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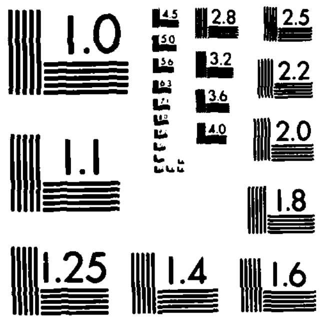

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SPLASHLESS BOW FLOWS IN TWO DIMENSIONS

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E. O. Tuck* and J.-M. Vanden-Broeck**

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ABSTRACT

In two-dimensional bow-like flows past a semi-infinite body, one must in general expect a free-surface discontinuity, in the form of a splash or spray jet. Similarly, if one reverses the flow direction, so generating a stern-like flow, one must expect a train of waves at infinity. ~~For example,~~ we have shown in previous work that there is no stern-like flow without waves for a flat-bottomed body with a single corner. However, this is not necessarily the case for polygonal bodies with two or more corners, or for smooth bodies. The question of the existence of smooth, continuous solutions, having neither splashes nor waves is considered in this paper. Conclusive numerical evidence is given of the existence of such solutions.

AMS (MOS) Subject Classifications: 76B20

Key Words: Ship waves, bow flow

Work Unit Number 2 (Physical Mathematics)

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SIGNIFICANCE AND EXPLANATION

The flow at the extreme bow of a ship is examined within the framework of the two-dimensional potential flow theory. For most bow shapes one must in general expect a free-surface discontinuity, in the form of a splash or spray jet. Reduction and if possible elimination of this splash is one of the important problems of modern ship hydrodynamics.

In this paper it is shown numerically that there eixsts particular bow shapes for which splashless flow exists. The bow shapes for which this elimination of the splash is possible are bulbous. This theoretical result agrees with the experiments of Baba (1976) and Miyata (1980) who found that a bulbous bow can reduce the splash at the extreme bow of a ship.

This work has potential applications to the design of ship bows.

The responsibility for the wording and views expressed in this descriptive summary lies with MRC, and not with the authors of this report.

SPLASHLESS BOW FLOWS IN TWO DIMENSIONS

E. O. Tuck* and J.-M. Vanden-Broeck**

1. INTRODUCTION

The experimental work of Baba (1976) and Miyata (1980) indicate that a bulbous bow can eliminate or at least reduce the splash at the extreme bow of a ship.

In the present paper we examine the flow at the bow of a ship within the framework of the steady two-dimensional potential flow theory. This problem was considered before by Vanden-Broeck and Tuck (1977), and Vanden-Broeck, Schwartz and Tuck (1978). These authors attempted to construct models for near stern flows and near bow flows. Although their scheme worked very well for stern flows, they did not succeed in finding continuous solutions without waves. On the other hand their work suggested the existence of waveless solutions with splashes.

It should be emphasized that elimination of waves from a stern flow is equivalent to elimination of splashes from a bow flow. That is if we have been able in one way or another to construct a waveless stern flow, there is no radiation condition for that flow, which can be reversed in direction to yield a splashless bow flow.

Vanden-Broeck et. al.'s analysis was restricted to bow shapes consisting of a plane lower surface and an oblique plane front. Although their work rules out splashless and waveless solutions, the possibility still exists that

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by considering different families of bow shapes one could identify a special shape for which splashless and waveless flow exists. This possibility is strongly suggested by the recent work of Schmidt (1981) and Vanden-Broeck and Tuck (1984).

One of the main results of this paper is the numerical demonstration of the existence of such shapes. The corresponding solutions model bow flows in which the splash drag component has been completely eliminated. The bow shapes for which this elimination is possible are bulbous.

In Section 2 we discuss some properties of bow flows with splashes. In Section 3 we derive a numerical scheme which enables us to compute splashless bow flows.

2. FLOWS WITH SPLASHES

What is a splash? In the present two-dimensional context, a flow meeting a body contains a splash if a portion of the incident stream is deflected upward and backward in the form of a jet, which then falls freely for ever in an approximately parabolic trajectory. Figure 1 shows a sketch of one possible flow.

