delta n \) are elements along the line and its normal. As usual, \( q_n, q_s \) are reckoned positive respectively along \( \delta s, \delta n \) positive; e. g. Figure 2. The components along \( x, y \) are

\[
\begin{align*}
    u &= \frac{\partial \varphi}{\partial x} - \frac{\partial \psi}{\partial y} \\
    v &= \frac{\partial \varphi}{\partial y} - \frac{\partial \psi}{\partial x}
\end{align*}
\]

(4)

In solid flow (3), (4) still hold for \( \varphi, \psi \), and further \( w = \partial \varphi/\partial z \). In general, \( q^2 = u^2 + v^2 + w^2 = q_n^2 + q_s^2 \). At any point of a surface drawn in the fluid \( q_s \) is taken in the plane of \( q_n \) and \( q_s \) positive; e. g. Figure 2. The components along \( x, y \) are

\[
\begin{align*}
    u &= \frac{\partial \varphi}{\partial x} - \frac{\partial \psi}{\partial y} \\
    v &= \frac{\partial \varphi}{\partial y} - \frac{\partial \psi}{\partial x}
\end{align*}
\]

(4)

More generally, for any surface with velocities \( \Omega_x, \Omega_y, \Omega_z \) about the axes \( x, y, z \),

\[
q_n = (ny - mz)\Omega_z + (lz - nx)\Omega_x + (mx - ly)\Omega_y
\]

(6)

where \( l, m, n \) are the direction cosines of the surface normal, as in (13). If the body is any cylinder rotating as in Figure 1,

\[
q_n = -\Omega R \frac{dR}{ds} = \Omega R \sin(\theta - \beta) = \Omega h = \Omega(m x - l y)
\]

(5)

where the symbols are as defined in Figures 1, 2.

More generally, for any surface with velocities \( \Omega_x, \Omega_y, \Omega_z \) about the axes \( x, y, z \),

\[
q_n = (ny - mz)\Omega_z + (lz - nx)\Omega_x + (mx - ly)\Omega_y
\]

(6)

where \( l, m, n \) are the direction cosines of the surface normal, as in (13). If the body is any cylinder rotating as in Figure 1,

\[
q_n = -\Omega R \frac{dR}{ds} = \Omega R \sin(\theta - \beta) = \Omega h = \Omega(m x - l y)
\]

(5)

where the symbols are as defined in Figures 1, 2.

9. ZONAL FORCES AND MOMENTS.—For any cylinder spinning about \( z \), as in Figure 1 or 5, surface integration of \( p \) gives, per unit of \( z \)-wise length, the zonal forces and moment, respectively,

\[
\begin{align*}
    X &= \int p\, dy \\
    Y &= \int p\, dx \\
    N &= \int p\, r\, dr
\end{align*}
\]

(8)

But (5), (6), (7) express \( q_n \) only at the model's surface.

Equations (1) to (7) obtain whether the fluid is inside or outside the body.

A surface of rotation about \( z \), spinning about its \( z \) axis, has zonal forces

\[
X = \int p\, dy \\
Y = \int p\, dx \\
N = \int p\, r\, dr
\]

(9)
If \( ds_1, ds_2 \) are elements of its lines of meridian and latitude, as in Figure 3, the moment about \( z \) of \( p \, ds_1, ds_2 \) in the plane \( \omega = 0 \), and \( p \, r \, dr \, ds_1, ds_2 \) \( \cos \omega = p \, r \, dr \, dz = dN \) for any meridian plane; hence the zonal moment is

\[
N = \int P \, dr. \tag{10}
\]

where \( P = \int_{-\pi}^{\pi} r \, dz = Y/dz \), is the y-wise pressure-force per unit length x-wise. \(^1\) Thus, as for (8), \( N \) varies as the area of the graph of \( P \) versus \( r^2 \). Also one notes that

\[
Y = \int P \, dx \quad P = z_0 \int_0^{2\pi} p \, \cos \omega \, d\omega. \tag{10.,}
\]

Since \( p \) is symmetrical about the \( x \) axis, \( Z = 0 = Y = L = M = N \); viz, the assumed zone is not urged along \( y, z \) or about \( x, y, z \). In general, \( X \) is not zero for such a zone, but is zero for the whole model. The zonal \( Y, N \) are zero for steady rotation about \( z \) in a frictionless liquid, because \( p \) is symmetrical about the \( x \) axis; but are not so in a viscid fluid, nor for accelerated spin in a perfect fluid.

For trisymmetrical surfaces we note also: If the zones were formed by planes normal to \( z \), zonal \( X \) would be zero for motion about \( z \); zonal \( N \) in general not zero; e.g., for a viscid fluid. Similarly for zones with faces normal to \( y \).

By (10) the bending moment about the \( z \) ordinate in the plane \( y = 0 \) is \( \int_0^\pi P \, r \, dr \). This is zero for a frictionless liquid; for a viscid fluid it increases with length of zone.

In addition to the pressure forces and moments just considered, due to rotation about \( z \), a viscid fluid exerts surface friction symmetrical about the \( z \) axis, but not treated here.

For any surface \( S \), clearly (9) still holds and (10) can be generalized to the usual form

\[
N = \int \int P (dx - ydy) \, dz. \tag{10.2}
\]

**Geometrical Formulas.**—Most of the surfaces treated in this text are members of the confocal ellipsoid family

\[
\frac{x^2}{a^2 + \lambda} + \frac{y^2}{b^2 + \lambda} + \frac{z^2}{c^2 + \lambda} = 1 = \frac{x^2}{a'^2} + \frac{y^2}{b'^2} + \frac{z^2}{c'^2}. \tag{11}
\]

whose semi axes are \( a' = \sqrt{a^2 + \lambda} \), etc. The following known properties are needed.

The distance from the center to the tangent plane at the point \( (x, y, z) \) of \( a'b'c' \) is

\[
h_3 = \left( \frac{x^2}{a'^2} + \frac{y^2}{b'^2} + \frac{z^2}{c'^2} \right)^{-1/2}. \tag{12}
\]

The direction-cosines of the normal to said plane are

\[
l, m, n = -\frac{h_x}{h_z}, -\frac{h_y}{h_z}, \frac{h_z}{h_z}. \tag{13}
\]

\(^1\) The radius of the latitude circle is denoted by \( n = y_0 \).
FLOW AND FORCE EQUATIONS FOR A BODY REVOLVING IN A FLUID

The partial derivatives of $\lambda$ are

\[
\frac{\partial \lambda}{\partial z} = 2m_n, \quad \frac{\partial \lambda}{\partial y} = 2m_n, \quad \frac{\partial \lambda}{\partial z} = 2n_m, \quad \frac{\partial \lambda}{\partial n} = 2h_z. \tag{14}
\]

More generally for any surface $f(x, y, z) = 0$, one knows

\[
l = \frac{\partial f}{\partial x}, \quad m = \frac{\partial f}{\partial y}, \quad n = \frac{\partial f}{\partial z}, \quad j = \left[\left(\frac{\partial f}{\partial x}\right)^2 + \left(\frac{\partial f}{\partial y}\right)^2 + \left(\frac{\partial f}{\partial z}\right)^2\right]^{-1} \tag{13}
\]

and the distance from the origin to the tangent plane at $(x, y, z)$ is

\[
h_z = l_x + m_y + n_z = r \cos \gamma \tag{12}
\]

$\gamma$ being the angle between the radius vector $r$ and the normal.

CONVENTIONS.—In all the text $x, y, z$ have the positive directions shown in Figure 3, as also have the $x, y, z$ components of velocity, acceleration, force, linear momentum. The angular components about $x, y, z$ of velocity, acceleration, moment, momentum are positive in the respective directions $y$ to $z$, $z$ to $x$, $x$ to $y$. The positive direction of a plane closed contour $s$ is that followed by one going round it with the inclusion on his left, as in Figure 2; the positive direction of the normal $n$ is from left to right across $s$; and $\delta s$, $\delta n$ determine the positive directions of the tangential and normal flow velocities $q_n$, $q_t$, as previously stated. For a closed surface $\delta n$ is positive outward and $\delta s$ is positive in the direction of one walking on the outer surface with $n$ on his left.

The word "displaced fluid," used in treating the motion of a submerged body, usually means fluid that would just replace the body if the latter were removed.
REPORT No. 323

FLOW AND FORCE EQUATIONS FOR A BODY REVOLVING IN A FLUID

PART II

VELOCITY AND PRESSURE

(A) BODIES IN SIMPLE ROTATION

ELLIPDIC CYLINDER.—For an endless elliptic cylinder, of semiaxes \( a, b, c (= \infty) \), rotating about \( c \) with angular speed \( \Omega \) in an infinite inviscid liquid, otherwise still, one knows

\[
\varphi = -m' \Omega xy = -\frac{1}{2} m' \Omega a'b' \sin 2\eta \quad \psi = -\frac{1}{2} m' \Omega a'b' \cos 2\eta \quad . . . . . . . . . . . . . . . . . . (15)
\]

the geometric symbols being as in Figure 2. For any outer confocal \( a'b' \) the potential coefficient has the constant value

\[
m' = (a + b)(a' - b')/2a'b'(a' - b') \quad . . . . . . . . . . . . . . . . . . (16)
\]

On the model's surface \( a' = a, b' = b; m' = (a^2 - b^2)/4ab \).

The equipotential lines on either surface \( ab \) or \( a'b' \) are its intersections with the corresponding family of hyperbolic cylinders \( xy = -\varphi/m', \Omega = \text{const.} \). Normal to the equipotentials are the streamlines \( \psi = \text{const.} \). Graphs for \( \psi = 0, 0.2, 0.4, \text{etc.} \), are shown in Figure 5 for a model having \( a/b = 4 \). They are instantaneous streamlines, and form with the model a constant pattern in uniform rotation about \( c \) in said infinite liquid.

At any outer confocal \( a'b' \) the velocity components are, if \( \kappa = m' a'b'/\Omega \),

\[
q' = -\frac{\partial \varphi}{\partial \eta} = -\kappa \cos 2\eta \quad \frac{d\eta}{ds} = -q' \tan 2\eta \quad . . . . . . . . . . . . . . . . . . (17)
\]

Equivalent to (16) is

\[
m' = \left( a + b \right) \left( a' - b' \right) / 2a'b'(a' - b') \quad . . . . . . . . . . . . . . . . . . (16)
\]

On \( ab \) this becomes

\[
m' = \left( e + e' \right) / 2 \quad e, e' \quad \text{the eccentricities of} \ a, a'. \]
FLOW AND FORCE EQUATIONS FOR A BODY REVOlVING IN A FLUID

where \( \frac{d\eta}{ds} = -a' \sqrt{1 - e'^2 \cos^2 \eta} \), as one easily finds. Alternative to (17) are

\[
q'_i = -m' \Omega r \frac{d}{ds} x = -m' \Omega r \cos (\theta + \beta) \quad q'_a = -q'_i \tan 2\eta. \tag{17_1}
\]

Thus for \( \eta = 0, 45^\circ, 90^\circ \) (17) and (17_1) give \( q'_i / \Omega = -m' \alpha', \Omega, m' \beta' \). At the model's surface, where \( m' = (a^2 - b^2) / 2ab \), (17_1) become

\[
q'_i = -\frac{a^2 - b^2}{2ab} \Omega r \cos (\theta + \beta) \quad q'_a = \Omega r \sin (\theta - \beta). \tag{17_2}
\]

the latter being \( h_{\alpha} \Omega r \), as in (5).

Where \( q'_i = 0 \), or \( \cos \eta = 1 / \sqrt{2} \), viz, at the stream poles, clearly \( x = a' / \sqrt{2}, y = b' / \sqrt{2} \),

\[
x^2 - y^2 = a'^2 / 2. \tag{18}
\]

a rectangular hyperbola. (18) is the instantaneous polar streamline, e. g., Figure 5, orthogonal to all the confocal ellipses. Its asymptotes are \( y = \pm x \); its vertices are at \( x = \pm a \epsilon / \sqrt{2} \); it cuts each ellipse where \( x / y = a' / b' \), viz, on the diagonals of the circumscribed rectangle. For an endless thin plate of width \( 2a \) the poles are at \( y = 0, x = \pm a / \sqrt{2} \).

Superposing \( -\Omega r \) on the body and fluid, and using (2), changes (15) to

\[
\psi = \frac{1}{2} (r^2 - m' a' b' \cos 2\eta) \Omega r. \tag{19}
\]

Its graph, with \( \Delta \psi = 0.2 \), gives the streamlines in Figure 6 for the flow \( \Omega r = -1 \) round a fixed cylinder having \( a/b = 4 \). About the point \( (0, 1.45) \) in Figure 6, is a whirl separated from the outer flow by the streamline \( \psi = 4.25 \). This line abuts on the model at the inflow points \( i, i \); spreads round it and emerges at the outflow points \( o, o \). The streamlines for an endless thin rectangle having \( b = 0, \epsilon = 1 \), are similar to those of Figure 6, but infinitely crowded at the edges.

