NATIONAL ADVISORY COMMITTEE FOR AERONAUTICS

TECHNICAL MEMORANDUM 1325

CONCERNING THE FLOW ABOUT RING-SHAPED COWLINGS OF FINITE THICKNESS

PART I

By Dietrich Küchemann

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PART I

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ABSTRACT:

It is shown how one may obtain, in a simple manner, the forms of ring-shaped bodies from existing tables of functions according to the customary method of superposition of flow due to singularities and parallel flow. A number of examples of the forms and pressure distributions of annular source bodies with and without hub body are given, and the inlet conditions of such ring-shaped cowlings are investigated. Furthermore, the annular bodies of finite length are indicated that correspond to Joukowsky profiles for the two-dimensional case. The examples are to give a basis for the design of cross-sectional forms of ring-shaped cowlings and a survey of the flows to be expected.

OUTLINE:

*"Über die Strömung an ringförmigen Verkleidungen endlicher Dicke." Zentrale für wissenschaftliches Berichtswesen über Luftfahrtforschung (ZWB), Berlin-Adlershof, Forschungsbericht Nr. 1236, Göttingen, June 13, 1940.

I. GENERALITIES CONCERNING RING-SHAPED COWLINGS AND PURPOSE OF THE REPORT

In techniques, annular bodies or ring-shaped cowlings are used mainly for two different purposes: In the cooling problem (cowlings of radial engines, nozzle radiators) and in the shrouding of propellers (Kort nozzle, axial blower). In both cases the cowling serves for regulating the flow and its velocity at the location of the cooling block or of the propeller, respectively, although in a different manner. One speaks in this connection mostly of cowled radiators and shrouded propellers, and links with this designation the following conception:

For the cooling problem, it appears useful to cool at minimum flow velocities; therefore, a diffuser is placed ahead of the cooling block and the through flow is regulated by an adjoining nozzle of variable opening. For the propeller, on the other hand, it is desired that the greatest possible mass of fluid be reached and accelerated, and that the propeller operate in a region of increased velocity. Thus the nozzle is arranged ahead of the propeller and the diffuser behind it. The theoretical calculations of the flow conditions are therefore so far based almost entirely on the conception of nozzle and diffuser.

Recently, in the reports of Horn (reference 1) and Dickmann (reference 2), another interpretation of the physical phenomena, particularly for ship propellers, is adopted and investigated. The cowling is regarded as a ring-shaped wing. For propellers, the shrouding is selected in such a manner that a (negative) circulation is produced which increases the velocity in the interior of the ring. This interpretation has already led to successes in the calculation of the Kort nozzle, and it may be surmised that a similar approach may be used for the cooling problem. Especially the question of regulating the mass flow thereby assumes new aspects. The ring-shaped wing has, compared to the ordinary wing, the advantage that a "two-dimensional" wing theory is sufficient since no tip vortices are present, due to the rotational symmetry. Thus it is necessary to extend the two-dimensional profile theory, which replaces the wing section by source, sink, and vortex arrangements, to include a ring-shaped wing; however, it becomes evident that difficulties arise in calculating the velocities induced by source and vortex rings; these velocities are no longer simple functions of the distance, but are composed of elliptic integrals in a complicated manner. Dickmann's theory represents an approximation in which the elliptic integrals are developed into exponential series, an approximation valid only for rings, the diameters of which are large in proportion to the length. In calculating rings of greater length, one must use numerical treatment. The numerical treatment is facilitated by setting up tables of functions for the velocity components of source and vortex rings (reference 3).

Comparisons with tests in shrouded ship propellers showed, moreover, that Dickmann's theory of the ring-shaped wing (in which the profile thickness, too, was neglected) cannot come fully into play if the flow conditions at the cowling, which, in many cases, lead to separation, are not completely under control. Thus consideration of the finite thickness of the cowling also seems necessary. Naturally, this influence of the finite thickness is of like importance in the fairing of radiators. In addition, any large incremental velocities at the cowling for high flight velocities must be avoided here.

The present report is intended as a first step in the direction of determining the influence of the finite thickness of annular bodies. We shall, at first, consider the annular body alone and disregard the propeller or the cooling block itself. In a few cases, the influences of a hub body will be investigated. First of all, we shall find out how the forms of the semibody (single source) and of the Joukowsky profile (source-sink distribution), known from two-dimensional flow, appear in the rotationally symmetrical case where the singularities are distributed on circles. Pressure distributions will then give us information on the flow conditions to be expected for inflow into ring-shaped cowlings. We are not treating the problem of finding for a prescribed cowling the substitute singularity and hence the flow, but the opposite and simpler one of determining the form for prescribed singularities.

II. METHOD AND RESULTS

1. The Method

We use the method of superposition. Since we want to treat flows free from circulation only, we select as singularities distributions of source and sink rings, and superimpose a parallel flow. We execute the calculation numerically, and take the stream function and the velocity components of the source rings from the tables mentioned above (reference 3). Reference 3 also contains the formulas for the velocity components and the stream function of vortex rings.

In the composite flow, we look for the streamline which gives the body contour. This streamline is characterized by the stagnation point lying on it. The thickness of the originating body is linked with the source strength E in the following manner:

We consider first an annular source body produced by a single source ring in a parallel flow. Designating the cross-sectional area at infinity by F and the velocity of the undisturbed parallel flow by U, we have, according to the continuity equation

$$E = FU \tag{1}$$

From reasons of symmetry F is annular

$$F = \pi\left(r_2^2 - r_1^2\right) = 2\pi \frac{r_1 + r_2}{2}\left(r_2 - r_1\right) = 2\pi Rd$$

with r_1 designating the inner radius, r_2 the outer radius, R the mean radius, and d the thickness. Thus we obtain

$$E = 2\pi RUd \tag{2}$$

The pressure distribution is obtained, as customary, by means of Bernoulli's equation from the velocity distribution at the body surface.