Such a flow is obviously an idealization of what might occur in practice near the bow of a ship. The most glaring non-physical feature is that Figure 1 has the jet and the incident stream apparently passing across each other without interference. The mathematical artifice that allows this to happen is that these two pieces of the flow do not occupy the same space, but lie on quite distinct "Riemann sheets".

In practice, unless some action is taken to avoid it, the falling jet must actually fall upon and hence interfere with the incident stream. The avoiding action could involve diverting the jet, catching it in a bucket, etc. Whether or not such action is taken there are interesting "St. Venant's principle" type of questions to be answered; that is, does action taken or interference caused at a point relatively far removed from the main domain of interest affect the flow significantly in that domain? The answer is clearly "No", providing the jet is suffi- ciently thin, but that observation merely shifts the nature of the question to one concerning whether or not the jet is indeed thin.

One form of "diverting action" for the jet is to re-introduce the third dimension. That is, the flow near a bluff but not quite plane bow could be expected to be close to two-dimensional. However, the ballistic trajectory of the jet will not in general quite lie in planes parallel to the incident stream, and hence the interference will be interference to another (further downstream) plane of nearly two-dimensional flow. Thus, paradoxically, one might expect to be able to see flows like those sketched in Figure 1 more easily in actual three-dimensional bow flows than in artificially-constructed two-dimensional experiments.

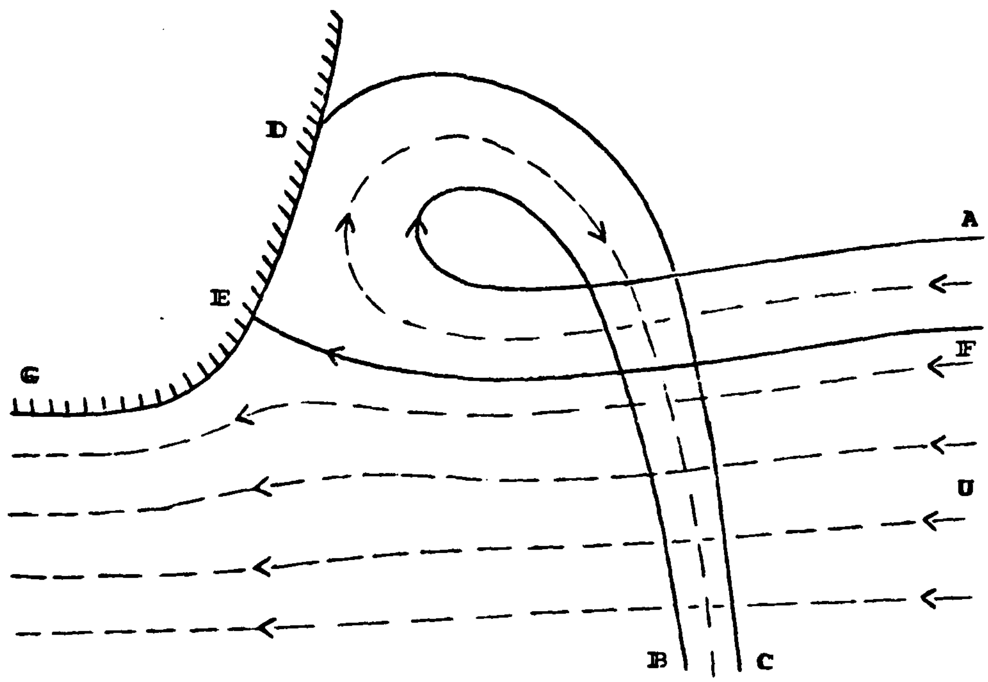

Figure 1: Sketch of a bow flow with splash.

Indeed, this does appear to be the case. Even for not-so-bluff bows, with V-shaped bows of small angle, a pronounced splash sheet often seems to be present, and furthermore appears to be thin. At first sight, one would not expect that a two dimensional flow model would have any validity for a fine three-dimensional bow flow, but there may exist a suitable set of planes such that the flow varies slowly with respect to a co-ordinate normal to these planes. This concept is being explored by one of us (E.O.T.) in on-going research.