The superposed particle velocity \( -\Omega r \) contributes to (17_1)

\[
q''_i = -\Omega r \cos (\theta - \beta) = -h_i \Omega r \quad q''_a = -\Omega r \sin (\theta - \beta) = -h_i \Omega r, \quad \tag{20}
\]

also \( q''_a = -q''_i \tan (\theta - \beta) \). Adding (17_1) and (20) gives the components \( q_i = q'_i + q''_i, q_a = q'_a + q''_a \), of the resultant flow velocity at any field point. One notes that (20) are the reverse of \( q_i, q_a \) in Figure 1.

In particular \( q_a = 0 \) on the fixed model and \( x, y \) axes; hence there

\[
q / a \Omega r = -r / a [m' \cos (\theta + \beta) + \cos (\theta - \beta)] \quad q / q_a = m' \cos (\theta + \beta) + \cos (\theta - \beta). \quad \tag{21}
\]

Thus \( q / q_a = 1 + m' \), on the \( x \) axis; \( 1 - m' \) on the \( y \) axis; and 1 at \( \infty \) where \( m' = 0 \). The dashed line in Figure 6 gives \( q / a \Omega r = -1 - (m' \cos \eta) / a \) for points on the \( y \) axis; it crosses \( y \) at the whirl center where \( q = 0, \epsilon \), viz, where \( m' = 1 \). By (16) \( m' \geq 1 \) for the surface of any model having \( a/b \geq 1 + \sqrt{2} \); and there is no whirl if \( a/b < 1 + \sqrt{2} \). Figure 7 shows \( q / a \Omega r \) for the surface of a model having \( a/b = 4, m' = (a^2 - b^2) / 2ab = 15/8 \).

Putting \( q / q_a \) of (21) in (1), where \( r^2 / a^2 = \cos^2 \eta / \cos^2 \beta \), gives

\[
p / a \Omega r = 1 - [m' \cos (\theta + \beta) + \cos (\theta - \beta)]^2 \cos^2 \eta / \cos^2 \beta. \tag{22}
\]

which is graphed in Figure 7 for a model having \( a/b = 4 \).

Integrating \( p / a \Omega r \Omega r \), as in (8), gives for an inviscid liquid \( Y = 0 = N; X \neq 0 \). Figure 7 delineates \( X \) for this case.

The points \( i, o \) are identical with those in Figure 5; viz, where the slip speed \( q \) in (31) is zero; they are called stop points, stagnation points, etc.
For the surface of an endless flat plate \((b=0, c=\infty)\) fixed in the stream \(\Omega\), clearly \(m'=a/2b\) and generally \(r \cos (\theta - \beta) = 0\); hence (21) gives

\[
g/a\Omega = -\frac{r}{2b} \cos (\theta + \beta) = -\sin \theta \cos \eta \cot 2\eta \tag{21}\]

which equals \(-\infty, 0, 1/2\) for \(\eta=0^\circ, 45^\circ, 90^\circ\). The flow resembles that in Figure 6; it has twin whirls abreast its middle, stop points at \(x = \pm a/\sqrt{2}\), and infinite velocity at the edges.

Putting in (1) \(r=x\) and \(q_0 = -xq_1\) gives the plate’s surface pressure

\[
p' = \frac{1}{2} p a^2 \Omega = -\frac{x^2}{a^2} \frac{q_0}{a^2 \Omega} = (1 - \cot^2 2\eta) \cos^2 \eta \tag{22}\]

Figure 6.—Streamlines about endless elliptic cylinder fixed in infinite inviscid liquid rotating about its long axis with uniform angular speed \(\omega\); shows \(\phi = \frac{1}{2} \Omega (r - m'y + a' \cos \eta)\) with increments \(\Delta \phi = 1, 0 = -1\). Dotted line portrays \(x\)-wise speed on \(y\) axis

which equals \(-1/4, 1/2, -\infty\) for \(x=0, \pm a/\sqrt{2}, \pm a\); viz, for \(\eta=90^\circ, 45^\circ, 0\), etc.

**Prolate Spheroid.**—For a prolate spheroid, of semiaxes \(a, b, c\), rotating about \(c\) with speed \(\Omega\), in an infinite inviscid liquid,

\[
\phi = -m' \Omega \sigma y = -\frac{1}{2} m' \Omega a'b' \sin 2\eta \cos \omega \tag{23}\]
FLOW AND FORCE EQUATIONS FOR A BODY REVOLVING IN A FLUID

Figure 7.—Endless elliptic cylinder fixed in infinite inviscid liquid uniformly rotating about it; shows (1) x-wise zonal pressure-force, \( \frac{1}{2} x \cos \theta \); (2) surface velocity \( q/a \) and surface pressure, \( p \sin \frac{1}{2} \theta \); above or below undisturbed local pressure in uniform stream, \( -\theta \).
the geometric symbols being as in Figure 3. For any outer confocal spheroid \( a'b'c' \) (23) has the known constant potential coefficient

\[
m' = \frac{3}{2} \log \frac{1+\epsilon'}{1-\epsilon'} - 3 - \frac{\epsilon'^2}{2} - \frac{e^2}{2} (2-\epsilon') \log \frac{1+\epsilon'}{1-\epsilon'} - \frac{e^2}{2} \epsilon' \]  \hspace{1cm} (24)

\( e, e' \) being the eccentricities of \( ab, a'b' \). Table IV gives surface values of \( m' \) for various shapes of prolate spheroid.

In the \( yz, zx \) planes \( \varphi = 0 \); in the \( xy \) plane, where \( \cos \omega = 1 \)

\[
\varphi = -\frac{1}{2} m', \Omega, a'b' \sin 2\eta \hspace{1cm} \psi = -\frac{1}{2} m', \Omega, a'b' \cos 2\eta \]  \hspace{1cm} (23a)

which, except for \( m' \), have the same values as (15), entailing the same polar streamlines (18). The equipotentials on \( a'b'c' \) are its intersections with the family \( xy = -\varphi/m' \), \( \Omega_{\eta} = \text{const.} \).

At any point \( (x, y, z) \) on \( a'b'c' \) the orthogonal velocity components are by (23)

\[
q_s = \frac{\partial \varphi}{\partial y} \frac{\partial y}{\partial s} \hspace{1cm} q_t = \frac{\partial \varphi}{\partial \eta} \frac{\partial \eta}{\partial s} \hspace{1cm} q_w = \frac{\partial \varphi}{\partial \varpi} \frac{\partial \varpi}{\partial s} \]  \hspace{1cm} (25)

\( \delta n, \delta s_\eta, \delta s, \) denoting line elements along the normal, meridian, and circle of latitude, as in Figure 3. Since \( q_s \) is absent from (1), we shall not need it; we merely note that on the model's surface it is \( \Omega \sin (\beta - \theta) \cos \omega \). By geometry \( \Omega \eta \sin \omega = 1/b' \sin \eta \); hence

\[
q_s = -m', \Omega, \Omega, \cos (\theta + \beta) \cos \omega \hspace{1cm} q_t = m', \Omega, \Omega, \cos \beta \sin \omega \]  \hspace{1cm} (25a)

For \( \omega = 0 \), \( q'(-q'_{\varpi}) \) differs only by \( m' \) from (17); for an elliptic cylinder; also \( \tau \cos \beta = x \).

Superposing \(-\Omega, \Omega, \) on the above system adds to (25a), as easily appears

\[
q''_s = -\Omega, \Omega, \sin (\theta - \beta) \cos \omega \hspace{1cm} q''_t = -\Omega, \Omega, \cos (\theta - \beta) \cos \omega \hspace{1cm} q''_w = \Omega, \Omega, \cos \beta \sin \omega \]  \hspace{1cm} (26)

At the now fixed surface and on the \( x, y \) axes \( q_s = 0 = q_t + q''_t \); hence summing (25a), (26) gives there

\[
q_s = [m', \cos (\theta + \beta) + \cos (\theta - \beta)] \Omega, \cos \omega = \frac{1}{2} \cos (\omega + \varpi) \cos \omega \]  \hspace{1cm} (27)

Thus for \( \omega = 0 \) clearly \( q/q_0 = m', \cos (\theta + \beta) + \cos (\theta - \beta) \), differing from (21) only by \( m' \); for \( \omega = \pi/2 \), \( q/q_0 = -(1 + m') \), a formula like that for a negative flow \( q_0 \) across a cylinder; for \( \omega = 0^\circ, 90^\circ, 45^\circ \), \( q = q_0 \sqrt{\frac{1}{2} (q'^2 + q''^2)} \). On the \( x \) axis \( q/q_0 = 1 + m' \); on the \( y \) axis \( q/q_0 = 1 - m' \), zero everywhere, hence no whirl centers on \( y \).

Figure 8 shows \( |q/q_0| \) on the meridians \( \omega = 0, \pm 45^\circ, \pm 90^\circ \) of a fixed spheroid with \( a:b = 4 \). Distributions symmetrical with these occur on the opposite half of the surface. Noteworthy is \( q \) for \( \omega = \pm 90^\circ \). By (27) it is \( q = \pm (1 + m') \Omega, x \); hence the straight-line graph in Figure 8.

Figure 8 shows also, for these meridians, the pressure computed with the working formula, derived from (1), (27).

\[
P = A \cos^2 \omega + B \sin^2 \omega \]  \hspace{1cm} (28)

\[ \frac{1}{2} \rho a^2 \Omega^2 \]
FLOW AND FORCE EQUATIONS FOR A BODY REVOLVING IN A FLUID

**Figure 8.** Prolate spheroid fixed in infinite inviscid liquid uniformly rotating about it; shows (1) z-wise zonal pressure-force, \( X \frac{1}{2} a^2 \Omega^2 \); (2) surface flow-speed, \( q \alpha \); (3) surface pressure, \( p = \frac{1}{2} \rho \Omega^2 \), above or below undisturbed local pressure in uniform stream, \( -\Omega \). Crosses and circles give measured air pressures for \( \Omega = -30.5 \) radians per second given in reference 3.
where \( A = (1 - [m'_\epsilon \cos (\theta + \beta) + \cos (\theta - \beta)]^2) \cos^2 \eta \cos^2 \beta, \) \( B = -m'_\epsilon (2 + m'_\epsilon) \cos^2 \eta. \) Here \( m'_\epsilon = .689 \) by Table IV. The crosses and circles, giving experimental values taken from Reference 3, show good agreement with (28) for a considerable part of the surface. For \( \cos \omega = 0, p \propto B \propto x^2; \) or the graph is parabolic.

Integrating \( p, \) as in (9), (10), gives for an inviscid liquid \( \eta = 0, \) \( X_0 \) computed from theory and experiment.

**ELLIPSOID.**—For an ellipsoid, of semiaxes \( a, b, c \) along \( x, y, z, \) rotating about \( c \) with speed \( \Omega, \) in an infinite inviscid liquid, otherwise still,

\[
\varphi = -m'_\epsilon \Omega \alpha y - \frac{a^2 - b^2}{c} \]

which for any outer confocal ellipsoid \( a'b'c', \) has the constant potential coefficient

\[
m'_\epsilon = C(\beta - \alpha) \quad C = 2(a^2 - b^2)/(a^2 + b^2)(\beta - \alpha) \]

the Greek letters being as in Part V. Surface values of \( m'_\epsilon \) are listed in Table IV.

By (29) the equipotential lines on \( a'b'c' \) are its intersections with the hyperbolic cylinder family \( x^2 = -\varphi/m'_\epsilon \Omega \alpha = \text{const.} \) The orthogonals to \( \varphi = \text{const.} \) at the surface \( a'b'c' \) are the streamlines there. These by (31) are parallel to \( x \) where \( x = 0; \) parallel to \( y \) where \( y = 0; \) normal to \( z \) where \( z = 0. \) The same obviously holds for spheroids and other ellipsoidal forms.

In the \( xy \) plane the flow has the polar streamlines (18); also it has there

\[
\varphi = -\frac{1}{2} m'_\epsilon \Omega a'b' \sin 2\eta \quad \psi = -\frac{1}{2} m'_\epsilon \Omega a'b' \cos 2\eta \]

whence the streamlines in that plane are plotted. The form of (29) is like those of (15) and (23), for the elliptic cylinder and prolate spheroid, entailing similar expressions for the velocity and pressure in the plane-flow field \( z = 0. \)

For the general flow the velocity components at \( a'b'c' \) are by (29)

\[
u' = -\left( z \frac{\partial m'_\epsilon}{\partial x} + m'_\epsilon \right) \Omega y \quad v' = -\left( y \frac{\partial m'_\epsilon}{\partial y} + m'_\epsilon \right) \Omega x \quad w' = -\Omega xy \frac{\partial m'_\epsilon}{\partial z} \]

and those due to the superposed velocity \( -\Omega R = q_0, \) are

\[
u'' = \Omega y \quad v'' = -\Omega x \quad w'' = 0. \]

whence the resultant velocity and pressure may be derived for all points of the flow field about the ellipsoid fixed in the steady stream \( -\Omega R. \) In forming the \( x, y, z \) derivatives of \( m'_\epsilon, \) one may use the relations (14) and (72).

