NATIONAL ADVISORY COMMITTEE FOR AERONAUTICS

TECHNICAL MEMORANDUM 1329

CONCERNING THE FLOW ABOUT RING-SHAPED COWLINGS

PART IX - THE INFLUENCE OF OBLIQUE ONCOMING FLOW ON THE

INCREMENTAL VELOCITIES AND AIR FORCES AT THE

FRONT PART OF CIRCULAR COWLS

By Dietrich Küchemann and Johanna Weber

Translation of "ZWB Forschungsbericht Nr. 1236/9,
June 10, 1943

Washington
February 1952

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ABSTRACT: The dependence of the maximum incremental velocities and air
forces on a circular cowling on the mass flow and the angle
of attack of the oblique flow is determined with the aid of
pressure-distribution measurements. The particular cowling
tested had been partially investigated in reference 1.

OUTLINE: I. THE PROBLEM
           II. THE METHOD OF MEASUREMENT
          III. RESULTS
           IV. SYNOPSIS
            V. REFERENCES

I. THE PROBLEM

    As a supplement to former measurements (compare reference 1 and
reference 2) where the main stress was laid on the development of usable
forms of circular cowls in the case of purely axial flow, the measurements
presented here are to give a survey of the phenomena in case of flow at
an oblique angle of attack. The occurring forces in the vertical direc-
tion to the axis of the cowl are of interest not only in aerodynamical
respect but also for the structural stress on the propulsion unit. It
was to be assumed that the magnitude of these transverse forces will be
a function not only of the geometrical dimensions of the entire engine

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nacelle and of the angle of attack but also of the mass-flow coefficient
and hence the strength and direction of the leaving jet, and of the
position of the engine with respect to other airplane parts. Of all
these interrelated questions, only a single one has been investigated
which could be answered the fastest with the means at disposal and which
is of fundamental importance for all further problems. What influence
does the oblique flow exert on the front part of the inlet of such an engine
cowling? In detail, it had to be determined for a characteristic example;
in what manner the transverse force depends on the angle of attack and
the mass-flow coefficient, where, approximately, lies the center of
gravity of these forces, and how strongly the maximum incremental veloc-
ities on the outside of the cowl increase in case of oblique flow.

II. THE METHOD OF MEASUREMENT

We shall use pressure-distribution measurements on a selected inlet
device in oblique flow. The pressure-distribution measurements in refer-
ence 1 and elsewhere[1] have proved to have many applications to our present
problem. It is necessary to select a circular cowl where the results
may, to some extent, be regarded as generally valid for the tests, thus,
extreme forms are a priori excluded. The cowling 1 with hub 2[2] investi-
gated in reference 1 is such a circular cowl which satisfies these require-
ments for all operating conditions with respect to its construction (ratio
between free entrance cross section F_E and maximum outer cross sec-
tion F_a, $[F_E/F_a = 0.27]$ with respect to its maximum incremental velocities
and with respect to the loss-free flow about it (compare reference 2).
The model of this cowling described in reference 1 could be used directly.
Thus, it was only necessary to expand the former program of measurements
in reference 1 insofar that more detailed and more finely subdivided
series of angles of attack are tested and that the measurements for
oblique flow are extended to include smaller mass-flow coefficients.
These new measurements are desirable because we had to assume that the
locally greatest stresses appear for such states of flight (which, it is
true, are extraordinary) where the mass flow is very small or in the
extreme case zero.

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[1]Among others, measurements by M. Schirmer (reference 3) on airship
bodies show that the forces and moments obtained from pressure distribu-
tions for nonseparated flow agree well with the results from a balance.

[2]This cowl differs only slightly from the circular cowls of class I
indicated in reference 2 by a somewhat greater slenderness (the cylindrical
piece begins at a distance $3R_a$ from the leading edge).