If we return now to truly two-dimensional flow, there is no reason to believe that the jet is thin in general. There will be a submerged stagnation point **E** on the body, with an attached stagnation streamline **EF** extending to **E** from a point **F** at upstream infinity beneath the free surface. All streamlines originating from above **F** will be diverted into the jet, while all below **F** will pass under the body. In the most general case, we must expect that **F** lies at a distance below the free surface that is comparable with the draft of the body, and hence the jet's thickness is likewise of the order of the draft.

Such a very thick jet is unlikely to be observed. So either circumstances must be such as to produce a thin jet (perhaps no jet at all!) or else the flow model of Figure 1 is not even qualitatively accurate. Indeed Hanji (1976) has demonstrated experimentally some two dimensional bow flows with a "forward wake", consisting of a closed region of high vorticity, lying above an essentially-irrotational flow field, as sketched in Figure 2. It is not implausible that such a rotating bubble is a final manifestation of a thick jet that has so thoroughly (and non-conservatively) interfered with the incident stream as to destroy irrotationality, and has converted itself into a distributed vortex.

Nevertheless, we are entitled to try to compute irrotational flows like those of Figure 1, and efforts are being made by both of the present authors to do so. In view of the above discussion, such efforts are worthwhile only if the jet that is produced is in some sense thin. One approach is to exploit existing thin-jet theories, e.g. as in Keller and Geer (1973) or Tuck (1976).

To indicate the type of mathematical considerations involved, whether or not the jet is thin, let us note that all falling jets will become thin eventually, and their asymptotic form will be a parabolic arc with a ballistic velocity distribution, i.e. with a speed of fall proportional to the square root of distance fallen, and a constant horizontal velocity. This is consistent with an asymptotic form

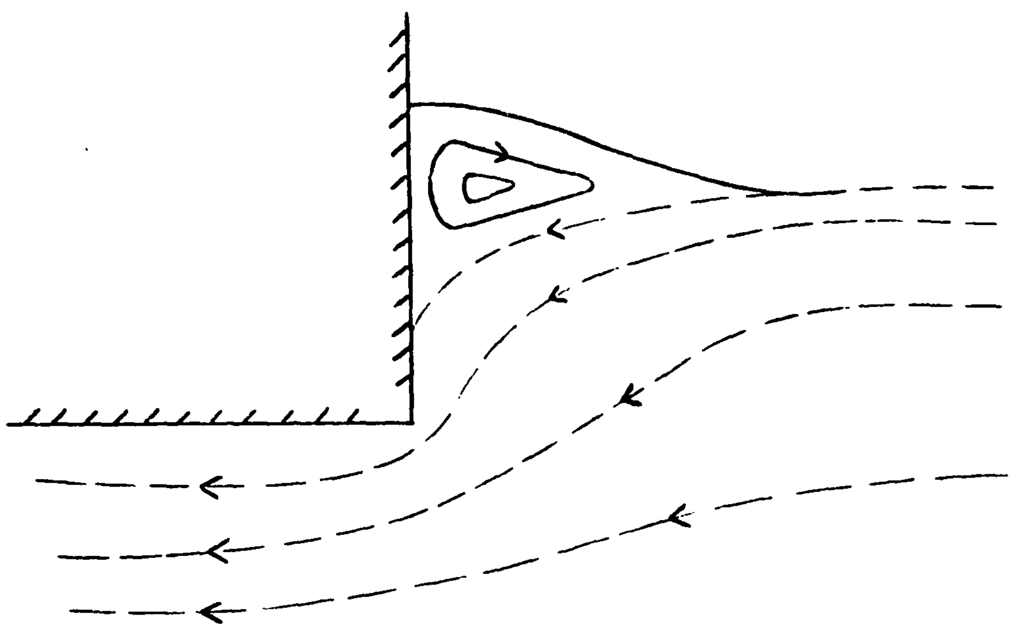

Figure 2: Sketch of a bow flow with a "forward wake".