Everywhere in the planes \( x = 0, \) \( y = 0, \) the resultant velocities are respectively, by (31) and (32),

\[
q = u = (1 - m'_\epsilon) \Omega y \quad q = v = (1 + m'_\epsilon) \Omega x \]

while in the plane \( z = 0, q \) can be found as indicated for an elliptic cylinder. (33) apply also to the elliptic cylinder and prolate spheroid previously treated, and to all other forms of the ellipsoid fixed in the flow \( -\Omega_c. \)

**(B) BODIES IN COMBINED TRANSLATION AND ROTATION**

**Most General Motion.**—The most general motion of any body through a fluid may have the components \( U, V, W \) along, and \( \Omega_s, \Omega_r, \Omega_c \) about, three axes, say \( a, b, c. \) The entailed resultant particle velocity \( q' \) at any flow point is found by compounding there the individual velocities severally due to \( U, V, W, \) \( \Omega_s, \) \( \Omega_r, \) \( \Omega_c, \) and computable for an ellipsoid by formulas in Reference 2 and the foregoing text.

**Yawing Flight.**—In airship study the flow velocity \( q' \) caused by a prolate spheroid in steady circular flight is specially interesting. Let the spheroid's center describe about 0,
FLOW AND FORCE EQUATIONS FOR A BODY REVOLVING IN A FLUID

Figure 9, a circle of radius na, with path speed nα. Then if α is the constant yaw angle of attack, the component centroid velocities along a, b, and the steady angular speed about c are, respectively,

\[ U = nα \cos α \quad V = nα \sin α \quad \Omega = \Omega \] ........................ (34)

If, now, velocities the reverse of (34) are imposed on the body and fluid, \( q_x = 0 \), and the surface velocity \( q \) on the fixed spheroid has in longitude and latitude the respective components

\[ q_x = (1 + k_x) U \sin θ - (1 + k_x) V \cos θ \cos ω - [m'_x \cos (θ + β) + \cos (θ - β)] Ω \cos ω \]
\[ q_y = (1 + k_x) U \sin θ + (1 + m'_x) Ω \cos ω \sin ω \] ........................ (35)

where positive flows along ds are, respectively, in the directions of increasing θ, ω, as in Figure 3. The terms in \( U, V \), are known formulas for translational flow, e.g., Reference 2; the others are from (27). Hence \( q^2 \) then \( p \) is found for any point (\( β, ω \)) on the spheroid.\(^3\) If \( Ω \), is negligible, \( q = \ddot{q} \sin ε \), where \( \ddot{q}^2 = (1 + k_x)^2 U^2 + (1 + k_x)^2 V^2 \), and \( ε \) is the angle between the local and polar normals, as proved in Reference 2.

Figure 9 portrays, for specified conditions, theoretical values of \( p_1 q \), \( q \) being the path speed \( \sqrt{U^2 + V^2} \) of the spheroid's center; it also portrays \( p_1 q \) for the model in rectilinear motion, with \( Q = U \). The difference of \( p_1 q \) for straight and curved paths, though material, is less than experiment gives, as shown by 9a. Fuller treatment and data are given in Reference 3.

The forces \( X, Y \) and moment \( N \), for any zone, may be computed as before; but for the whole model they are more readily found by the method of Part IV. Zonal \( Y \) and \( N \) for a hull form are found in Part III.

The first of (35) applies also to an elliptic cylinder, with \( \cos ω = 1 \), \( m'_x = \frac{(a^2 - b^2)}{2ab} \). Fixed in a flow \( -U, -V, -Ω \), it has the surface velocity

\[ q = (1 + b/a) U \sin θ - (1 + a/b) V \cos θ \left[ \frac{a^2 - b^2}{2ab} \cos (θ + β) + \cos (θ - β) \right] Ω \cos ω \] ........................ (36)

For an endless flat plate \( b = 0 \), \( \cos θ = a/c \), \( \sin θ \cot ε \); and the last term of (36) may be rewritten by (21); thus (36) becomes

\[ \ddot{q} = (U - V \cot η - aΩ \cos η \cot 2η) \sin θ \] ........................ (37)

These two values of \( q \) with (1) give the pressure distribution over an elliptic cylinder or flat plate revolving about an axis parallel to its length or fixed in a fluid rotating about that axis.

Thus an endless plate of width 2a, revolving with angular speed \( Ω \), path radius na, and incidence \( α \), as in Figure 10, has by (37) the relative surface velocity, viz, slip velocity

\[ \ddot{q}/aΩ = (n \cos α - n \sin α \cot η - \cos η \cot 2η) \sin θ \] ........................ (38)

and since \( \sin θ = 1 \), \( q^2 = U^2 + (V + aΩ)^2 = a^2Ω^2 (n^2 + 2n \sin α \cos η + \cos^2 η) \), (1) gives

\[ \rho \frac{1}{2} \ddot{q} a^2 Ω^2 = q^2 + 2n \sin α \cos η + \cos^2 η - n^2 (\cos α - \sin α \cot η - \frac{1}{n} \cos η \cot 2η)^2 \] ........................ (39)

For \( n = 3 \), \( α = 30° \), Figure 10 delineates the distribution of slip velocity \( \ddot{q}/aΩ \) on both sides of the plate; 10a that of the pressure \( \rho \frac{1}{2} \ddot{q} a^2 Ω^2 \) on its two faces. This pressure integrated over the plate's double surface gives \( Y = 0 \), as may be shown. The dashed line in Figure 10b is the pressure-difference graph whose integral for \( η = 0 \) to \( π \) is also zero. The resultant forces \( X, Y \) and moment \( N \) for such a plate are found in Part IV by a method simpler than surface integration of the pressure.

\(^1\) Here again \( q \) is the slip speed of the flow at any point of the body's surface, and depends only on the relative motion of body and fluid.
Flow Inside Ellipsoid.—At any point inside an ellipsoid with speeds $U, V, W, \Omega_x, \Omega_y, \Omega_z$ along and about $a, b, c$, filled with inviscid liquid otherwise still,

$$\nu = U x + V y + W z + \frac{b^2 - c^2}{b^2 + c^2} \Omega_y y z + \frac{c^2 - a^2}{a^2 + b^2} \Omega_x x z + \frac{a^2 - b^2}{a^2 + b^2} \Omega_z x y.$$  \hspace{1cm} (40)

whose coefficients are constant for the whole interior. Hence the components of the particle velocity $\nu$ are

$$\frac{\partial \nu}{\partial x} = U = U,$$

$$\frac{\partial \nu}{\partial y} = V = V,$$

$$\frac{\partial \nu}{\partial z} = W = W.$$  \hspace{1cm} (41)

FIGURE 9.—Prolate spheroid in steady yawing flight. (1) Defines velocity conditions; (2) delineates theoretical pressure distribution; (3) experimental pressure distribution for $Q = 40$ feet per second. In (2) and (3), full lines indicate rectilinear, dashed lines curvilinear motion.
and like values for \( v, w \) found by permuting the symbols. If the fluid were solidified any particle would have
\[
u = U + \Omega x - \omega y, \text{ etc., etc.} \tag{42}
\]
Thus when an ellipsoid full of inviscid still fluid is given any pure translation its content moves as a solid; but when given pure rotation each particle moves with less speed than if the fluid were solidified, since the fractions in (41) are less than unity.

For velocities \( U, V, \Omega, \omega \) of the ellipsoid
\[
\varphi = Ux + Vy + \frac{a^2 - b^2}{a^2 + b^2} \Omega x y \tag{43}
\]
for which \( w = \partial \varphi / \partial z = 0 \). For this plane flow (4) with (43) gives
\[
\varphi = Uy - Vz - \frac{1}{2} \Omega \frac{a^2 - b^2}{a^2 + b^2} (x^2 - y^2) \tag{44}
\]
whence the streamlines may be plotted. In particular if the model has simple rotation \( \Omega = \omega \),
\[
x^2 - y^2 = -2 \frac{a^2 + b^2}{a^2 - b^2} \psi / \Omega = \text{const.} \tag{45}
\]
and the interior streamlines are hyperbolas, as in Figure 5.

Adding (2) to \( \psi \) in (45) gives the steady flow
\[
\varphi = \frac{\Omega x}{a^2 + b^2} (a^2 y^2 + b^2 x^2) \tag{46}
\]
hence the streamlines lie on the elliptic cylinders
\[
a^2 y^2 + b^2 x^2 = (a^2 + b^2) / \Omega \psi = \text{const.} \tag{47}
\]
By (46) $q = 2\Omega_c(a'y^2 + b'z^2) / (a^2 + b'^2)$, which put in (1) gives at $(x, y)$, since $q_0 = -\Omega_c R$,

$$p_* - p = \frac{4(a'y^2 + b'z^2)}{(a^2 + b'^2)^2 (x^2 + y^2)^2} p_* - p,$$

where $p_*$ is the centrifugal pressure due to the fluid's peripheral velocity $q_0$, and $p$ is the pressure change due to $q_0 - q$, $q$ being the relative velocity of fluid and container. In a like balloon hull $g$ would quickly damp out, leaving only $p_*$ as the dynamic pressure. At the ends of $a$, $b$, $c$, respectively, (48) gives

$$p_* - p = \frac{4b'^4}{(a^2 + b'^2)^2} \frac{4a^4}{(a^2 + b'^2)^2} p_* - 0.$$

For large $a/b$ the first is negligible, the second approaches 4, giving $p = -3p_* = -1.5\rho\Omega_c b'$ as the temporary dynamic pressure drop inside the hull at the end of $b$. Experimental proof would be interesting.

**Potential Coefficients.**—An ellipsoid of semiaxes $a$, $b$, $c$ along $x$, $y$, $z$, when moving through an infinite inviscid liquid, otherwise still, with velocities $U$, $V$, $W$, $\Omega_a$, $\Omega_b$, $\Omega_c$ along and about the instantaneous lines of $a$, $b$, $c$, begets the known velocity potential

$$\varphi = -m_a Ux - m_b Vy - m_c Wz - m'_a \Omega_a x y - m'_b \Omega_b x z - m'_c \Omega_c x y \ldots \ldots (49)$$

the six potential coefficients $m$ being constant over any outer confocal ellipsoid $a'b'c'$. Their values for $abc$ are given in Tables III, IV. Alternatively (49) can be written for this surface

$$\varphi = -k_a Ux - k_b Vy - k_c Wz - \frac{b'^2 + c^2}{b^2 - c'^2} \Omega_a x y - \frac{a'^2 + c^2}{a^2 - c^2} \Omega_b x z - \frac{a'^2 + b'^2}{a^2 - b'^2} \Omega_c x y \ldots \ldots (50)$$

the $k$s being the more familiar inertia coefficients defined and tabulated in Part V. Of the six potential coefficients in (50) the first three are the same as the inertia coefficients $k_a$, $k_b$, $k_c$; the last three are greater except when $c/b$ or $a/c$ or $b/a$ is zero. Thus, if $b/a = 0$ the last term of (50) is $-k'_b \Omega_c x y$, which is the potential on the outer surface of an elliptic cylinder ($a = \infty$) rotating about $c$. Everywhere inside of it the potential is $\Omega_c x y$, as (40) shows.

For the flow (40) textbooks give the inertia coefficients

$$k_a, k_b, k_c = 1 \quad k'_a = \left(\frac{b'^2 - c'^2}{b^2 + c^2}\right)^{1/2} \quad k'_b = \left(\frac{c'^2 - a'^2}{c^2 + a^2}\right)^{1/2}, \text{ etc.} \quad \ldots \ldots \ldots (51)$$

which are the squares of the potential coefficients. One notes too that the ratios of like terms in (40), (50) equal the ratios of like potential coefficients and like inertia coefficients, which latter in turn are known to equal the ratios of like kinetic energies of the whole outer and inner fluids, if the inner moves as a solid.