Because of the disturbed rotational symmetry, an evaluation of pressure-distribution measurements for transverse forces requires the placing of test points over the circumference of the cowl since the pressure p depends - besides being a function of the space coordinates x and r in axial and radial direction - on the angle φ (compare fig. 1). The entire air force, N, that acts vertically to the axis of rotation for a circular cowl of the axial length l is obtained by integration of the respective corresponding component of the local pressure $p(x,r,\varphi)$

$$N = \int_0^l \int_0^{2\pi} p(x,r,\varphi) ds \frac{dx}{ds} \cos \varphi r(x) d\varphi \qquad (1)$$

with s as arc length along the body contour. A simple estimate can be made with the assumption that the difference between the local pressure for oblique flow and the corresponding value without oblique flow ($\alpha = 0$) is distributed over the circumference of the cowl according to a cosine law[3]. Thus,

$$p(x,r,\varphi,\alpha) - p(x,r,\alpha = 0) = \left[p(x,r,\varphi = 0,\alpha) - p(x,r,\alpha = 0) \right] \cos \varphi$$

$$= \left[p_\alpha - p_{\alpha=0} \right] \cos \varphi \qquad (2)$$

Under this assumption of the cosine relationship for oblique flow, one pressure-distribution measurement in the upper part of the meridian section ($\varphi = 0$) is sufficient and the integration over the periphery of the circle can be performed. Equation (1) becomes

$$N = \int_0^l \int_0^{2\pi} \left[p_\alpha - p_{\alpha=0} \right] \cos^2\varphi r(x) dx \ d\varphi \qquad \cdot$$

$$= \pi \int_0^l \left[p_\alpha - p_{\alpha=0} \right] r(x) \ dx \qquad (3)$$

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[3]Theoretically, more complicated relations may be assumed as was the case in a report by J. Lotz (reference 4) on airship bodies in oblique flow.

If one would, instead of the assumption of equation (2), make the extreme presupposition that the pressure has on the entire upper side of the body $(-\pi/2 \leq \varphi \leq +\pi/2)$ the same value as for $\varphi = 0$ and on the entire lower side the same value as for $\varphi = \pi$, a factor 4 instead of the factor π would result in equation (3). Thus, the values given later would, at the worst, have to be multiplied by $4/\pi = 1.27$.

If one makes the normal force N dimensionless by means of the free-stream dynamic pressure

$$q_o = \frac{\rho}{2} v_o{}^2$$

and the maximum cross sectional area $\pi R_a{}^2$, one obtains from equation (3)

$$\frac{N}{q_o \pi R_a{}^2} = \int_0^{l/R_a} \frac{p_\alpha - p_{\alpha=0}}{q_o} \frac{r(x)}{R_a} d\left(\frac{x}{R_a}\right) \tag{4}$$

This evaluation method can be improved by measuring with each positive angle $+\alpha$ at the same time the corresponding negative angle $-\alpha$ which, for reasons of symmetry, represents a second series of pressure test points for $\varphi = 180^o$. If our above assumption were justified, the corresponding value of the integral, equation (4), would equal, except for the sign, that for the positive angle. In the evaluation of the measurements, it was found that these two values were no longer equal for larger angles of attack ($\alpha = 9^o$ and more); however, the deviations were such that the use of the simple arithmetic mean between the two values appeared justified.

Aside from the total force normal to the axis which was thus obtained, equation (4), the point of application of this force in the x-direction, or the moment of these forces for instance referred to the point $x = l$; $r = 0$, are of interest. These are obtained by the further integration

$$\frac{M}{q_o \pi R_a{}^3} = \int_0^{l/R_a} \frac{p_\alpha - p_{\alpha=0}}{q_o} \frac{r(x)}{R_a}\left(\frac{l}{R_a} - \frac{x}{R_a}\right) d\left(\frac{x}{R_a}\right) \tag{5}$$