$$z(f) = -iaf^{2/3} + bf^{1/3} + O(1), \quad \phi \to +\infty , \tag{1}$$

for the relationship between complex potential $f = \phi + i\psi$ and co-ordinate

$z = x + iy$, where a and b are real positive constants. For example, on the streamline $\psi = 0$ to leading order as $\phi \to +\infty$,

$$x = b\phi^{1/3} \tag{2}$$

and

$$y = -a\phi^{2/3} = -a(x/b)^2 . \tag{3}$$

The corresponding velocity components are

$$u = \frac{3b}{4a^2} = \text{constant} \tag{4}$$

and

$$v = -\frac{3}{2a}\phi^{1/3} = -\frac{3}{2a}(-y/a)^{1/2} , \tag{5}$$

as for a free ballistic projectile.

The pressure is given by Bernoulli's equation as

$$\frac{p}{\rho} = \frac{1}{2}U^2 - \frac{1}{2}(u^2 + v^2) - gy \tag{6}$$

$$= \left(ga - \frac{9}{8a^2}\right)\phi^{2/3} + O(1) . \tag{7}$$

Providing we choose the constant a as

$$a = \left(\frac{9}{8g}\right)^{1/3} , \tag{8}$$

the pressure remains bounded throughout the jet as $\phi \to \infty$. In fact, we require $p = 0$ on both of its free boundaries, but we can only distinguish between different finite values of ψ as $\phi \to +\infty$ by including more terms in the asymptotic representation (1). The usefulness of (1) is that any attempt to solve for a general flow of the type sketched in Figure 1 must build in an analytic character like (1) near the jet asymptote BC, with a given by (8) and b to be determined.

Although numerical solution of such problems seems somewhat distant, the following simple explicit example is of illustrative value. Suppose we concentrate attention on the portion of Figure 1 lying above the dividing streamline **EF**. Then the curve **DEF** can be replaced by a given boundary. That is, this part of the flow will look like that for a stream in water of finite non-uniform depth, in a channel that terminates with a barrier.

Suppose we normalise the stream velocity at **AF** to unity, i.e.

$$z \to -f + \text{constant, as} \quad \phi \to -\infty \; . \tag{9}$$

We also normalise the length scale so that $g = 9/8$; hence $a = 1$. Then one function satisfying both (1) and (9) is

$$z(f) \quad \frac{-if^{2/3} + f^{1/3} + 1.69i}{1 - 1.3ie^{-2f}} + \frac{-f + 0.85i}{1 + ie^{2f}} \; i \tag{10}$$

noting that the first term vanishes as $\phi \to -\infty$, and the second as $\phi \to +\infty$. The various constants in (10) were chosen by trial and error, so that the pressure would be as small as possible on the part **CD** of the streamline $\psi = 0$, and also on all of the streamline **AB** with $\psi = -0.15$, and these two streamlines are shown in Figure 3. The numbers written outside the curves are values of p, with $\rho = U = 1$ and $g = 9/8$.

Although the pressure on **AB** and **CD** is not yet low enough for us to claim that these streamlines are "free", Figure 3 at least demonstrates that the type of jet-like flow sketched in Figure 1 can be achieved mathematically, and represents a possible starting point for an accurate numerical solution. An important output from any such solution would be information concerning dependence of jet thickness upon the geometric shape of the body surface. We should be particularly interested to establish conditions in which the jet can be thin. Lacking such a numerical solution for the general problem, let us now turn to an indirect search for the very special set of circumstances when the jet is not just thin, but absent.