In order to obtain a hub body, we superimpose on this flow that of a single source on the symmetry axis. Let the latter have the strength E_o. The thickness d_o of the originating hub body is linked with E_o and U by the relation

$$E_o = \frac{\pi d_o^2}{4} U \tag{3}$$

Thus we may write in this case the equation (2)

$$E = 8 \frac{Rd}{d_o^2} E_o \tag{2a}$$

For a given value of Rd/d_o^2 the ratio of the two source strengths is fixed. If, in addition, we express d_o as a function of the radius r' of the source ring, for a given value of d_o/r' the quantity Rd/r'^2 characterizes the ratio of the source strengths.

In a further series of examples, we place a distribution of source and sink rings on a coaxial circular cylinder (stream surface of the parallel flow). We then obtain, if the combined strength of all source and sink rings is zero, a closed profile, a streamline, which is in a flow without circulation ($c_a = 0$). We select the intensity of the distribution in the form

$$E = E'\sqrt{\frac{1 - x/r'}{1 + x/r'}}\left(1 + 2\frac{x}{r'}\right) \tag{4}$$

(x = coordinate in the direction of the symmetry axis, r' radius of the source and sink rings). For the corresponding two-dimensional problem, we obtain a Joukowsky profile[1] from this source sink distribution. The method of determining the contour corresponds in every detail to that used for the single source ring except for the fact that one now must integrate over the entire distribution.

2. A Ring of Singularities in a Parallel Flow

As a preliminary remark to this section, we want to show as an example the appearance, in the rotationally symmetrical case, of a flow about a circular cylinder, obtained (as is well known) by superposition of a parallel flow on a plane dipole. The result is shown in figure 1 which originated by superposition of a dipole ring and a parallel flow. One sees clearly the deviation from the two-dimensional analogue, also from that of a flow about a sphere in the proximity of a wall[2]. It is particularly striking that the two stagnation points no longer lie diametrically opposite each other.

The following figures show the conditions for a flow about a source ring. Figure 2 gives the contours of annular source bodies of various thicknesses. The straight line $d/r' = 0$ is the streamline of the parallel flow which passes through the location of the source ring ($r = r'$). The contours of the bodies of a thickness different from zero do not lie symmetrical to this straight line, and again the stagnation points do not lie directly ahead of the source ring. Since for all x-values the same mass flow, which at infinity has the velocity U of the undisturbed parallel flow, must flow through between this stagnation point streamline and the axis, this streamline (the interior of the body) rises, for large positive x-values, behind the narrowest place of the cross section again to the same distance from the axis it has had infinitely far ahead of the body. The mean radius R of the annular body, that is, the arithmetic mean of outer and inner radius at infinity is therefore larger than r'. In figure 3 the ratio R/r' is plotted against the thickness. From this state of affairs it follows that the "mean camber line" of the body is not a coaxial straight line, but a line pulled inward toward the leading edge. In practice, where smooth entrance flow is desired, one always uses this "lip" for ring-shaped cowlings even though conditions there may be slightly different, for instance, due to the presence of the cooling block. For the body shapes indicated, the pressure distribution on the outside is given in figure 4, that on the inside in figure 5. A negative-pressure region with slight

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[1]Compare F. Keune (reference 4).

[2]Compare Prandtl-Tietjens, Hydro-and Aeromechanics, Vol. 2, page 125.

pressure increase results on both sides shortly behind the stagnation point so that for such body shapes probably no separation phenomena will occur. Figure 6 shows how contour and pressure distribution of the annular source body differ from that of the two-dimensional semibody. It is noteworthy that the pressure distribution on the outside is hardly different from that of the two-dimensional semibody whereas on the inside, for understandable reasons, a greater negative pressure prevails.

3. Annular Source Body with Hub

The following examples show the body shapes resulting if, aside from a source ring in a parallel flow, in addition, a three-dimensional single source is assumed on the symmetry axis. We then obtain a ring-shaped cowling with a hub. The most essential result of these calculations is the fact that noteworthy differences appear according to whether the hub is inside or outside of the ring. Figure 7 shows in the heavily drawn lines the streamline pattern about the hub body alone, the well known three-dimensional semibody flow. If we put into this flow a source ring so that its x-coordinate is equal to or larger than that of the single source, there results the annular body cross-hatched throughout. The third streamline from the axis, in the undisturbed flow, forms its contour (fig. 7). This stagnation-point streamline of the composite flow is plotted as a dashed line. Far ahead of, and far behind the annular source body, it approaches the previous undisturbed streamline. If one now places a source ring of the same strength at a certain distance ahead of the single source in such a manner that again the same streamline of the undisturbed flow becomes the body contour, an annular body results which, it is true, at infinity has the same thickness and the same distance from the axis as the previous one, but an entirely differently formed front part. The form of this body is plotted in figure 7 partly cross-hatched and shows at the entrance a thickening caused by the stagnation due to the hub body, in contrast to the annular body behind the hub, the form of which does not differ essentially from the afore-treated annular bodies without hub. What additional conclusions may be drawn from this state of affairs will be seen later. The annular bodies with outward protruding hub will now be investigated somewhat more closely. Such bodies of various thicknesses are plotted in figure 8. The thickness d_o of the hub is kept constant at $1.38\ r'$, and the x-coordinate of source-ring and single source is equated. The rearward widening which occured before may again be observed; the form of the hub body also is slightly changed with increasing thickness of the cowling. The pressure distribution over the outside of the body (fig. 9) does not essentially differ from that of the source-ring body without hub, even though the pressure increase behind the minimum is somewhat reduced due to the hub, so that the flow conditions on the outside appear slightly more favorable with respect to separation in the presence than in the absence of a hub. In contrast, true to expectation, on the inside (fig. 10) a considerably higher negative pressure results than without hub; however, these conditions improve greatly if the cowling is extended beyond the hub. Figure 11 shows again, more accurately, the resulting body shapes for the special position of the ring $r' = d_o/2$; $x' = -d_o/2$,[3] figures 12 and 13 show the pressure distributions over the outside and inside of the body surface. It is a particularly striking fact about these pressure distributions that the suction peaks are almost entirely eliminated, due to the incremental excess pressure ahead of the hub body. For the body of the thickness $d/r' = 0.5$, one no longer has any suction peak at all. When this case will arise depends, of course, on the special position of the source ring with respect to the single source; for other positions, it could be attained for lesser thicknesses of the cowling. Thus, one may assume that for cowlings of this type, an inflow particularly free from losses is insured.