III. RESULTS

Figures 2 through 4 show the wall pressure distributions for three different mass flow coefficients.[4] The resulting dependence of the pressure minimum on the angle of attack was evaluated with respect to the maximum excess velocities v_{max} (compare fig. 5). The known characteristic variation of v_{max}/v_O against the mass-flow coefficient v_E/v_O (with v_E = mean velocity in the entrance cross section F_E) is repeated for the different angles of attack; the incremental velocities increase considerably with angle of attack. The increase of the incremental velocities which is expressed by the quotient

$$\frac{d\left(v_{max}/v_O\right)}{d\alpha}$$

depends, aside from being a function of the mass-flow coefficient, on the constriction and, to a high degree, also on the nose form, particularly the nose radius. For the cowling investigated here which is equivalent to a circular cowl of class I in reference 2, the following equations are approximately valid:

$$\frac{d\left(v_{max}/v_O\right)}{d\alpha} = 2.7$$

for $v_E = 0$ and

$$\frac{d\left(v_{max}/v_O\right)}{d\alpha} = 1.5$$

for $v_E = v_O$.

For the circular cowls of class II with more pronounced rounding of the nose, a lesser degree of dependence of the incremental velocities on the angle of attack of the oblique flow is to be expected. Thus follows, for instance, from measurements here not described in detail that for circular cowl of the class II with $F_E/F_a = 0.3$ for $v_E/v_O = 0.27$ approximately

$$\frac{d\left(v_{max}/v_O\right)}{d\alpha} = 1.6$$

applies whereas for the corresponding cowl of class I

$$\frac{d\left(v_{max}/v_O\right)}{d\alpha} = 2.2$$

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[4]Corresponding results for larger v_E/v_O are to be found in reference 1.

For comparison, we further consider the measurement (reference 5) on a
Ruden nose inlet of minimum constriction with a much more pointed nose.
For equal constriction and equal mass-flow coefficient, here

$$\frac{d\left(v_{max}/v_0\right)}{d\alpha} = 4.7$$

is found. The dependence discussed just now also appears in two-
dimensional profiles and is in the same direction. For customary profiles,
for instance, of the NACA series with standard nose rounding, one finds
gradients of the same order of magnitude as for the cowls of the classes I
and II in the range of small angles-of-attack.

These measurements prove that the dependence of v_{max}/v_0 on the
angle of attack has the same significance as the dependence of v_{max}/v_0
on the constriction (compare reference 2). It is therefore very important
as to how such an engine cowling is installed in the airplane. Particu-
larly, one problem therein is still unsolved: how far the flow direction
at the entrance is influenced, for instance, by a wing or other airplane
parts close by.

We determined the normal forces according to equation (4) from the
pressure-distribution measurements. The integration was carried out
only over the front part of the cowl up to the cylindrical part so that
l/R_a was set equal 3. For small mass-flow coefficients, the main
contribution to the transverse forces is made by the outside of the
cowling, whereas the share of the inside becomes significant only for
larger v_E/v_0. The pressure distribution at the hub shows a very minor
dependence on α and, therefore, contributes practically nothing to the
transverse force. This fact is a renewed confirmation of the rule dis-
cussed in detail in reference (2) that the flow in the interior is almost
independent of the flow outside. Figure 6 shows the result of this
evaluation; aside from the linear variation with the angle of attack,
the slight degree of dependence on the mass flow is noteworthy. This
phenomenon probably is interrelated with the fact that for larger mass-
flow coefficients, the outside experiences less normal forces but, on
the other hand, the inside gets a larger share. How far this result
repeats itself for arbitrary forms as well is still undecided. Certainly
deviations will result if the flow separates at any location along the
cowl which, for the cowl investigated here, was the case to a slight
extent at $v_E = 0$ and $\alpha = 12°$, but is otherwise avoided. The evalua-
tion of the moments of these air forces, according to equation (5),
showed that the center of gravity of the air force distribution lies, for
all mass-flow coefficients and angles of attack, approximately in the
same plane $x/R_a = 0.8$ (x being counted from the entrance plane). The

air-force moment of the noncylindrical front part of the inlet referred
to the point $x = 3R_a$ then is with

$$\frac{N}{q_o \pi R_a{}^2} = 2.2\alpha$$

(compare fig. 6)