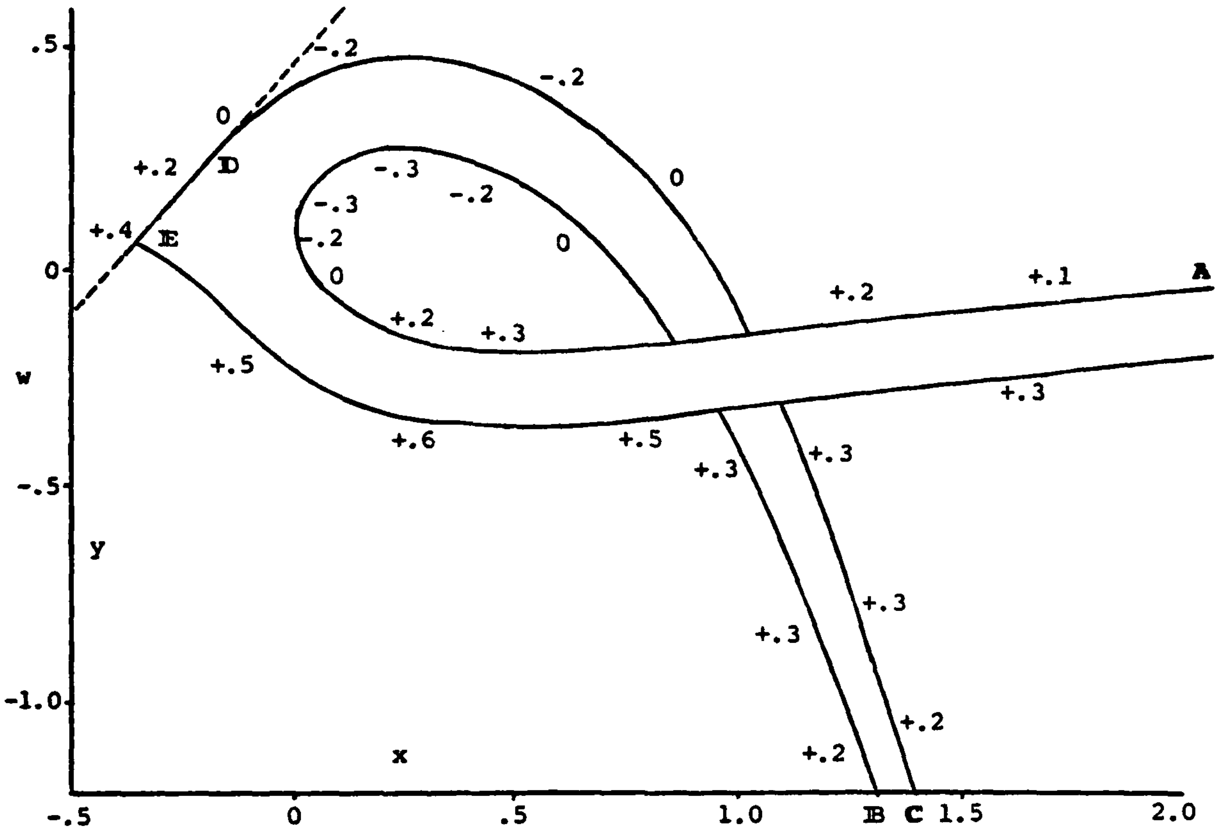

Figure 3: Computed bow flow with splash.

3. SPLASHLESS BOWS

3.1 Formulation

We consider the steady two-dimensional potential flow of an inviscid incompressible fluid past a semi-infinite body whose lower surface $y^* = -H$, $x^* < 0$ is plane (see Figure 4). As $x^* \to -\infty$, the velocity is assumed to approach a constant U. The level $y^* = 0$ corresponds to the level of the free surface at which the velocity is equal to U. We assume that the flow rises up the rear face of the body up to a stagnation point S at which separation occurs. Other flow configurations in which the flow separates tangentially from the body are also possible (Vanden-Broeck (1980)). However they will not be considered in this paper.

In previous work Vanden-Broeck and Tuck (1977) and Vanden-Broeck, Schwartz and Tuck (1978) solved numerically the problem sketched in Figure 4 with a plane oblique rear face. All their solutions contain a train of waves on the free surface. Therefore they can not serve as models for bow flows.