The pressure distributions on the hub body itself are represented in figure 14 for both cases. It can be seen that on the hub body, too, the effect is more favorable when the cowling is extended beyond the hub.

All these results apply, at first, only to the special case where no circulation develops about the cowling; however, they will permit a survey of the conditions to be expected in the presence of a circulation as well, since the flow which is free from circulation may always be regarded as the initial state. Thus these results may offer a basis for the construction of ring-shaped cowlings.

4. Ring-Shaped Cowlings of Finite Length

Whereas only ring-shaped bodies extending to infinity have been treated so far, one may cause the body contour to close again by a distribution of source and sink rings on a coaxial circular cylinder in a parallel flow. We choose the distribution given by reference 4 which results, for the two-dimensional case, in the Joukowsky profile drawn in dashed lines in figure 15. The corresponding annular body (drawn solidly in fig. 15), however, has a quite different cross section. In the region of the sources, the mean camber line rises; in the region of the sinks, it drops off again. Thus the profile obtains a camber with the maximum rise at about 1/4 of the length counted from the leading edge. Profile forms of various thicknesses are plotted in figure 16. All of them show the characteristic criterion of these annular-body profiles. The camber increases with the thickness of the profile.

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[3]By x' one designates the distance of the source ring from the single source in x-direction.

This result becomes significant if one wants to obtain a circulation by means of the cowling. If one wants to produce the circulation by giving the profile a camber, one must not (for $c_a = 0$) start from the symmetrical section but from a section cambered in the indicated manner. Thus, the profiles for producing a positive circulation (reduction of the velocity in the interior of the cowling) must have a large positive camber whereas negative circulations are obtained with uncambered profiles. From these results there follows a new two-dimensional interpretation for the well-known phenomena on annular-shaped cowlings so far explained by a one-dimensional nozzle theory.

III. SUMMARY

The present report represents a first step in recognizing the influence of the finite thickness on the flow about annular-shaped cowlings. It is shown how one may obtain in a simple manner the forms of ring-shaped bodies from existing tables of functions according to the customary method of superposition of flow due to singularities and parallel flow. Knowledge of these forms is important for evaluating the entrance phenomena into ring-shaped cowlings, particularly for the fairings of radial engines, for ring-shaped radiators and shrouded ship's propellers. A series of examples show the cross sections of such annular source bodies as well as their pressure distributions without and with the presence of a hub body. It is shown that, among the forms investigated, the entrance of cowlings slightly thickened at the leading edge with a hub body within is particularly favorable and free from dangerous separation. Furthermore, the profiles of annular bodies of finite length are given to which Joukowsky profiles correspond for the two-dimensional case. These profiles show a camber dependent on the thickness, with the maximum rise at about 1/4 of the length counted from the leading edge. All calculations have been performed with the assumption that the flow about the body is free from circulation; however, they may serve as a guide for the flow conditions to be expected also in case of the existence of a circulation or of disturbance bodies (cooling block, propeller).

Translated by Mary L. Mahler
National Advisory Committee
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3. Küchemann, D.: Tafeln für die Stromfunktion und die Geschwindigkeitskomponenten von Quellring und Wirbelring. Jahrbuch 1940 der deutschen Luftfahrtforschung, p. I 547.

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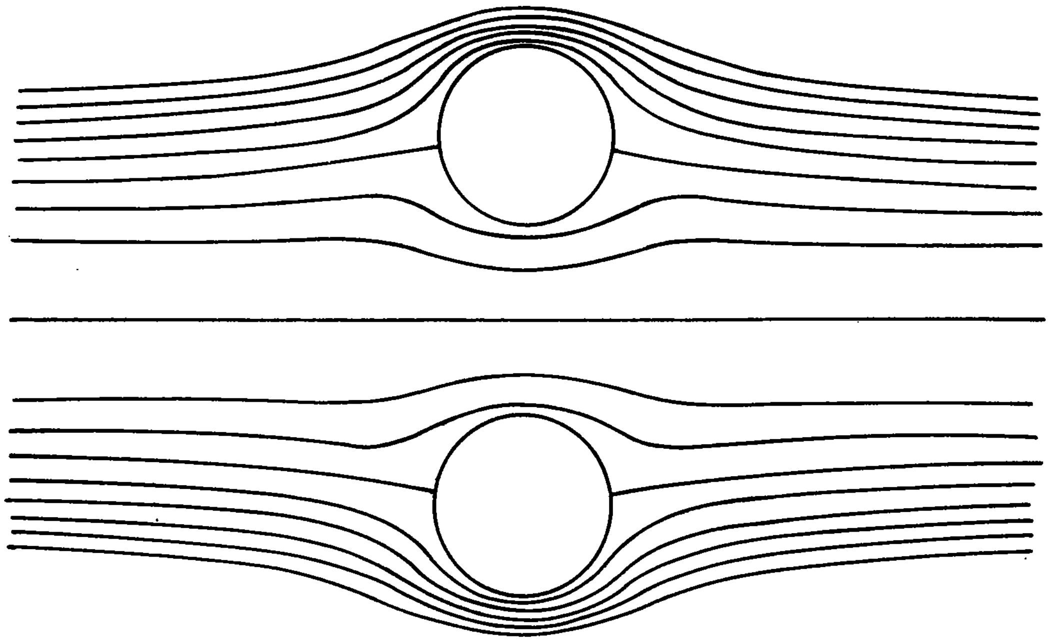

Figure 1.- Streamline pattern about a torus (dipole ring in parallel flow).