$$\frac{M}{q_o \pi R_a{}^3} = 2.2\alpha(3 - 0.8) = 4.8\alpha$$

The independence of the moment of the internal mass flow becomes under-
standable by means of the following deliberation: An arbitrary body,
immersed in a flow approaching at the angle of attack α referred to
the x,z-plane with the velocity v_o parallel to the x axis, experi-
ences a longitudinal moment of the magnitude

$$M = \frac{\rho}{2} v_o{}^2 \left(K_z - K_x\right) \sin 2\alpha$$

(compare F. Vandrey (reference 6)). Therein ρK_x or ρK_z are
apparent additional masses of the body for oncoming flow in x or
z direction. For elongated bodies K_x is, in general, considerably
smaller than K_z (for instance, for a spheroid of the axis ratio 4:1,
the value of K_z is 10 times that of K_x). If we have, as in our case,
a body through which the flow passes in the direction of the x-axis, K_x
only is important, not K_z. Furthermore, the mass flow Q also is small
in the cases considered, since

$$Q/\pi R_a{}^2 v_o = \left(v_E/v_o\right)\left(F_E/F_a\right) = 0.27\left(v_E/v_o\right)$$

so that the mass to be deflected may be neglected compared to ρK_z. For
larger mass-flow coefficients, however, a modification of the moment is
to be expected. It is true that even for v_E/v_o up to 1 no significant
deviation from the given values could be established. These larger mass-
flow coefficients are of less interest in practice since the transverse
forces and moments, taken absolutely, become significant only in case of
larger v_o, that is, of smaller v_E/v_o.

Our simple result suggests a comparison with the instability moment
of nacelle bodies calculated by, among others, F. Vandrey in reference 6.

This report gives the moments of ellipsoids. If one selects a semi-
spheroid shown as the dashed line b in figure 7 with the same semiaxis R_a
and length l, as the investigated circular cowl, a, there results
according to reference 6, a moment[5]

$$\frac{M}{q_o \pi R_a^3} = 2.8\alpha$$

This is a smaller value than the one measured at the circular cowl;
however, a comparison of the forms makes this understandable. The
spheroid c in figure 7, which yields the same moment as the circular
cowl, fits the latter very well. Thus, there exists the possibility for
rough calculations of replacing in this manner a prescribed cowl by a
spheroid.[6] Our simple result subsequently justifies the used method of
investigating only the front part of the cowling. It furthermore opens
up the possiblity of separate treatment also for the processes at the
exit and in the jet.

IV. SYNOPSIS

     The previously published measurements made on circular cowls are
herein supplemented by detailed ones for oblique flow. With reference
to the maximum incremental velocities on the outside, a considerable
dependence on the angle of attack manifests itself which can be kept
within tolerable limits only by a sufficient rounding of the nose. The
transverse forces acting on the front part of the cowling are determined
from pressure-distribution measurements on a circular cowl characteristic
for the general case and result, for small mass flow, as almost independ-
ent of the mass-flow coefficient and increasing linearly with the angle
of attack if the flow does not separate. For the circular cowl investi-
gated, a flow free from separation may still be realized for zero mass
flow up to an angle of attack of the oblique flow of about 10°. Since
the aerodynamic center of the transverse forces is, furthermore, almost
independent of the angle of attack and the mass flow, a linear relation
between the air-force moment about an arbitrary point of reference and
the angle of attack results. A simple rule of thumb for the magnitude
of this moment may be given by replacing the circular cowl by a suitable
semiellipsoid.

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     [5]Since, of the ellipsoid as well, only the front part is considered,
the moments indicated in reference 6 are to be divided by 2.
     [6]Measured air force moments of other body forms may be found in
reference 3.