**Relative Velocity and Kinetic Pressure.**—When a body moves steadily through a perfect fluid, otherwise still, the absolute flow velocity it begets at any point $(x, y, z)$, being unsteady, is not a measure of the pressure change there. The relative velocity is such a measure. To find it we superposed on the moving body and its flow field an equal counter velocity, thus reducing the body to rest and making the flow about it steady. The same result would follow from geometrically adding to said absolute flow velocity the reversed velocity of $(x, y, z)$ assumed fixed to the body. In particular this process gives for any point of the body's surface the wash velocity, or slip speed, which with Bernoulli's principle determines the entailed change of surface pressure. Conversely, if the pressure change at a point is known or measured, it determines the relative velocity there. In hydrodynamic books the above reversal is used commonly enough for bodies in translation. In this text it is employed as well for rotation; also for combined translation and rotation. However general its steady motion, the body is steadily accompanied by a flow pattern whose every point, fixed relatively to the body, has constant relative velocity and constant magnitude of instantaneous absolute velocity and pressure.
FLOW AND FORCE EQUATIONS FOR A BODY REVOLVING IN A FLUID

PART III

ZONAL FORCES ON HULL FORMS

Pressure Loading.—For a prolate spheroid $abc$ with speeds $U$, $V$, $\Omega$, Figure 91, or fixed in a stream $-U$, $-V$, $-\Omega$, (35) gives at $(x, y, z)$ on $abe$ the relative velocity

$$q^2 = q_x^2 + q_y^2 = A - B \cos \omega + C \cos^2 \omega$$

$A$, $B$, $C$ being constant for any latitude circle. In forming this equation one finds

$$B = 2(1 + k_a) U \sin \theta \{ (1 + k_b) V \cos \theta + [m' \cos (\theta + \beta) + \cos (\theta - \beta)] r \Omega_z \},$$

e tc., for $A$, $C$. In the body's absence said stream has, at said point $(x, y, z)$,

$$q^2 = (-U + y \Omega_x)^2 + ( -V - x \Omega_x)^2 = \{-A - B_1 \cos \omega + C_1 \cos^2 \omega, \}
$$

where $\omega$ alone varies on the latitude circle. Its radius being $y_0 = z_0$, makes $y = y_0 \cos \omega,

$$B_1 = 2 U_0 \Omega_x,$$

e tc., for $A_1$, $C_1$. Putting $q$, $q_0$ in (1) gives the surface pressure

$$p_{.5p} = q_x^2 - q^2 = (A_1 - A) + (B - B_1) \cos \omega + (C_1 - C) \cos^2 \omega.$$ 

By (10), the loading per unit length of $x$ is, since $\int_0^{2\pi} \cos \omega = 0 = \int_0^{2\pi} \cos^3 \omega,$

$$P_{.5p} = -\frac{z_0}{5p} \int_0^{2\pi} p \cos \omega \, d\omega = -(B - B_1)z_0 \int_0^{2\pi} \cos^2 \omega \, d\omega = -\pi (B - B_1) z_0.$$

$A$, $A_1$, $C$, $C_1$ vanishing on integration of $p$. Thus, finally,

$$P_{.5pQ^2} = -\pi (B - B_1) z_0 Q^2.$$ 

$P$ having the direction of the cross-hull component of $p$ at $\omega = 0$.

One notes that $q_y^2 (x \sin^2 \omega)$ contributes nothing to $B$ or the integral in (a); viz, the loading $P$ is unaffected by $q_y$, and depends solely on $q_x$, the meridian component of the wash velocity. Also for $\beta = 0$ and $\pi$, $B - B_1 = 0 = P$.

In Figure 94 the full line depicts (a$_1$) for the spheroid shown in 9$_1$, circling steadily at 40 feet per second. The theoretical dots closely agreeing with it are from Jones, Reference 3, as is also the experimental graph. Beside them is a second theoretical graph plotted from Doctor Munk's approximate formula derived in Reference 8 and given in the next paragraph. But that Professor Jones omitted some minor terms in his value of $p$, his theoretical $P_{.5pQ^2}$ should exactly equal (a$_1$). His formula, derived by use of Kelvin's $p_{.x} = \dot{\phi} - q^2/2$, can best be studied in the detailed treatment of Reference 3.

In Reference 8 Professor Ames derives Munk's airship hull formula

$$P_{.5pQ^2} = \sin 2\alpha \frac{dS}{dx} + \frac{2 \, d}{dz} (2S),$$

This part was added after Parts I, II, IV, V were typed; hence the special numbering of the equations.
S being the area of a cross-section; \( R \) the radius of the path of the ship's center. This was assumed valid for a quite longish solid of revolution; for a short one it was hypothetically changed to

\[
P_{.5pQ^2} = (k_s - k_x) \sin 2\alpha \frac{dS}{dx} + 2k' \frac{d}{dx} (xS)
\]

Applying this to a prolate spheroid we derive the working formula

\[
P_{.5pQ^2} = -Lx - Mx^3 + N
\]

where the constants for a fixed angle of attack are:

\[
L = 2(k_s - k_x) \frac{b^2}{a_s} \pi \sin 2\alpha, \quad M = 3k' \frac{b^2}{a_s} \frac{2\pi}{R} \cos \alpha, \quad N = k' b^2 \frac{2\pi}{R} \cos \alpha.
\]

Plotting \( P_{.5pQ^2} \) for the conditions in 9e gives the dotted curve in 9a. It shows large values of \( P_{.5pQ^2} \) for the ends of the spheroid, where \( \alpha_0 \) gives zero. To a large extent it fails, though with little consequent error in the zonal force and moment at the hull extremities. It has the merit of being convenient and applicable to any round hull whose equation may be unknown or difficult to use.

Zonal Force.—An end segment of the prolate spheroid, say beyond the section \( x = x_c \), bears the resultant cross pressure

\[
Y = \int_{z_1}^{z_2} P \frac{dz}{x}
\]

which with the resisting shear at \( x \) must balance the cross-hull acceleration force on the segment in yawing flight. For the whole model \( P_{.5pQ^2} \) with \( \alpha \) gives \( Y = 0 \), which is not strictly true for curvilinear motion; but \( \alpha_0 \) with \( \alpha \) gives the correct theoretical value of \( Y \), and agrees with (67).

In Figure 9a graphs of \( Y_{.5pQ^2} \), for the values \( \alpha_0 \) and \( \alpha_1 \) of \( P \), are shown beside those derived from Jones' experimental pressure curve. Since \( Y \) is proportional to the area of a segment of the graph of \( P \), it can be found by planimetering the segment or by integrating \( Pdx \).

Zonal Moment.—The loading \( P \) exerts on any end segment, say of length \( a-x \), the moment about its base diameter \( z \)

\[
N_z = \int_{z}^{a} Y \frac{dz}{x}
\]

which can be found by planimetering the graph of \( Y \). Figure 9a delineates \( N_z \) so derived from the three graphs of \( Y \). They show the moment on the right-hand segment varying in length from 0 to 2a; also on the left segment of length from 0 to 2a. The resisting moment of the cross section must balance \( N_z \) and the acceleration moment of the segment.

Correction Factors.—No attempt is here made to deduce theoretically a correction factor to reconcile the computed and measured \( p \). In Reference 3 Jones shows that the theoretical and experimental graphs of \( P_{.5pQ^2} \) have, for any given latitude \( x_1 > a/2 \), the same difference of ordinate whatever the incidence \( 0 < \alpha < 20^\circ \). Thus the ordinate difference found for the zero-incidence graphs, when applied to the theoretical graph for any fixed \( 0 < \alpha < 20^\circ \), determines the experimental one with good accuracy. Such established agreement in loading favorably affects, in turn, the graphs of \( Y \), \( N_z \) the transverse force and moment on any end segment of the spheroid.

---

1 From the meridian curve: \( \frac{ds}{dt} = \frac{b^2}{a_s} \), \( \frac{dy}{dz} = \frac{-b^2}{a_s} \), \( S = \frac{dy}{dy} \), hence \( \frac{dS}{dS} = -2\pi y \frac{dy}{dz} = -2\pi b^2 \), which put in (b) leads to (b1).
REPORT No. 323

FLOW AND FORCE EQUATIONS FOR A BODY REVOLVING IN A FLUID

PART IV
RESULTANT FORCE AND MOMENT

BODY IN FREE SPACE.—Let a homogeneous ellipsoid of semiaxes $a$, $b$, $c$ move freely with component velocities $u$, $v$, $w$, $p$, $q$, $r$ respectively along and about instantaneous fixed space axes $x$, $y$, $z$ coinciding at the instant with $a$, $b$, $c$. Then the linear and angular momenta referred to $x$, $y$, $z$ are

$$m_1u, m_1v, m_1w, A_1p, B_1q, C_1r$$ ............ (52)

$m_1$ being the body’s mass, $A_1$, $B_1$, $C_1$ its moments of inertia about $a$, $b$, $c$. If, now, forces $X_1$, $Y_1$, $Z_1$ and moments $L_1$, $M_1$, $N_1$ are applied to the body along and about $x$, $y$, $z$, they cause in the vectors (52) the well-known change rates

$$m_1(\dot{u} - rv + qw) = X_1 \quad A_1 \dot{p} - (B_1 - C_1)qr = L_1$$
$$m_1(\dot{v} - pw + rw) = Y_1 \quad B_1 \dot{q} - (C_1 - A_1)rp = M_1$$
$$m_1(\dot{w} - qa + pq) = Z_1 \quad C_1 \dot{r} - (A_1 - B_1)pq = N_1$$ ............. (53)

which apply to any homogeneous solid symmetrical about the planes $ab$, $bc$, $ca$.

For motion in the $ab$ plane; viz, for $u, v, p, q = 0$; (53) give

$$X_1 = m_1(\dot{u} - rv) \quad Y_1 = m_1(\dot{v} + ru) \quad N_1 = C_1 \dot{r}$$ ............ (54)

and for uniform revolution about an axis parallel to $z$, as in Figure II, viz, for $\dot{r} = 0$, (54) become

$$X_1 = -m_1 rv \quad Y_1 = m_1 ru \quad N_1 = 0$$ ............. (55)

where now $X_1$, $Y_1$ are merely components of the centripetal force $m_1r \sqrt{u^2 + v^2}$, whose slope is $Y_1/X_1 = -u/v$. Also if $Q = \sqrt{u^2 + v^2}$ is the path velocity of the body’s centroid, $h$ its path radius, $r = Q/h$ is the angular velocity of $h$ and of vector $m_1Q$.

REACTIONS OF FLUID.—If external forces impel the ellipsoid from rest in a quiescent frictionless infinite liquid, with said velocities $u$, $v$, $w$, $p$, $q$, $r$, they beget in the fluid the corresponding linear and angular momenta

$$k_1su, k_1mv, k_1iw, k'_1Ap, k'_1Bq, k'_1Cr$$ ............. (56)

where $m$ is the mass of the displaced fluid, and $A$, $B$, $C$ its moments of inertia about $a$, $b$, $c$.

One calls $k_1s$, $k_1m$, $k_1i$, $k_1$, the “apparent additional masses”; $k'_1A$, $k'_1B$, $k'_1C$ the “apparent additional moments of inertia” of the body for its axial directions; because the fluid’s resistance to its linear and angular acceleration gives the appearance of such added inertia in the body. The six $k$’s are called “inertia coefficients,” and are shape constants. Values of them are given in Tables III, VI, VIII for various simple quadrics.

The component flow momenta (56), like (52), are vectors along the instantaneous directions of $a$, $b$, $c$; viz, along $x$, $y$, $z$; hence their time rates of change must equal the forces and moments which the body exerts on the fluid; viz,

$$X = m(k_1s\dot{u} - k_1iw + k_1pw) \quad L = k'_1Ap - (k'_1B - k'_1C)qr - (k_1 - k_1)su$$
$$Y = m(k_1s\dot{v} - k_1iw + k_1pw) \quad M = k'_1Bq - (k'_1C - k'_1A)rp - (k_1 - k_1)mv$$
$$Z = m(k_1s\dot{w} - k_1iw + k_1pw) \quad N = k'_1Cr - (k'_1A - k'_1B)pq - (k_1 - k_1)mu$$ ............. (57)

These new meanings of $u$, $v$, $w$, $p$, $q$, $r$ are assigned for convenience’s sake and for convenience.
all written from (53) on replacing its momenta by those of (56), and adding vector-shift terms. Thus the vector $k_m w$ shifts with speed $v$ entailing the change rate $k_m w v$ of angular momentum about $z$, while $k_m w$ shifts with speed $w$ entailing the opposite rate $-k_m w v$. Their sum is $(k_e - k_s)m w v$. Permuting these gives for the $y, z$ axes $(k_e - k_s)m v u$, $(k_e - k_s)m u v$. When the $k$'s are equal the vector-shift terms vanish, as for said free body, or for a sphere, cube, etc., in a fluid. The fluid reactions are (57) reversed. (57) apply also to fluid inside the triaxial symmetrical surface.

If the angle of attack is $\alpha = \tan^{-1} v/u$, we may write in (53), (57)

$$r = Q/h \quad u = Q \cos \alpha \quad v = Q \sin \alpha \quad u v = \frac{1}{2} Q^2 \sin 2\alpha \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots (58)$$

Of special aeronautic interest are (57) for plane motion, such as in yawing airship flight, for which $w, p, q = 0$, giving

$$X = m (k_e u - k_s v) \quad Y = m (k_e v + k_s u) \quad N = k_e C r + (k_b - k_s) m w v \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots (59)$$

Thus for uniform circular flight

$$X = -k_s m v \quad Y = k_b m r u \quad N = (k_b - k_s) m u v \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots (60)$$

which are the analogues of (55) for the free body. Or in notation (58)

$$X = -k_s \rho Q \sin \alpha \quad Y = k_b \rho Q \cos \alpha \quad N = (k_b - k_s) \frac{\rho Q^2}{2} \sin 2\alpha \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots (61)$$

$r$ being the volume of the model.
FLOW AND FORCE EQUATIONS FOR A BODY REVOLVING IN A FLUID

As shown in Figure 12 (60) give the resultant force and slope

\[ R^2 = mr \sqrt{k_a^2 + k_b^2} \]
\[ Y/X = \frac{k_a}{k_b} \cot \alpha = -\cot \beta \tag{62} \]

Also \( R \) and \( N \) at the origin are equivalent to a parallel force \( R \) through the path center 0, along a line (called the central axis of the force system) whose arm and intercepts are

\[ l = N/R = k \sin (\beta - \alpha) \quad x = l \sec \beta \quad y = l \csc \beta \tag{63} \]

For steady motion (60) show that the body sustains no force in pure translation \((r = 0)\); no force nor moment in pure rotation \((u, v = 0)\); no moment in revolution about a point on \(x\) or \(y\); viz, for \(u = 0\), \(v = 0\). For given \(u, v\) the moment is the same for revolution as for pure translation. The forces result from combined translation and rotation; the moment from translation oblique to the axes, \(a, b\), irrespective of rotational speed.