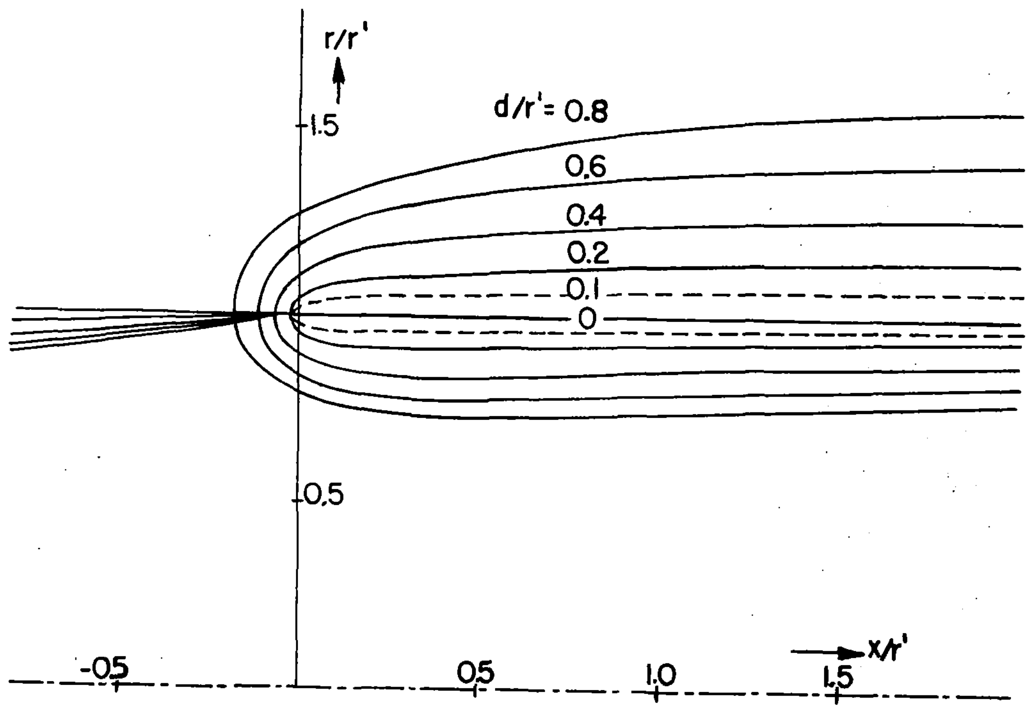

Figure 2.- Annular source bodies of various thicknesses.

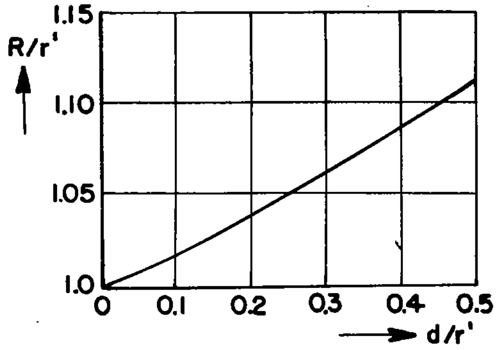

Figure 3.- The mean radius at infinity of annular source bodies as a function of the thickness of the body.

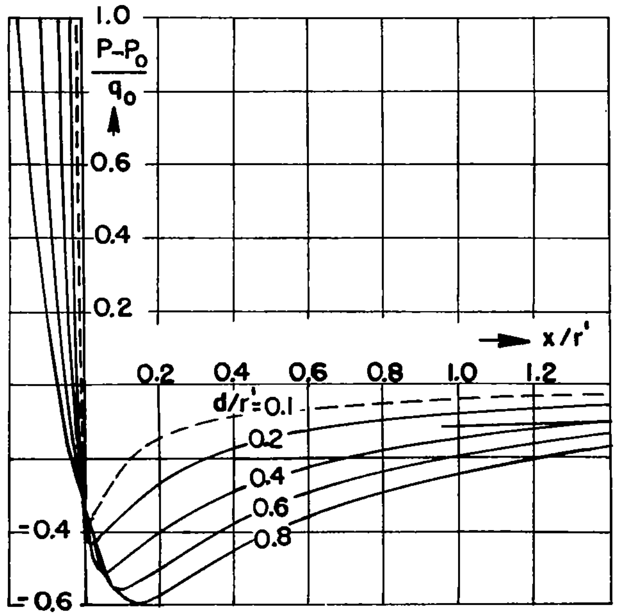

Figure 4.- Pressure distribution over the exterior of annular source bodies of various thicknesses.

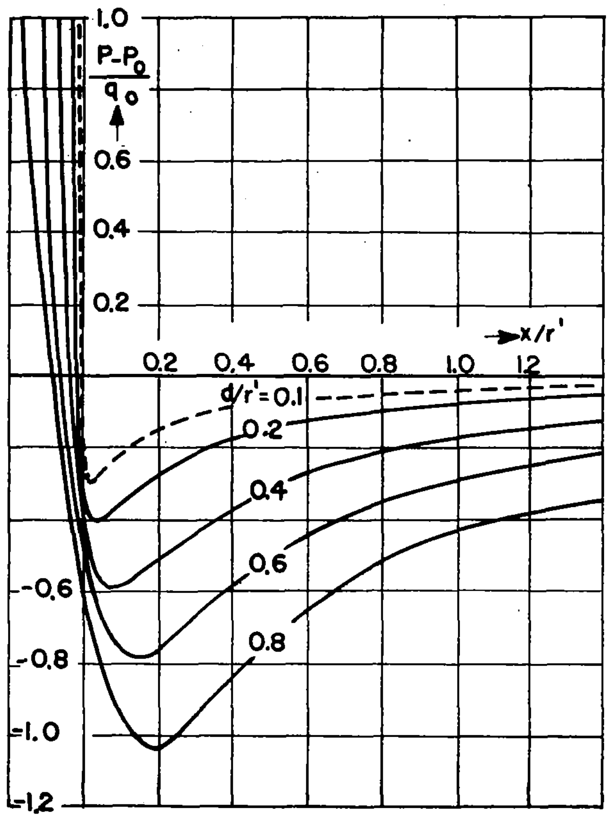

Figure 5.- Pressure distribution over the interior of annular source bodies of various thicknesses.