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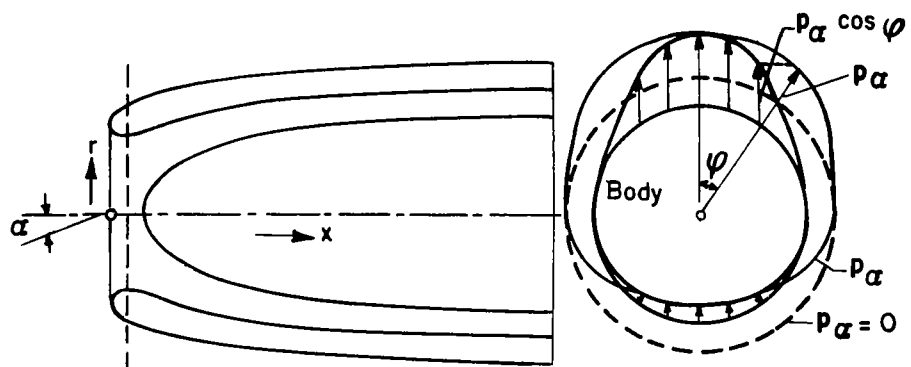   eines Flugzeugs. Jahrb. 1940 d.dtsch. Luftfahrtforschg. I 367.

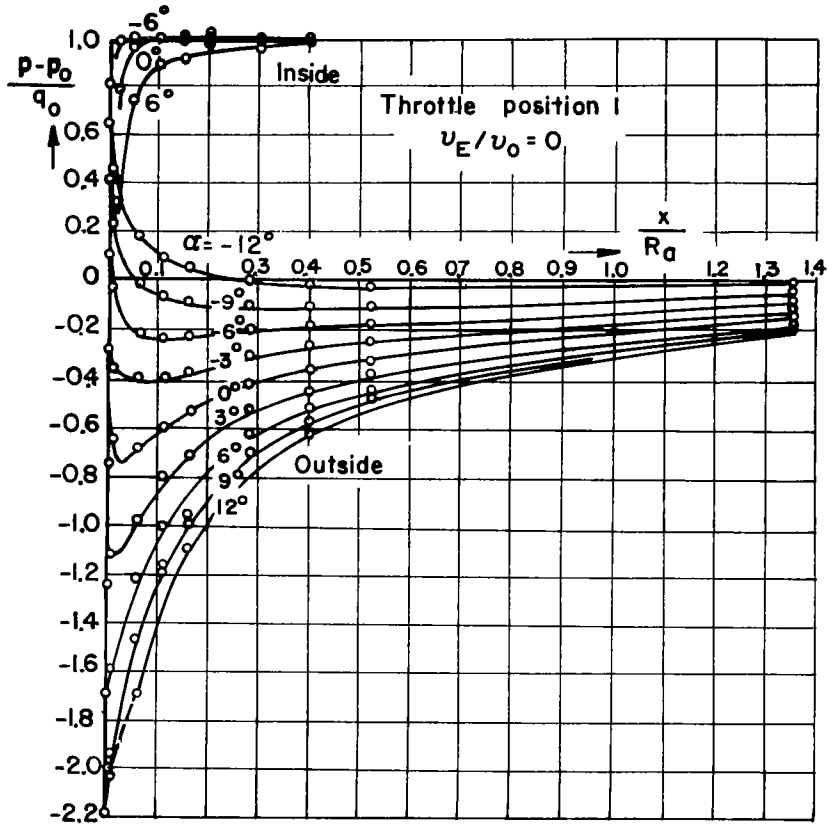Figure 1.- Over-all sketches of the model and the occurring forces.