COMBINATION OF APPLIED FORCES.—To find the whole applied force constraining a body to uniform circular motion in a perfect, fluid (55), (60) may be added, or graphs like those of Figures 11, 12, may be superposed. For an airship having \(m_1 = m_2\), (55), (60) give

\[ \bar{X} = -(1 + k_a)mur \quad Y = (1 + k_a)mur \quad \bar{N} = (k_b - k_a)muv \tag{64} \]

Writing \(R = Qm \sqrt{k_a \cos \omega + k_b \sin \omega} \) we may call it the centripetal force of the apparent mass \(m \sqrt{k_a \cos \omega + k_b \sin \omega}\) for the body direction of \(Q\).
where $X = X_1 + X$, etc. Figure 13, compounded of Figures 11, 12, shows that a submerged plane-force model, revolving uniformly about its path center, may have as sole constraint a single force $R$ through that center, and outside itself; that is attached to an extension of the model. Such conditions appear commonly in vector diagrams of aircraft. The line of $R$, so defined, is the central axis of the force system.

**Hydrokinetically Symmetric Forms.**—Equations (56), (57), for trisymmetrical shapes, apply also to others having hydrokinetic symmetry. Examples of these are: All surfaces of revolution, axially symmetric surfaces whose cross sections are regular polygons; torpedo forms symmetrically finned, etc. All these figures, as has been known many decades,\(^3\) have three orthogonal axes with origin at the body's impulse center,\(^4\) such that if the body, resting in a quiet sea of perfect fluid, is impelled along or about either axis it begets in the fluid a linear or angular momentum expressible by a vector along that axis.

**Examples.**—We may apply (60) to some simple cases interesting to the aeronautical engineer.

1. For an endless elliptic cylinder in uniform yawing flight, as in Figure 12, $m = \pi \rho ab$ per unit length, and by comparison with Table VIII $k_a = b/a$, $k_b = a/b$; hence by (60) $\frac{a}{1 + kb}$.

---

\(^{1}\) See Reference 7.
\(^{2}\) The point of intersection of $k_m V$, $k_m W$, it may be found as in the last paragraph of Part V.
FLOW AND FORCE EQUATIONS FOR A BODY REVOLVING IN A FLUID

\[ X = -\pi a^2 prv \quad Y = \pi b^2 prv \quad N = \pi (a^2 - b^2) \rho Q ^2 \sin 2\alpha \quad \text{........... (65)} \]

The resultant force \( \pi r \sqrt{a^2 + b^2} \) has the slope \(-b^2/a^2\) through the path center; \( X \) is the same as for a round cylinder of radius \( a \); \( Y \) the same as for one of radius \( b \). For a good elliptic aircraft strut \( a/b = 3 \); hence \( X/Y = -9 \cot \alpha \); \( N = 8\pi b^2 \rho Q^2 \sin 2\alpha \). By (65) \( N \) is the same for all confocal elliptic cylinders, since \( a^2 - b^2 \) is so.

If \( a = b \), as for a round strut, \( N = 0 \), \( R = \pi a^2 \rho Q^2 \) and coincides with the body's previously found centripetal force to which it bears the ratio \( m/m_1 \).

If \( b = 0 \), as for a flat plate, (65) become

\[ X = -\pi a^2 prv \quad Y = 0 \quad N = \pi a^2 \rho Q^2 \sin 2\alpha \quad \text{........... (66)} \]

The resultant force \( \pi a^2 \rho Q^2 \), with slope \( Y/X = -0 \), runs through the path center parallel to \( z \). If \( r = 0 \), the plate has pure translation, with forces \( X, Y = 0 \), and moment \( N = \pi a^2 \rho Q^2 \), a well known result. \( X \) in (66), being the same as in (65), is independent of the strut thickness \( b \).

(2) For a prolate spheroid, of semiaxes \( a, b, c \), in uniform yawing flight, \( m = 4/3 \pi a b^2 \), and \( k_a, k_b, k_c \) are as given in Table III. Thus for \( a/b = 4, k_a \), \( k_b = 0.082, 0.860 \); hence by (66)

\[ X = -3.6ab^2 prv \quad Y = 0 \quad N = 3.26ab^2 \rho Q^2 \quad \text{........... (67)} \]

(3) For an elliptic disk of semiaxes \( a, b, c \), moving as in Figure 14, Table VIII gives \( k_m = 4 \pi a b^2 / E \); hence by (57) the forces and moment are

\[ Y = -k_m \rho Q^2 \sin 2\alpha \quad Z = 0 \]

\[ L = k_m \rho Q^2 \sin 2\alpha \quad \text{........... (68)} \]

the other pertinent terms in (57) vanishing, as appears on numerical substitution. Here \( E = E(\theta, \pi/2) \), \( \sin^2 \theta = (a^2 - b^2)/a^2 \); also \( L = 4a \pi b^2 \rho Q^2 / 2 \sin 2\alpha \). Compare (68) with (66), calling \( b \) the width in both.

THEORY VERSUS EXPERIMENT.—In favorable cases the moment formulas of Part IV accord fairly well with experiment, as the following instances show. For lack of available data the force formulas for curvilinear motion are not compared with experiment.

(1) By (65) an endless elliptic strut with \( a = 1/3 \) foot, \( b = 1/12 \) foot, \( c = 5 \) feet, held at \( \alpha \) degrees incidence in a uniform stream of standard air at 40 miles an hour, for which \( \rho Q^2/2 = 4093 \) pounds per square foot, sustains the yawing moment per foot length

\[ N = \pi (a^2 - b^2) \rho Q^2 / 2 \sin 2\alpha = 1.3392 \sin 2\alpha \text{ lb. ft.} \quad \text{........... (69)} \]

This compares with the values found in the Navy 8 by 8 foot tunnel, as shown in Table IX, as compared to Figure 15. The agreement is approximate for small angles of attack. The model was of varnished mahogany, and during test was held with its long axis \( c \) level across stream, and with two closely adjacent sheet metal end plates, 2 feet square, to give the effect of plane flow.

---

Equations (66) were published in Reference 8 as the result of a special research to determine the fluid forces and moment on a revolving plate. In the present text they follow as corollaries from more general formulas.

---

221
(2) By (66) an endless thin flat plate of width \(2a = 5/12\) feet, similarly held in the same air stream, has per unit length the moment

\[
N = \frac{\pi a^2 pQ^2}{2} \sin 2\alpha = 0.5581 \sin 2\alpha \text{ lb. ft.} \quad (70)
\]

This is compared in Table X and Figure 16 with the values found in the Navy 8 by 8 foot tunnel. The flat plate was of polished sheet aluminum 3/32 inch thick, with half round edges front and rear.

Again for an endless flat steel plate 5.95 inches wide by 0.178 inch thick at the center, with its front face flat and back face V-tapered to sharp edges, Fage and Johansen, Reference 6, found, at 50 feet per second and 5.85° angle of attack, \(N = 0.125\) pound foot as the moment per foot run about the long axis, computed from the measured pressure over the median section. By (66), a thin flat plate would have

\[
N = \pi a^2 \cdot \frac{pQ^2}{2} \cdot \sin 2\alpha = 0.1931 \times 2.9725 \times 0.2028 = 0.116 \text{ lb. ft.}
\]

which is 7 per cent less than 0.125 found with their slightly cambered plate.

(3) An elliptic disk 3/32 inch thick with \(a, b = 15, 2.5\) inches, when held as a wing in the Navy 40-mile-an-hour stream, had the moment \(L\) versus angle of attack \(\alpha\) shown in Figure 17 and Table XI. For this case

\[
\sin^2 \theta = \left(\frac{a^2 - b^2}{a^2}\right) = 875/900, \quad \theta = 80^\circ - 24', \quad E = 1.03758.
\]

Also in (68) \(a = 5/4\) feet, \(b = 5/24\) feet, \(Q^2 = 4.093\); hence

\[
L = \frac{4a}{3E} \cdot \pi b^2 \cdot \frac{pQ^2}{2} \cdot \sin 2\alpha = 0.8963 \sin 2\alpha \text{ lb. ft.} \quad (71)
\]
which gives the theoretical values in Figure 17 and Table XI. The agreement is fair at small incidences. The disk as tested was of sheet aluminum cut square at the edges without any rounding or sharpening.

(4) For a wooden prolate spheroid 24 inches long by 6 inches thick, carried as in Figure 12 round a circle of radius \( h = 27.96 \) feet to the model's center, Jones, Reference 3, found at 40 feet per second the values of \( N \) listed in Table XII. For this case Table III gives \( k_b-k_a = 0.778 \), and (61) gives

\[ N = (k_b - k_a) r \cdot \frac{\rho Q^2}{2} \cdot \sin 2\alpha = 0.388 \sin 2\alpha. \]

These values appear from Table XII not to accord closely with the experimental ones.

Correction Factors.—Figures 15, 16, 17 portray experimental moments, at small angles, as accurately equal to the theoretical times an empirical correction factor \( \kappa \). Thus amended (61) gives for the experimental moment

\[ N_e = \kappa N = \kappa (k_b - k_a) r \cdot \frac{\rho Q^2}{2} \cdot \sin 2\alpha. \]

For the given elliptical cylinder \( \kappa = 0.912 \) with \(-8^\circ < \alpha < 6^\circ\); for the endless plate \( \kappa = 0.860 \) with \(-6^\circ < \alpha < 6^\circ\); for the elliptic disk \( \kappa = 0.887 \) with \(-5^\circ < \alpha < 4^\circ\). In such cases one should expect to find the actual air pressure nearly equal to the theoretical over the model's forward part, but so deficient along the rear upper surface as to cause a defect of resultant moment. No effort is made here to estimate it theoretically, nor to determine it empirically for a wide range of conditions.

The measurements shown in Table X, for the flat plate, were repeated at 50 and 60 miles an hour without perceptible scale effect.
REPORT No. 323

FLOW AND FORCE EQUATIONS FOR A BODY REVOLVING IN A FLUID

PART V

POTENTIAL COEFFICIENTS, INERTIA COEFFICIENTS

Green's Integrals.—The foregoing text employs Green's well-known integrals, which for the ellipsoid $abc$ may be symbolized thus:

\[
\alpha = \frac{abc}{a'b''c''} \int_0^1 \frac{d\lambda}{a''b''c''} \quad \beta = \frac{abc}{a'b''c''} \int_0^1 \frac{d\lambda}{a'b''c''} \quad \gamma = \frac{abc}{a'b''c''} \int_0^1 \frac{d\lambda}{a'b''c''} \tag{72}
\]

where $a'' = \sqrt{a^2 + \lambda}$, $b'' = \sqrt{b^2 + \lambda}$, etc., are semiaxes of the confocal ellipsoid $a''b''c''$. The integrals have the following values, Reference 4:

\[
\begin{align*}
\alpha &= A \left( b^2 - c^2 \right) \left[ F(\theta, \phi) - E(\theta, \phi) \right] \\
\beta &= A \left( c^2 - a^2 \right) \left[ \frac{b^2}{a^2} \right] F(\theta, \phi) + \frac{c^2 - b^2}{a^2} \left[ E(\theta, \phi) \right] \\
\gamma &= A \left( a^2 - b^2 \right) \left[ \frac{c^2}{a^2} \right] E(\theta, \phi) \\
\end{align*} \tag{73}
\]

where

\[
A = \frac{2abc}{(a''^2 - b''^2)(b''^2 - c''^2)} \quad \sin^2 \theta = \frac{a^2 - b^2}{a^2 - c^2} \quad \sin^2 \phi = \frac{a^2 - c^2}{a^2 + \lambda} \tag{74}
\]

and the elliptic integrals are

\[
F(\theta, \phi) = \int (1 - \sin^2 \theta \sin^2 \phi)^{-\frac{1}{2}} d\phi \quad E(\theta, \phi) = \int (1 - \sin^2 \theta \sin^2 \phi)^{\frac{1}{2}} d\phi \tag{75}
\]

Numerical values of $F(\theta, \phi)$, $E(\theta, \phi)$, $\alpha$, $\beta$, $\gamma$ are given in Tables I, II for $\lambda = 0$ and various ratios $a/b$, $b/c$; viz, for various shapes of the ellipsoid $abc$. For $\varphi = \pi/2$ one writes $F(\theta, \varphi) = K$, $E(\theta, \varphi) = E$, by convention.