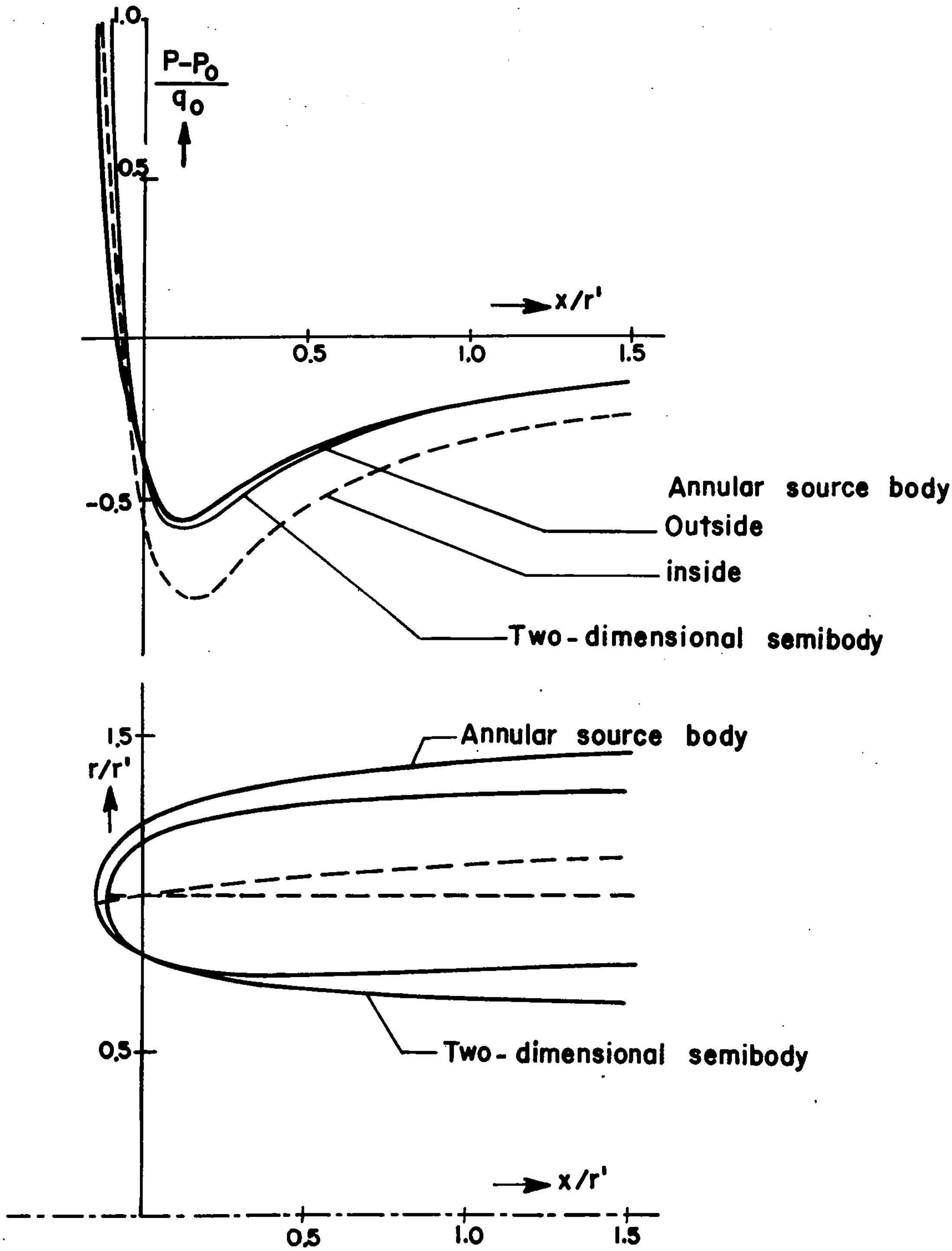

Figure 6.- Comparison between form and pressure distribution of the two-dimensional semibody and the annular source body.

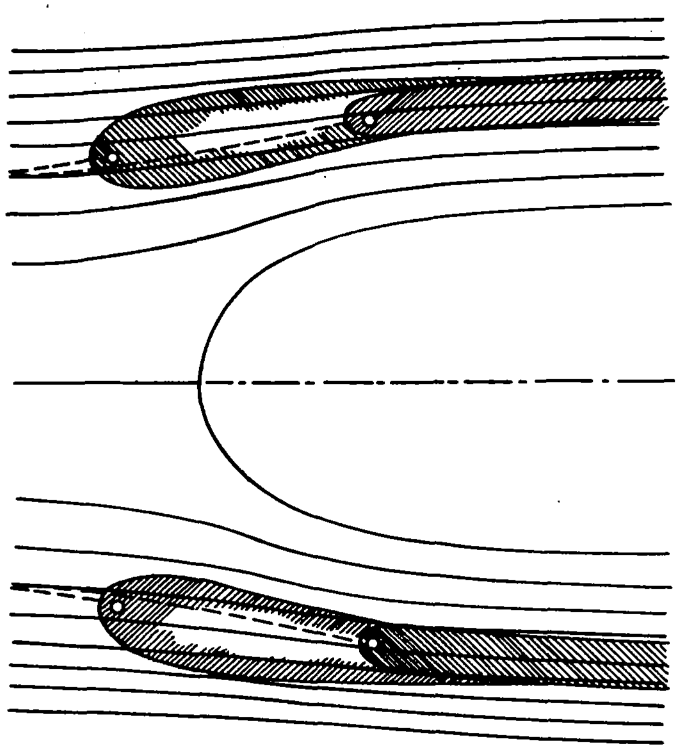

Figure 7.- Heavily drawn, streamline pattern about a three-dimensional semibody (hub body); fully cross-hatched, annular source body behind the hub; partly cross-hatched, annular source body ahead of the hub.