Figure 2.- Wall pressure distributions on the arrangement 121 of reference 1 for different angles of attack α in the extreme meridian section.
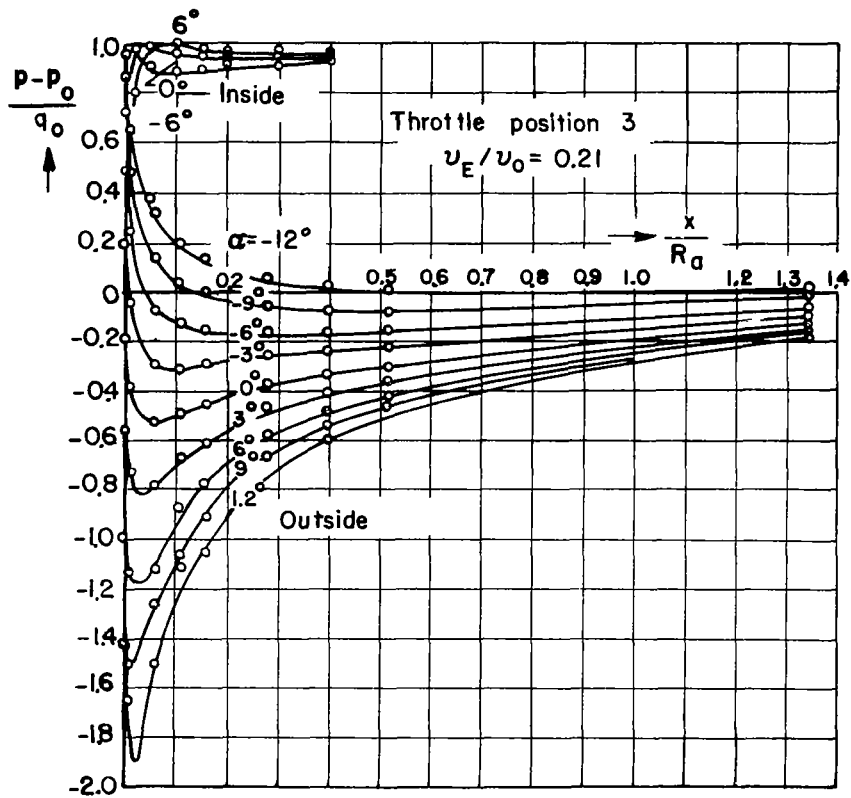
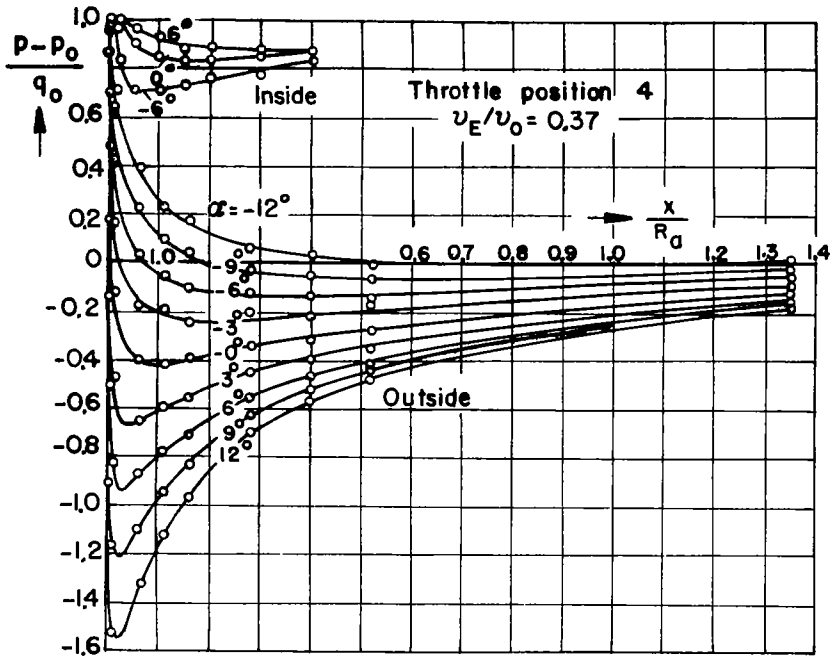Figure 3.- Wall pressure distributions.
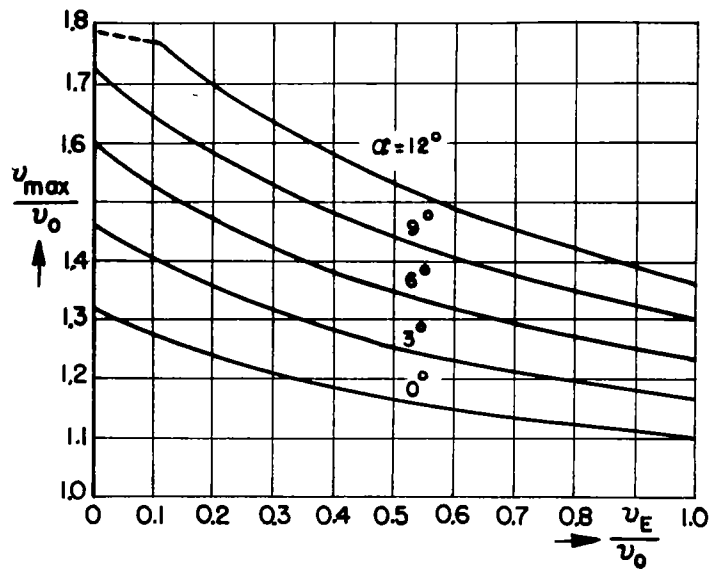
Figure 4.- Wall pressure distributions.