Potential Coefficients.—For motion (49) the ellipsoid $abc$ has the potential coefficients known from textbooks.

\[
\begin{align*}
m & = 2 - \alpha_0 \\
m' & = 2 - \alpha_0 \\
m'' & = 2 - \alpha_0 \\
m''' & = 2 - \alpha_0 \\
\end{align*} \tag{76}
\]

$m$, $m'$, $m''$, $m'''$ being for translation along $a$, $b$, $c$ and $m'$, $m''$, $m'''$, for rotation about them, and $\alpha_0$, $\beta_0$, $\gamma_0$ being (73) for $\lambda = 0$; viz, for $a'$, $b'$, $c'$ = $a$, $b$, $c$. Surface values of (76), viz, for $\alpha$, $\beta$, $\gamma$ = $\alpha_0$, $\beta_0$, $\gamma_0$ are given in Tables III, IV. For fluid inside the ellipsoid the potential coefficients are as in (40) and given numerically in Table V.

Inertia Coefficients.—From (76) are derived the conventional linear and angular inertia coefficients

\[
\begin{align*}
k & = m - \alpha \quad k' & = m - \alpha \quad k'' & = m - \alpha \quad k''' & = Gm - Hm' - Im' \\
k & = m - \alpha \quad k' & = m - \alpha \quad k'' & = m - \alpha \quad k''' & = Gm - Hm' - Im' \\
k & = m - \alpha \quad k' & = m - \alpha \quad k'' & = m - \alpha \quad k''' & = Gm - Hm' - Im' \\
k & = m - \alpha \quad k' & = m - \alpha \quad k'' & = m - \alpha \quad k''' & = Gm - Hm' - Im' \\
\end{align*} \tag{77}
\]

for the ellipsoid moving through or containing liquid, as in (40), (49). Surface values are given in Tables III, VI, VII.

1 (73) satisfy the known relation $\alpha + \beta + \gamma = 2abc/a'b''c''$, as appears on adding.
FLOW AND FORCE EQUATIONS FOR A BODY REVOLVING IN A FLUID

LIMITING CONDITIONS.—In some limiting cases, as for $c=0$, or $a=b$, etc., (73) may become indeterminate and require evaluation, as in Reference 4. In such cases the formulas in Table VIII may be used. For $c=0$, entailing zero mass and infinite $k$, $k'$, one may use in (57) the values of $k, m, k'A, k'B$ given at the bottom of Table VIII.

PHYSICAL MEANING OF THE COEFFICIENTS.—The tabulated potential coefficients, put in (40) or (49), serve to find the numerical value of the potential $\varphi$, or impulse $-\rho \varphi$ per unit area, at any point $(x, y, z)$ of an ellipsoid surface. Integration of $\rho \varphi$ over any surface, as explained for $p$ in Part I, gives the component linear and angular zonal impulses. So, too, integration of $-\rho \varphi q_{n}/2$, where $q_{n}$ is the normal surface velocity at $(x, y, z)$, gives the kinetic energy imparted to the fluid; and integration of the impulsive pressure $-\rho \varphi_{t}/t$ gives the impulsive zonal forces and moments. One finds $\rho \varphi_{t}/t$ for (40), (49) by using with them the specified density $\rho$, accelerations $U, V, W, \dot{\Omega}_{x}, \dot{\Omega}_{y}, \dot{\Omega}_{z}$, and tabulated potential coefficients for the given semiaxes $a, b, c$.

Thus putting $-\rho \varphi, -\rho \varphi'$ for $p$ in (9), (10), and integrating over the whole ellipsoid surface, easily gives the fluid's linear and angular momenta

$$k_{m}mW = k'_{m}C_{m},$$

where $mW, C_{m}$ are respectively the linear and angular momenta of the displaced fluid moving as a solid with velocities $W, \Omega_{c}$. The like surface integration of $-\rho \varphi_{n}/2$ gives, as is well known,

$$k_{m}mW^{2}/2 = k'_{m}C_{m}^{2}/2,$$

where $mW^{2}/2, C_{m}^{2}/2$ are the kinetic energies of the displaced fluid so moving. Each inertia coefficient therefore is a ratio of the body's apparent inertia, due to the field fluid, to the like inertia of the displaced fluid moving as a solid.

By (49) the potential coefficients due to velocities $W, \Omega_{c}$ are

$$m_{e} = -\varphi_{e}/W_{z} \quad m'_{e} = -\varphi'_{e}/\Omega_{xy}$$

The first is the ratio of the outer and inner surface potentials due to $W$ at any point $z$ on the ellipsoid $abc$; the second is the ratio of the potentials due to $\Omega_{c}$ at $(x, y)$, respectively on the outer surface of that ellipsoid and inside the cylinder of semiaxes $a, b, c$.

One notes that the momenta (78) times half the velocities give (79); also that the time derivatives of (78) are the force and moment $Z, N = k_{m}mW, k'_{m}C_{m}$, as in (57) for the simple $\alpha$-wise motions, $W, \Omega$.

For any axial surface, say of torpedo form, moving as in Figure 12, the ratio $k'_{m}C_{m}/k_{m}mV$ is the distance from the arbitrary origin $0_{t}$ to the impulse center $0_{3}$, or center of virtual mass. This may be taken as origin, and if the body's center of mass also is there Figures 11, 12 can still be superposed as in Figure 13. In the same way are related the acceleration force and moment $k_{m}m\dot{V}, k'_{m}C_{m}$, thus illustrating the doctrine that the motion of a hydrokinetically symmetric form in a boundless perfect fluid, without circulation, obeys the ordinary dynamic equations for a rigid body.

AERODYNAMICAL LABORATORY,
BUREAU OF CONSTRUCTION AND REPAIR, U. S. NAVY,
WASHINGTON, D. C., December 17, 1928.

1 This impulse is imparted by the moving surface to the fluid, otherwise still; the fluid in turn tends to impart to the body the impulse $\rho \varphi$ per unit area at $(x, y, z)$. 

225
REPORT NATIONAL ADVISORY COMMITTEE FOR AERONAUTICS

CHIEF SYMBOLS USED IN THE TEXT

GEOMETRICAL

a, b, c............. Semiaxes of ellipsoid abc.

a', b', c'............. Semiaxes of confocal ellipsoid a'b'c'.

e, e'............. Eccentricities of ellipse ab and its confocal a'b'; ae = ae' = \sqrt{a^2 - b^2}

a; b; b............. Normal to ellipse ab; distances from origin to normal and tangent.

l, m, n............. Direction cosines of normal a to any surface.

x; y; z............. Length along any line; lengths along meridian and circle of latitude.

r, \theta............. Cartesian coordinates; also coordinate axes.

\mu, \nu............. Eccentric angle of ab, inclination to x of normal to ab.

KINEMATICAL

u, v, w............. Component velocities of fluid parallel to x, y, z axes.

q, q............. Component velocities of fluid parallel to tangent and normal.

u, v, w............. Resultant velocity of fluid before and after disturbance.

U, V, W............. Component translation velocities of abc parallel to a, b, c

p, q, r............. Component rotation velocities of abc about a, b, c.

\Omega, \Omega, \Omega............. Component rotation velocities of abc about a, b, c.

w, \psi............. Velocity potential, stream function.

m, m, m............. Potential coefficients for abc with velocities u, v, w or U, V, W.

m', m', m'............. Potential coefficients for abc with velocities p, q, r or \Omega, \Omega, \Omega.

O = \sqrt{U^2 + V^2 + W^2}............. Resultant velocity of abc.

DYNAMICAL

A, B, C............. Moments of inertia of rigid body about its axes a, b, c.

A, B, C............. Moments of inertia of displaced fluid moving as a solid.

m, m............. Mass of body, mass of displaced fluid.

\alpha, \beta............. Density of fluid, volume of model or displaced fluid.

p, p............. Pressure of fluid moving, pressure on coming to rest.

X, Y, Z; R............. Component moments about a, b, c applied to rigid body.

L, M, N............. Component moments about a, b, c exerted by body on fluid.

k, k, k............. Inertia coefficients for abc moving parallel to a, b, c in fluid.

k', k', k'............. Inertia coefficients for abc rotating about a, b, c in fluid.

REFERENCES


### FLOW AND FORCE EQUATIONS FOR A BODY REVOLVING IN A FLUID

#### TABLE I
**ELLIPTIC INTEGRALS \( F(\theta, \phi), E(\theta, \phi) \)**

[Defined in eq. (75), Part VI]

<table>
<thead>
<tr>
<th>a/c</th>
<th>b/c</th>
<th>F((\theta, \phi))</th>
<th>E((\theta, \phi))</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>1.00000</td>
<td>1.04720</td>
<td>1.20065</td>
</tr>
<tr>
<td>2</td>
<td>1.20965</td>
<td>1.49870</td>
<td>3.09996</td>
</tr>
<tr>
<td>3</td>
<td>1.09629</td>
<td>1.31398</td>
<td>3.29617</td>
</tr>
<tr>
<td>4</td>
<td>1.31933</td>
<td>1.24113</td>
<td>1.84711</td>
</tr>
<tr>
<td>5</td>
<td>1.29185</td>
<td>1.19310</td>
<td>6.09650</td>
</tr>
<tr>
<td>6</td>
<td>1.24034</td>
<td>1.14848</td>
<td>6.52094</td>
</tr>
<tr>
<td>7</td>
<td>1.19400</td>
<td>1.09821</td>
<td>1.02995</td>
</tr>
<tr>
<td>8</td>
<td>1.14780</td>
<td>1.04959</td>
<td>1.52059</td>
</tr>
<tr>
<td>9</td>
<td>1.10068</td>
<td>0.99827</td>
<td>1.27057</td>
</tr>
<tr>
<td>10</td>
<td>1.05274</td>
<td>0.94197</td>
<td>1.22100</td>
</tr>
</tbody>
</table>

#### TABLE II
**GREEN'S INTEGRALS \( a_0, b_0, \gamma_0 \)**

[Defined in eq. (78), Part VI]

<table>
<thead>
<tr>
<th>a/c</th>
<th>b/c</th>
<th>(a_0)</th>
<th>(b_0)</th>
<th>(\gamma_0)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>1.00000</td>
<td>0.05734</td>
<td>0.06054</td>
<td></td>
</tr>
<tr>
<td>2</td>
<td>0.04720</td>
<td>0.21862</td>
<td>0.25045</td>
<td></td>
</tr>
<tr>
<td>3</td>
<td>0.27362</td>
<td>0.36600</td>
<td>0.65400</td>
<td></td>
</tr>
<tr>
<td>4</td>
<td>0.47268</td>
<td>0.47268</td>
<td>0.47268</td>
<td></td>
</tr>
<tr>
<td>5</td>
<td>0.67087</td>
<td>0.67087</td>
<td>0.67087</td>
<td></td>
</tr>
<tr>
<td>6</td>
<td>0.86774</td>
<td>0.86774</td>
<td>0.86774</td>
<td></td>
</tr>
</tbody>
</table>

1 The Integrals in this table are called from L. Poitn's Formules et Tables Numerique.
TABLE III

POTENTIAL COEFFICIENTS $m_a$, $m_b$, $m_c$* FOR ELLIPSOIDS IN TRANSLATION

(For outer surface of $a b c$

*Defined in eq. (76)

<table>
<thead>
<tr>
<th>$a/c$</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
<th>6</th>
<th>7</th>
<th>8</th>
<th>9</th>
<th>10</th>
</tr>
</thead>
<tbody>
<tr>
<td>$m_a$</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1.0000</td>
<td>0.2096</td>
<td>0.2229</td>
<td>0.2960</td>
<td>0.1247</td>
<td>0.0591</td>
<td>0.0297</td>
<td>0.0098</td>
<td>0.0000</td>
<td>0.0000</td>
<td>0.0000</td>
</tr>
<tr>
<td>0.5000</td>
<td>0.2229</td>
<td>0.2556</td>
<td>0.2960</td>
<td>0.1247</td>
<td>0.0591</td>
<td>0.0297</td>
<td>0.0098</td>
<td>0.0000</td>
<td>0.0000</td>
<td>0.0000</td>
</tr>
<tr>
<td>0.2500</td>
<td>0.2556</td>
<td>0.2880</td>
<td>0.2960</td>
<td>0.1247</td>
<td>0.0591</td>
<td>0.0297</td>
<td>0.0098</td>
<td>0.0000</td>
<td>0.0000</td>
<td>0.0000</td>
</tr>
<tr>
<td>0.1000</td>
<td>0.2880</td>
<td>0.3184</td>
<td>0.2960</td>
<td>0.1247</td>
<td>0.0591</td>
<td>0.0297</td>
<td>0.0098</td>
<td>0.0000</td>
<td>0.0000</td>
<td>0.0000</td>
</tr>
</tbody>
</table>

$mb$ |

| $m_c$ |

| 1.0000 | 0.5000 | 0.7042 | 0.8039 | 0.9171 | 1.115 | 1.362 | 0.1425 | 0.1425 | 0.1425 | 0.1425 |
| 0.5000 | 0.7042 | 0.8039 | 0.9171 | 1.115 | 1.362 | 0.1425 | 0.1425 | 0.1425 | 0.1425 | 0.1425 |
| 0.2500 | 0.8039 | 0.9171 | 1.115 | 1.362 | 0.1425 | 0.1425 | 0.1425 | 0.1425 | 0.1425 | 0.1425 |
| 0.1000 | 0.9171 | 1.115 | 1.362 | 0.1425 | 0.1425 | 0.1425 | 0.1425 | 0.1425 | 0.1425 | 0.1425 |

* These have the same values as the inertia coefficients $k_a$, $k_b$, $k_c$. 