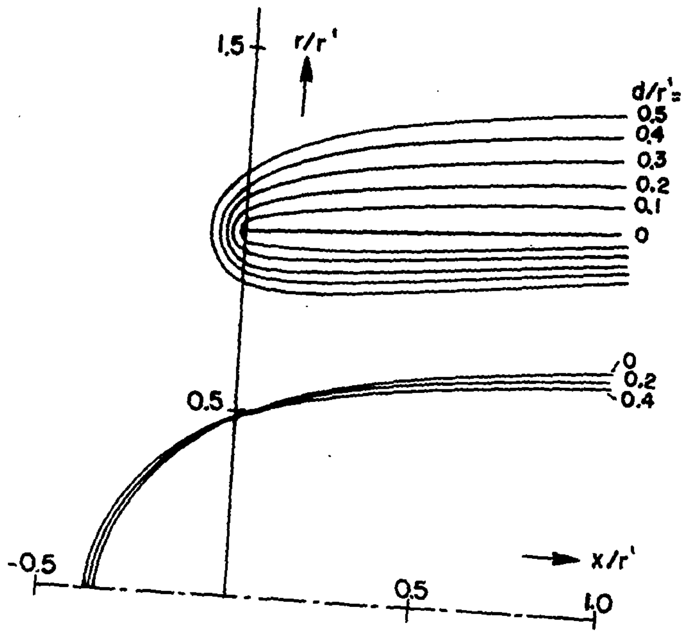

Figure 8.- Annular source bodies of various thicknesses with hub outside.

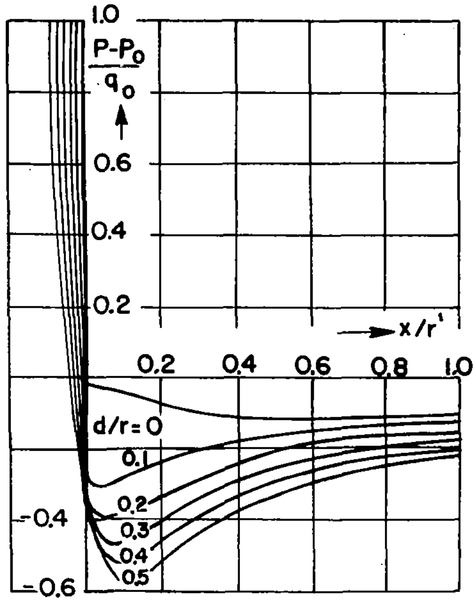

Figure 9.- Pressure distribution over the outside of the bodies represented in figure 8.

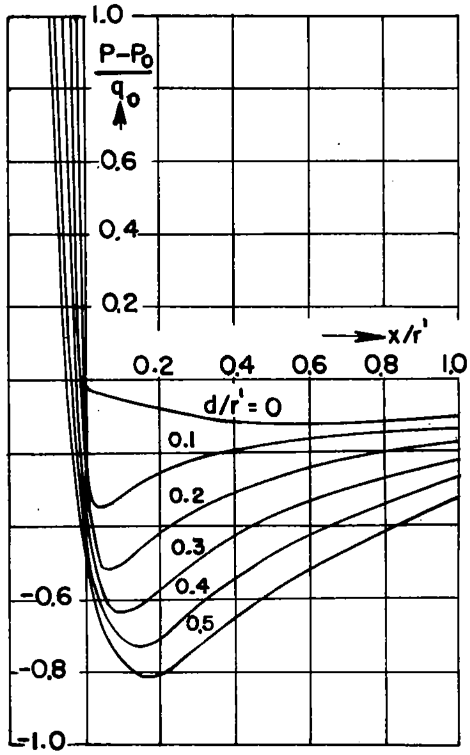

Figure 10.- Pressure distribution over the inside of the bodies represented in figure 8.

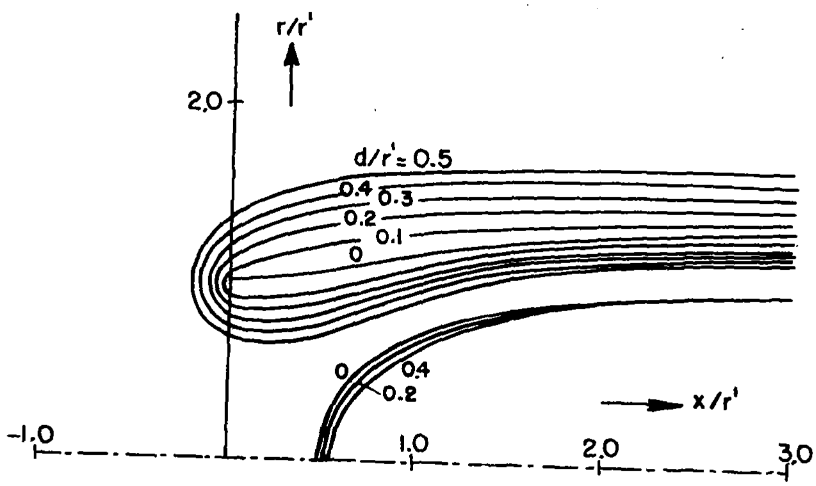

Figure 11.- Annular source bodies of various thicknesses with hub inside.