Figure 5.- The incremental velocities to be expected for various mass-flow coefficients on the outside of a circular cowl with $F_E/F_a = 0.27$ as functions of the oblique angle of attack α.
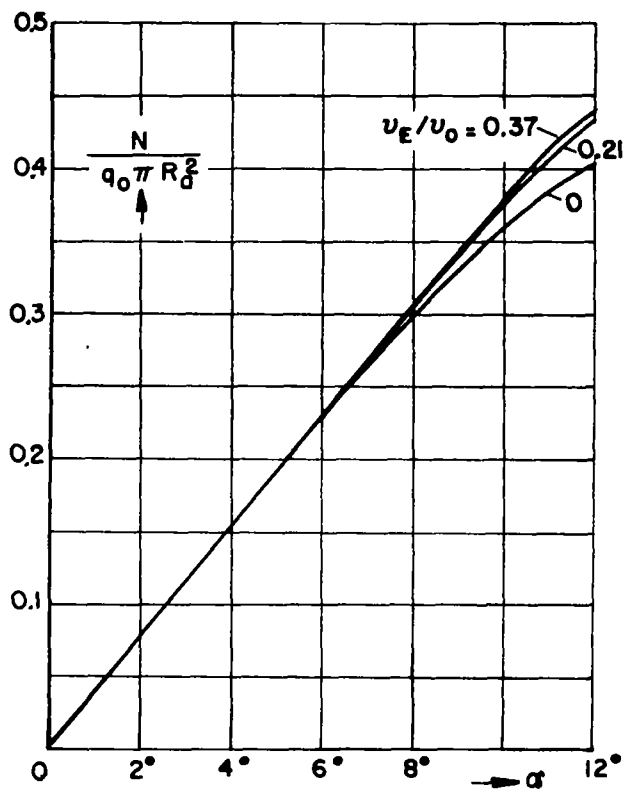
Figure 6.- Coefficient of the transverse force perpendicular to the axis of rotation acting on the noncylindrical part of the cowl of the length $l = 3R_a$ as a function of the angle of attack and the mass-flow coefficient.
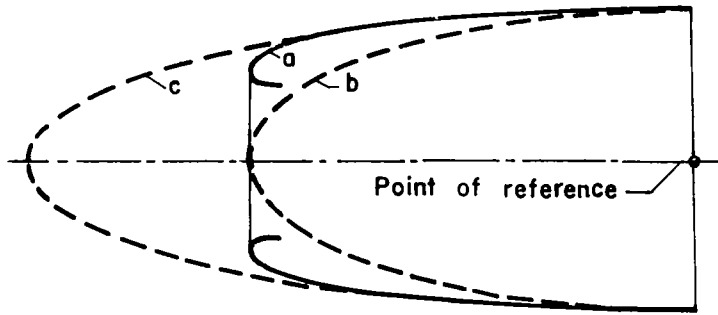
Figure 7.- Concerning replacement of the circular cowl by semiellipsoids.