* These have the same values as the inertia coefficients $k_a$, $k_b$, $k_c$. 

228
### TABLE IV

**Potential Coefficients** $m'_a, m'_b, m'_c$ for Ellipsoids in Rotation

(For outer surface of $a \ b \ c$)

[Defined in eq. (76)]

<table>
<thead>
<tr>
<th>$a/c$</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
<th>6</th>
<th>7</th>
<th>8</th>
<th>9</th>
<th>10</th>
<th>$\infty$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$m'_a$</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1</td>
<td>0</td>
<td>0.5843</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>2</td>
<td>0</td>
<td>0.9995</td>
<td>1.045</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>3</td>
<td>0</td>
<td>1.276</td>
<td>1.135</td>
<td>1.459</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>4</td>
<td>0</td>
<td>1.699</td>
<td>1.190</td>
<td>1.306</td>
<td>1.943</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>5</td>
<td>0</td>
<td>2.135</td>
<td>1.225</td>
<td>1.661</td>
<td>2.642</td>
<td>2.180</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>6</td>
<td>0</td>
<td>2.589</td>
<td>1.290</td>
<td>1.403</td>
<td>2.165</td>
<td>2.642</td>
<td>2.180</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>7</td>
<td>0</td>
<td>3.062</td>
<td>1.356</td>
<td>1.552</td>
<td>2.396</td>
<td>2.956</td>
<td>2.461</td>
<td>2.180</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>8</td>
<td>0</td>
<td>3.554</td>
<td>1.422</td>
<td>1.703</td>
<td>2.666</td>
<td>3.198</td>
<td>3.198</td>
<td>3.346</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>9</td>
<td>0</td>
<td>4.065</td>
<td>1.490</td>
<td>1.854</td>
<td>2.948</td>
<td>3.430</td>
<td>3.778</td>
<td>3.778</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>10</td>
<td>0</td>
<td>4.587</td>
<td>1.558</td>
<td>2.006</td>
<td>3.239</td>
<td>3.968</td>
<td>4.103</td>
<td>4.103</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$m'_b$</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1</td>
<td>-0.3990</td>
<td>-0.3990</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>2</td>
<td>-0.5619</td>
<td>-0.5619</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>3</td>
<td>-0.7252</td>
<td>-0.7252</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>4</td>
<td>-0.8887</td>
<td>-0.8887</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>5</td>
<td>-1.0515</td>
<td>-1.0515</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>6</td>
<td>-1.2136</td>
<td>-1.2136</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>7</td>
<td>-1.3751</td>
<td>-1.3751</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>8</td>
<td>-1.5365</td>
<td>-1.5365</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>9</td>
<td>-1.6979</td>
<td>-1.6979</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>10</td>
<td>-1.8592</td>
<td>-1.8592</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$m'_c$</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1</td>
<td>0</td>
<td>0.5000</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>2</td>
<td>0</td>
<td>0.2819</td>
<td>0.1206</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>3</td>
<td>0</td>
<td>0.8084</td>
<td>0.2920</td>
<td>0.09332</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>4</td>
<td>0</td>
<td>0.7781</td>
<td>0.2999</td>
<td>0.13309</td>
<td>0.00110</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>5</td>
<td>0</td>
<td>0.8056</td>
<td>0.3502</td>
<td>0.21719</td>
<td>0.02106</td>
<td>0.03549</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>6</td>
<td>0</td>
<td>0.8402</td>
<td>0.3867</td>
<td>0.19847</td>
<td>0.19114</td>
<td>0.02127</td>
<td>0.03569</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>7</td>
<td>0</td>
<td>0.8634</td>
<td>0.4036</td>
<td>0.23592</td>
<td>0.38981</td>
<td>0.04529</td>
<td>0.01951</td>
<td>0.05214</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>8</td>
<td>0</td>
<td>0.8628</td>
<td>0.4006</td>
<td>0.23384</td>
<td>0.49410</td>
<td>0.08048</td>
<td>0.043126</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>9</td>
<td>0</td>
<td>0.8585</td>
<td>0.3946</td>
<td>0.19088</td>
<td>0.22401</td>
<td>0.14761</td>
<td>0.07270</td>
<td>0.01951</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>10</td>
<td>0</td>
<td>0.8433</td>
<td>0.3786</td>
<td>0.15084</td>
<td>0.20728</td>
<td>0.16667</td>
<td>0.14286</td>
<td>0.11111</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

104307—200—20

229
TABLE V
POTENTIAL COEFFICIENTS $m'_e$, $m'_h$, $m'_e$ FOR ELLIPSOIDS IN ROTATION
(For all points inside of $a \ b \ c$)
[Defined in eq. (40)]

<table>
<thead>
<tr>
<th>$a/c$</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
<th>6</th>
<th>7</th>
<th>8</th>
<th>9</th>
<th>10</th>
</tr>
</thead>
<tbody>
<tr>
<td>$m'_e = 0$</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$m'_h = H$</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$m'_e = l$</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>$b/c$</th>
<th>0 to $m$</th>
<th>0.00000</th>
<th>0.60000</th>
<th>0.62363</th>
<th>0.45160</th>
<th>0.60000</th>
<th>0.60936</th>
<th>0.60000</th>
<th>0.60000</th>
<th>0.60000</th>
<th>0.60000</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>0</td>
<td>0.00000</td>
<td>0.60000</td>
<td>0.62363</td>
<td>0.45160</td>
<td>0.60000</td>
<td>0.60936</td>
<td>0.60000</td>
<td>0.60000</td>
<td>0.60000</td>
<td>0.60000</td>
</tr>
<tr>
<td>2</td>
<td>0</td>
<td>0.00000</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>3</td>
<td>0</td>
<td>0.00000</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>4</td>
<td>0</td>
<td>0.00000</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>5</td>
<td>0</td>
<td>0.00000</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>6</td>
<td>0</td>
<td>0.00000</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>7</td>
<td>0</td>
<td>0.00000</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>8</td>
<td>0</td>
<td>0.00000</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>9</td>
<td>0</td>
<td>0.00000</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>10</td>
<td>0</td>
<td>0.00000</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Note: Same for all values of $b/c$
FLOW AND FORCE EQUATIONS FOR A BODY REVOLVING IN A FLUID

TABLE VI

INERTIA COEFFICIENTS \( k', k'_b, k'_c \) FOR ELLIPSOIDS IN ROTATION

(For outer surface of \( a \ b \ c \))

[Defined in eq. (77)]

<table>
<thead>
<tr>
<th>( a/c )</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
<th>6</th>
<th>7</th>
<th>8</th>
<th>9</th>
<th>10</th>
<th>( \infty )</th>
</tr>
</thead>
<tbody>
<tr>
<td>( \beta )</td>
<td>( k'_a = \alpha m'_a )</td>
<td>( k'_b = \alpha m'_b )</td>
<td>( k'_c = \alpha m'_c )</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1</td>
<td>0</td>
<td>0.3386</td>
<td>0.6358</td>
<td>0.8339</td>
<td>1.0000</td>
<td>1.191</td>
<td>1.382</td>
<td>1.586</td>
<td>1.785</td>
<td>( \infty )</td>
<td></td>
</tr>
<tr>
<td>2</td>
<td>0</td>
<td>0.3386</td>
<td>0.6358</td>
<td>0.8339</td>
<td>1.0000</td>
<td>1.191</td>
<td>1.382</td>
<td>1.586</td>
<td>1.785</td>
<td>( \infty )</td>
<td></td>
</tr>
<tr>
<td>3</td>
<td>0</td>
<td>0.3386</td>
<td>0.6358</td>
<td>0.8339</td>
<td>1.0000</td>
<td>1.191</td>
<td>1.382</td>
<td>1.586</td>
<td>1.785</td>
<td>( \infty )</td>
<td></td>
</tr>
<tr>
<td>4</td>
<td>0</td>
<td>0.3386</td>
<td>0.6358</td>
<td>0.8339</td>
<td>1.0000</td>
<td>1.191</td>
<td>1.382</td>
<td>1.586</td>
<td>1.785</td>
<td>( \infty )</td>
<td></td>
</tr>
<tr>
<td>5</td>
<td>0</td>
<td>0.3386</td>
<td>0.6358</td>
<td>0.8339</td>
<td>1.0000</td>
<td>1.191</td>
<td>1.382</td>
<td>1.586</td>
<td>1.785</td>
<td>( \infty )</td>
<td></td>
</tr>
<tr>
<td>6</td>
<td>0</td>
<td>0.3386</td>
<td>0.6358</td>
<td>0.8339</td>
<td>1.0000</td>
<td>1.191</td>
<td>1.382</td>
<td>1.586</td>
<td>1.785</td>
<td>( \infty )</td>
<td></td>
</tr>
<tr>
<td>7</td>
<td>0</td>
<td>0.3386</td>
<td>0.6358</td>
<td>0.8339</td>
<td>1.0000</td>
<td>1.191</td>
<td>1.382</td>
<td>1.586</td>
<td>1.785</td>
<td>( \infty )</td>
<td></td>
</tr>
<tr>
<td>8</td>
<td>0</td>
<td>0.3386</td>
<td>0.6358</td>
<td>0.8339</td>
<td>1.0000</td>
<td>1.191</td>
<td>1.382</td>
<td>1.586</td>
<td>1.785</td>
<td>( \infty )</td>
<td></td>
</tr>
<tr>
<td>9</td>
<td>0</td>
<td>0.3386</td>
<td>0.6358</td>
<td>0.8339</td>
<td>1.0000</td>
<td>1.191</td>
<td>1.382</td>
<td>1.586</td>
<td>1.785</td>
<td>( \infty )</td>
<td></td>
</tr>
<tr>
<td>10</td>
<td>0</td>
<td>0.3386</td>
<td>0.6358</td>
<td>0.8339</td>
<td>1.0000</td>
<td>1.191</td>
<td>1.382</td>
<td>1.586</td>
<td>1.785</td>
<td>( \infty )</td>
<td></td>
</tr>
<tr>
<td>( \infty )</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>( \infty )</td>
<td></td>
</tr>
</tbody>
</table>

1 For translation \( \alpha, \beta, \gamma \) are given in Table III.
TABLE VII

INERTIA COEFFICIENTS $k'_a$, $k'_b$, $k'_c$ FOR ELLIPSOIDS IN ROTATION.

(Inner surface of a b c)

[Defined in eq. (77)]

<table>
<thead>
<tr>
<th>a/c</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
<th>6</th>
<th>7</th>
<th>8</th>
<th>9</th>
<th>10</th>
<th>=</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>$k'_a = Gm'_a$</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>0 to</td>
<td>0</td>
<td>0.36000</td>
<td>0.64000</td>
<td>0.77854</td>
<td>0.82308</td>
<td>0.89482</td>
<td>0.92040</td>
<td>0.93941</td>
<td>0.95181</td>
<td>0.96079</td>
<td>1.00000</td>
</tr>
<tr>
<td>1</td>
<td>0.36000</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>2</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>3</td>
<td>.54000</td>
<td>.81238</td>
<td>.84500</td>
<td>.84500</td>
<td>.84500</td>
<td>.84500</td>
<td>.84500</td>
<td>.84500</td>
<td>.84500</td>
<td>.84500</td>
<td>.84500</td>
</tr>
<tr>
<td>4</td>
<td>.84500</td>
<td>.84500</td>
<td>.84500</td>
<td>.84500</td>
<td>.84500</td>
<td>.84500</td>
<td>.84500</td>
<td>.84500</td>
<td>.84500</td>
<td>.84500</td>
<td>.84500</td>
</tr>
<tr>
<td>5</td>
<td>.84500</td>
<td>.84500</td>
<td>.84500</td>
<td>.84500</td>
<td>.84500</td>
<td>.84500</td>
<td>.84500</td>
<td>.84500</td>
<td>.84500</td>
<td>.84500</td>
<td>.84500</td>
</tr>
<tr>
<td>6</td>
<td>.84500</td>
<td>.84500</td>
<td>.84500</td>
<td>.84500</td>
<td>.84500</td>
<td>.84500</td>
<td>.84500</td>
<td>.84500</td>
<td>.84500</td>
<td>.84500</td>
<td>.84500</td>
</tr>
<tr>
<td>7</td>
<td>.84500</td>
<td>.84500</td>
<td>.84500</td>
<td>.84500</td>
<td>.84500</td>
<td>.84500</td>
<td>.84500</td>
<td>.84500</td>
<td>.84500</td>
<td>.84500</td>
<td>.84500</td>
</tr>
<tr>
<td>8</td>
<td>.84500</td>
<td>.84500</td>
<td>.84500</td>
<td>.84500</td>
<td>.84500</td>
<td>.84500</td>
<td>.84500</td>
<td>.84500</td>
<td>.84500</td>
<td>.84500</td>
<td>.84500</td>
</tr>
<tr>
<td>9</td>
<td>.84500</td>
<td>.84500</td>
<td>.84500</td>
<td>.84500</td>
<td>.84500</td>
<td>.84500</td>
<td>.84500</td>
<td>.84500</td>
<td>.84500</td>
<td>.84500</td>
<td>.84500</td>
</tr>
<tr>
<td>10</td>
<td>.84500</td>
<td>.84500</td>
<td>.84500</td>
<td>.84500</td>
<td>.84500</td>
<td>.84500</td>
<td>.84500</td>
<td>.84500</td>
<td>.84500</td>
<td>.84500</td>
<td>.84500</td>
</tr>
<tr>
<td>=</td>
<td>1.00000</td>
<td>1.00000</td>
<td>1.00000</td>
<td>1.00000</td>
<td>1.00000</td>
<td>1.00000</td>
<td>1.00000</td>
<td>1.00000</td>
<td>1.00000</td>
<td>1.00000</td>
<td>1.00000</td>
</tr>
</tbody>
</table>