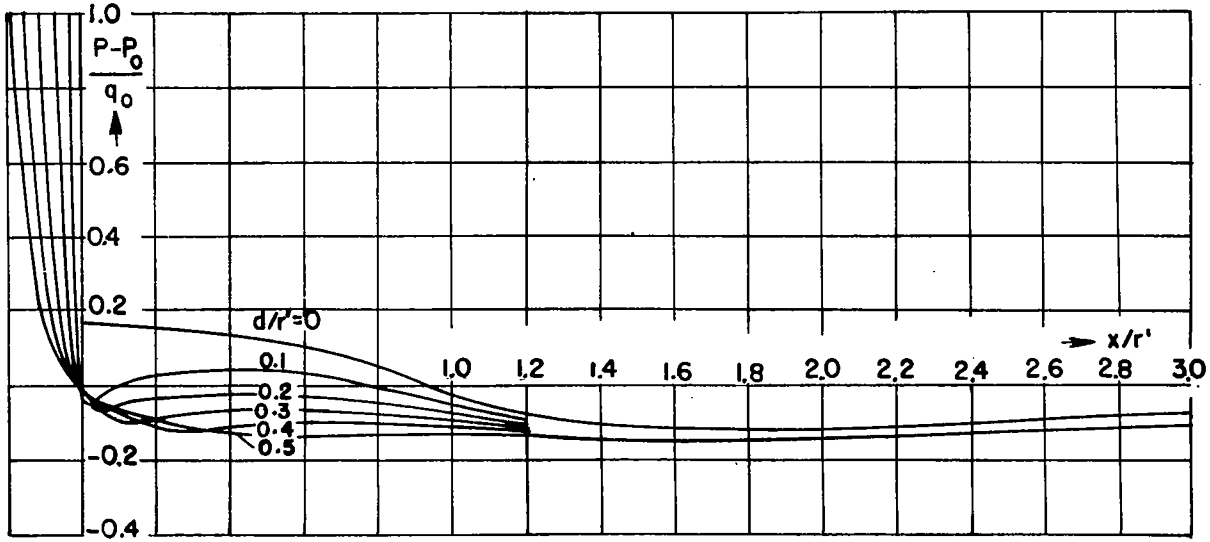

Figure 12.- Pressure distribution over the outside of the bodies represented in figure 11.

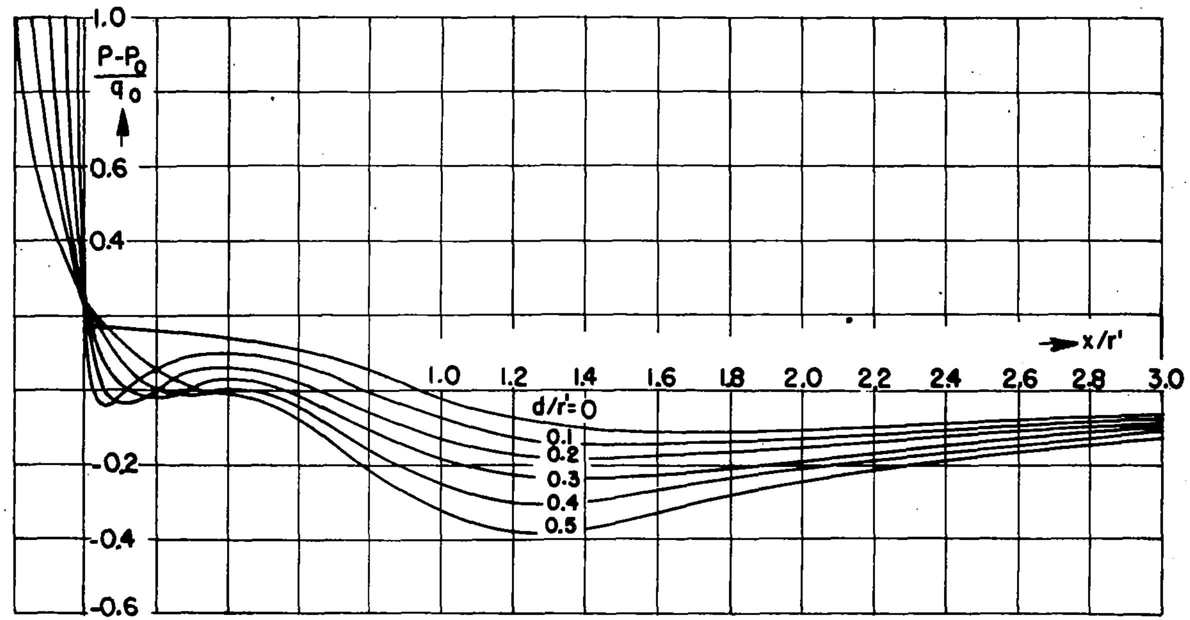

Figure 13.- Pressure distribution over the inside of the bodies represented in figure 11.

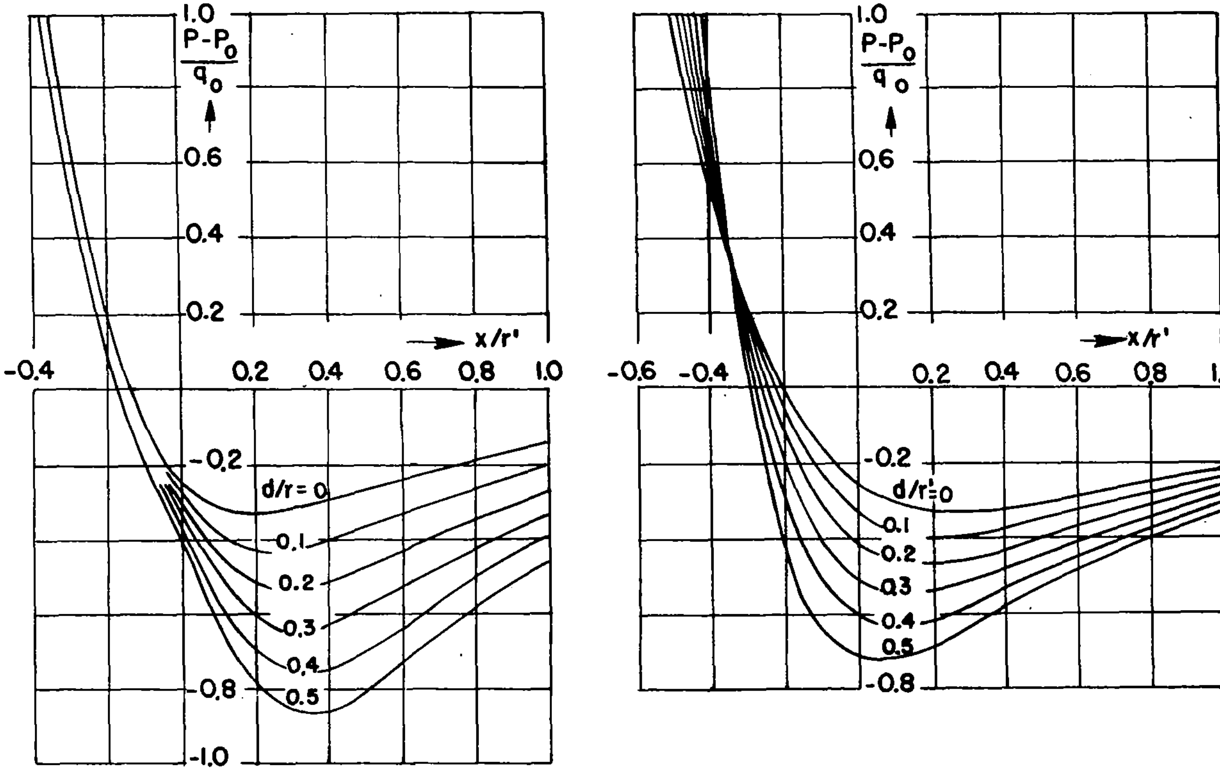

Figure 14.- Left: Pressure distribution over the hub bodies represented in figure 8.

Right: Pressure distribution over the hub bodies represented in figure 11.

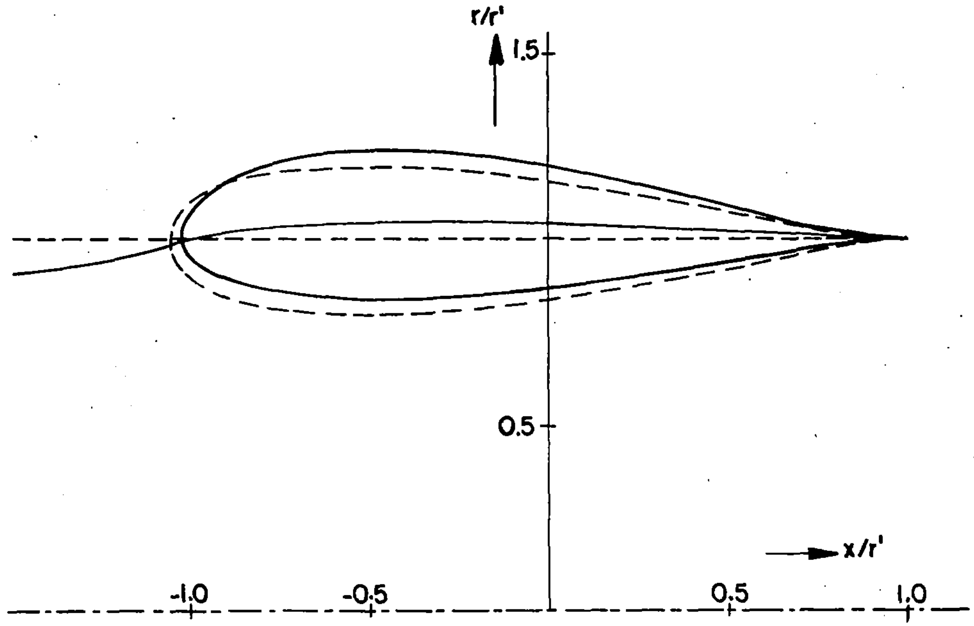

Figure 15.- Comparison between an annular-body profile (drawn solidly) and a Joukowsky profile (dashed) of equal thickness.

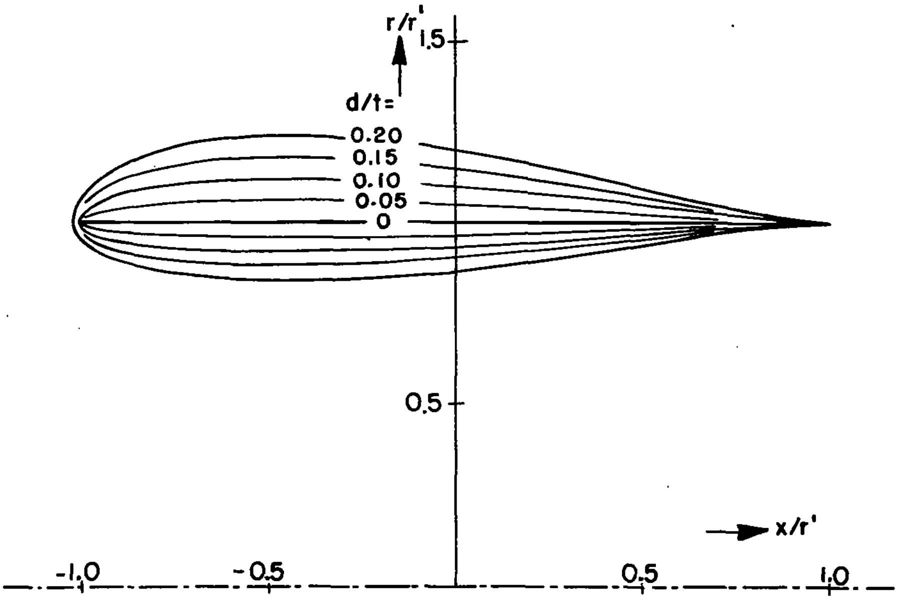

Figure 16.- Annular-body profiles of various thicknesses.

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