$k'_a = Hm'_a$

$k'_c = 1/m'_c$
FLOW AND FORCE EQUATIONS FOR A BODY REVOLVING IN A FLUID

TABLE VIII

INERTIA VALUES FOR LIMITING FORMS OF ELLIPSOIDS $a>b>c$

<table>
<thead>
<tr>
<th>Shape</th>
<th>$k_a$</th>
<th>$k_b$</th>
<th>$k_c$</th>
<th>$k'_a$</th>
<th>$k'_b$</th>
<th>$k'_c$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Circular disk</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Elliptical disk</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Long rectangle</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Oblate spheroid $e=1-c/a$</td>
<td>$c a(1+e)-c$</td>
<td>$c a(1+e)-c$</td>
<td>$e a c-2e c-c$</td>
<td>$c a(1+e)-c$</td>
<td>$c a(1+e)-c$</td>
<td>$c a(1+e)-c$</td>
</tr>
<tr>
<td>Ellipsoid</td>
<td>0</td>
<td>$cb$</td>
<td>$b c$</td>
<td>0</td>
<td>$bc$</td>
<td>$bc$</td>
</tr>
<tr>
<td>Elliptical cylinder</td>
<td>0</td>
<td>$c/b$</td>
<td>$b/c$</td>
<td>$c/b$</td>
<td>$b/c$</td>
<td>$c/b$</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Sphere $e=1-c/a$</td>
<td>$1/2\log(1-c/e)$</td>
<td>$1/2\log(1-c/e)$</td>
<td>$1/2\log(1-c/e)$</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Prolate spheroid $e=1-c/a$</td>
<td>$1+e$</td>
<td>$1/e$</td>
<td>$1/e$</td>
<td>0</td>
<td>$1+e$</td>
<td>$1/e$</td>
</tr>
<tr>
<td>Round cylinder</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>1</td>
<td>1</td>
</tr>
</tbody>
</table>

APPARENT MASSES AND MOMENTS OF INERTIA WHEN $c=0$

<table>
<thead>
<tr>
<th>Shape</th>
<th>$k_a m$</th>
<th>$k_b m$</th>
<th>$k_c m$</th>
<th>$k'_a A$</th>
<th>$k'_b B$</th>
<th>$k'_c C$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Circular disk</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Elliptical disk</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>$3(p a b b/E)$</td>
<td>15(p a b b/E)</td>
<td>15(p a b b/E)</td>
</tr>
<tr>
<td>Long rectangle $a=b$</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
</tbody>
</table>

1 $a^2-a_c=-1+2\sqrt{\pi}\csc\theta$, $b=ae=-2+2\sqrt{\pi}\csc\theta$ and $c=ae$, $\theta=\frac{1}{2}\log(1-c/e)$.

* Per unit length of model.
TABLE IX
LIFT, DRAG, AND MOMENT ON ENDLESS ELLIPTIC CYLINDER

<table>
<thead>
<tr>
<th>Angle of attack $\alpha$, degrees</th>
<th>Lift</th>
<th>Drag</th>
<th>Moment about long axis</th>
<th>Theoretical $N$</th>
<th>Experimen-</th>
<th>Tnal $N$</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Pound per foot run</td>
<td>Pound per foot run</td>
<td>$=1.3092$</td>
<td>$=0.5581$</td>
<td></td>
<td></td>
</tr>
<tr>
<td>$-8$</td>
<td>0.100</td>
<td>-0.335</td>
<td>-0.3991</td>
<td>0.190</td>
<td>-0.107</td>
<td>-0.1538</td>
</tr>
<tr>
<td>$-6$</td>
<td>0.139</td>
<td>-0.254</td>
<td>-0.2784</td>
<td>0.172</td>
<td>-0.127</td>
<td>-0.1716</td>
</tr>
<tr>
<td>$-4$</td>
<td>0.111</td>
<td>-0.084</td>
<td>-0.0904</td>
<td>0.142</td>
<td>-0.086</td>
<td>-0.1141</td>
</tr>
<tr>
<td>$-2$</td>
<td>0.108</td>
<td>-0.042</td>
<td>-0.0467</td>
<td>0.108</td>
<td>-0.044</td>
<td>-0.0487</td>
</tr>
<tr>
<td>0</td>
<td>0.115</td>
<td>0.042</td>
<td>0.0467</td>
<td>0.111</td>
<td>0.046</td>
<td>0.0487</td>
</tr>
<tr>
<td>$+2$</td>
<td>0.122</td>
<td>0.120</td>
<td>0.1400</td>
<td>0.123</td>
<td>0.123</td>
<td>0.1400</td>
</tr>
<tr>
<td>$+4$</td>
<td>0.140</td>
<td>0.249</td>
<td>0.2784</td>
<td>0.140</td>
<td>0.249</td>
<td>0.2784</td>
</tr>
<tr>
<td>$+6$</td>
<td>0.185</td>
<td>-0.323</td>
<td>-0.3601</td>
<td>0.185</td>
<td>-0.323</td>
<td>-0.3601</td>
</tr>
</tbody>
</table>

*As the test angles $\alpha$ were in part fractional, all measurements in Table IX are faired from the original graphs of lift, drag, and moment versus $\alpha$, in fig. 12.

TABLE X
LIFT, DRAG, AND MOMENT ON ENDLESS THIN FLAT PLATE

<table>
<thead>
<tr>
<th>Angle of attack $\alpha$, degrees</th>
<th>Lift</th>
<th>Drag</th>
<th>Moment about long axis</th>
<th>Theoretical $N$</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Pound per foot run</td>
<td>Pound per foot run</td>
<td>$=0.5581$</td>
<td>$=0.5581$</td>
</tr>
<tr>
<td>$-8$</td>
<td>0.190</td>
<td>-0.107</td>
<td>-0.1538</td>
<td>0.190</td>
</tr>
<tr>
<td>$-6$</td>
<td>0.112</td>
<td>-0.100</td>
<td>-0.1380</td>
<td>0.112</td>
</tr>
<tr>
<td>$-4$</td>
<td>0.065</td>
<td>-0.083</td>
<td>-0.0983</td>
<td>0.065</td>
</tr>
<tr>
<td>$-2$</td>
<td>0.021</td>
<td>-0.050</td>
<td>-0.0610</td>
<td>0.021</td>
</tr>
<tr>
<td>0</td>
<td>0.032</td>
<td>0.016</td>
<td>0.0180</td>
<td>0.032</td>
</tr>
<tr>
<td>$+2$</td>
<td>0.038</td>
<td>0.007</td>
<td>0.0099</td>
<td>0.038</td>
</tr>
<tr>
<td>$+4$</td>
<td>0.050</td>
<td>0.059</td>
<td>0.0680</td>
<td>0.050</td>
</tr>
<tr>
<td>$+6$</td>
<td>0.075</td>
<td>0.107</td>
<td>0.1150</td>
<td>0.075</td>
</tr>
<tr>
<td>$+8$</td>
<td>0.100</td>
<td>0.138</td>
<td>0.1538</td>
<td>0.100</td>
</tr>
<tr>
<td>$+10$</td>
<td>0.135</td>
<td>0.184</td>
<td>0.1909</td>
<td>0.135</td>
</tr>
<tr>
<td>$+12$</td>
<td>0.165</td>
<td>0.207</td>
<td>0.2264</td>
<td>0.165</td>
</tr>
<tr>
<td>$+14$</td>
<td>0.192</td>
<td>0.222</td>
<td>0.2484</td>
<td>0.192</td>
</tr>
<tr>
<td>$+16$</td>
<td>0.218</td>
<td>0.245</td>
<td>0.2685</td>
<td>0.218</td>
</tr>
<tr>
<td>$-18$</td>
<td>0.342</td>
<td>0.390</td>
<td>0.4010</td>
<td>0.342</td>
</tr>
</tbody>
</table>

234
FLOW AND FORCE EQUATIONS FOR A BODY REVOLVING IN A FLUID

TABLE XI
LIFT, DRAG, AND MOMENT ON THIN ELLIPTIC WING
[Length 30 inches, width 5 inches, air speed 40 miles per hour]

<table>
<thead>
<tr>
<th>Angle of attack a degrees</th>
<th>Lift Pounds</th>
<th>Drag</th>
<th>Moment about long axis, pound foot</th>
</tr>
</thead>
<tbody>
<tr>
<td>-8</td>
<td>-2.415</td>
<td>0.426</td>
<td>-0.173</td>
</tr>
<tr>
<td>-6</td>
<td>-1.853</td>
<td>0.265</td>
<td>-0.154</td>
</tr>
<tr>
<td>-4</td>
<td>-1.158</td>
<td>0.199</td>
<td>-0.106</td>
</tr>
<tr>
<td>-3</td>
<td>-0.865</td>
<td>0.128</td>
<td>-0.062</td>
</tr>
<tr>
<td>-2</td>
<td>-0.587</td>
<td>0.115</td>
<td>-0.033</td>
</tr>
<tr>
<td>-1</td>
<td>-0.394</td>
<td>0.103</td>
<td>-0.011</td>
</tr>
<tr>
<td>0</td>
<td>+0.053</td>
<td>0.103</td>
<td>0</td>
</tr>
<tr>
<td>+1</td>
<td>+0.373</td>
<td>0.106</td>
<td>+0.020</td>
</tr>
<tr>
<td>3</td>
<td>+0.589</td>
<td>0.118</td>
<td>+0.058</td>
</tr>
<tr>
<td>5</td>
<td>+0.699</td>
<td>0.126</td>
<td>+0.064</td>
</tr>
<tr>
<td>6</td>
<td>+1.139</td>
<td>0.168</td>
<td>+0.113</td>
</tr>
<tr>
<td>8</td>
<td>+2.674</td>
<td>0.207</td>
<td>+0.156</td>
</tr>
<tr>
<td>10</td>
<td>+2.956</td>
<td>0.239</td>
<td>+0.179</td>
</tr>
<tr>
<td>12</td>
<td>+3.808</td>
<td>0.296</td>
<td>+0.199</td>
</tr>
<tr>
<td>14</td>
<td>+5.052</td>
<td>0.348</td>
<td>+0.222</td>
</tr>
<tr>
<td>16</td>
<td>+2.859</td>
<td>0.267</td>
<td>+0.188</td>
</tr>
<tr>
<td>18</td>
<td>+2.705</td>
<td>0.247</td>
<td>+0.168</td>
</tr>
<tr>
<td>+20</td>
<td>+2.745</td>
<td>1.065</td>
<td>+0.065</td>
</tr>
</tbody>
</table>

Theoretical
\[ L = 0.9863 \sin 2a \]

<table>
<thead>
<tr>
<th>Angle of attack a degrees</th>
<th>Lift Pounds</th>
<th>Drag</th>
<th>Moment about long axis, pound foot</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

TABLE XII
MOMENT ON PROLATE SPHEROID
[Length 24 inches, diameter 6 inches, through-air speed 40 feet per second]

<table>
<thead>
<tr>
<th>Angle of attack a degrees</th>
<th>Moment about minor axis, pound foot</th>
</tr>
</thead>
<tbody>
<tr>
<td>Rectilinear motion</td>
<td>Curvilinear motion</td>
</tr>
<tr>
<td>Measured on balance</td>
<td>Found by pressure integration</td>
</tr>
<tr>
<td>Theoretical</td>
<td></td>
</tr>
<tr>
<td></td>
<td>[ N = 0.388 \sin 2a ]</td>
</tr>
<tr>
<td></td>
<td></td>
</tr>
</tbody>
</table>

-30 -0.179 -0.207 -0.157 -0.249
-20 -1.06 -0.122 -0.075 -0.153
-10 -0.041 -0.033 -0.018 -0.044
0 0 0 0 0
+10 +0.106 +0.122 +0.087 +0.132
+20 +1.179 +1.27 +0.247 +0.349

Data taken from Reference 3.

235