In this paper we generalize Vanden-Broeck et al's approach for bodies of arbitrary shape. For most shapes, waves are present on the free surface. However we shall see that there exists particular shapes for which the waves are absent.

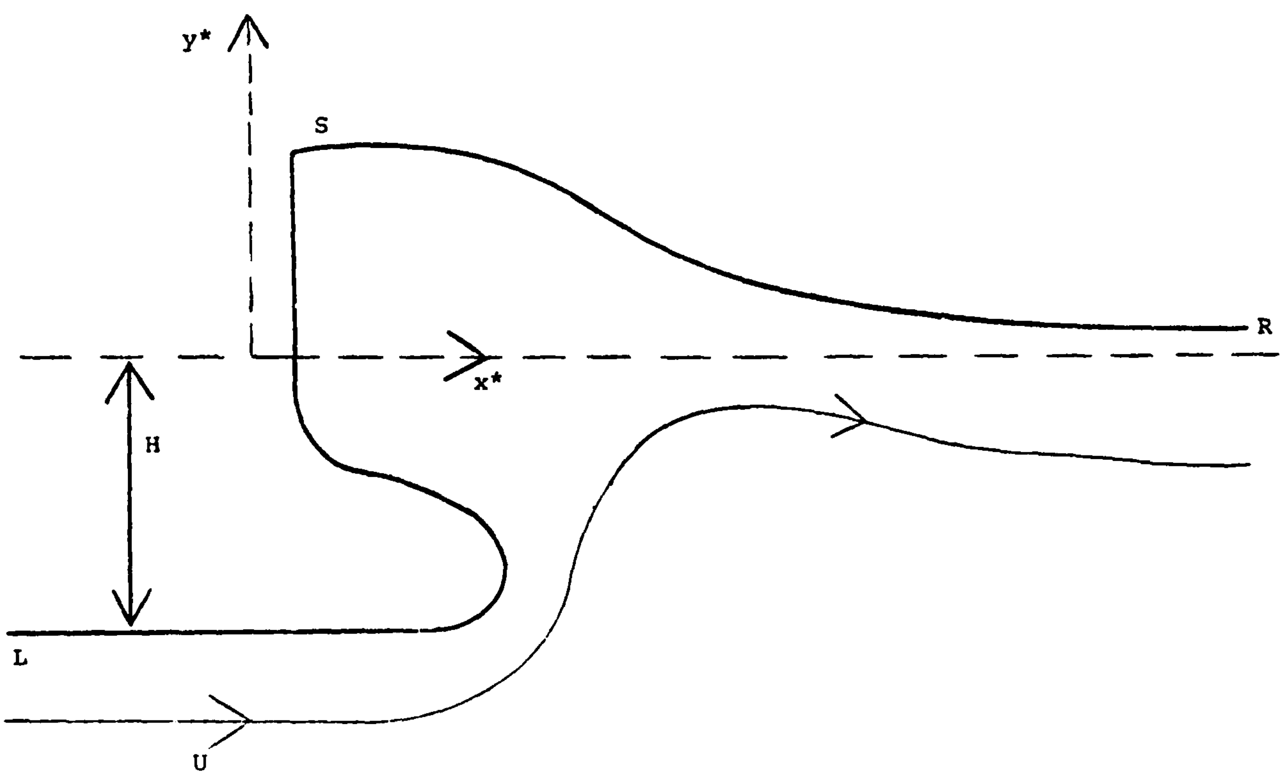

Figure 4. Sketch of a flow past of a semi-infinite body.

We denote the potential function by ϕ^* and the stream function by ψ^*. We choose $\phi^* = 0$ at the stagnation point and $\psi^* = 0$ on the free surface and on the surface of the body (see Figure 4). We denote by $-K$ the value of ϕ^* at $x^* = 0$, $y^* = -H$. We shall seek the complex velocity $u^* - iv^*$ as an analytic function of the complex potential $f^* = \phi^* + i\psi^*$. We make the variables dimensionless by referring them to the velocity scale U and the length scale $\frac{K}{U}$. Thus we introduce the new dimensionless variables

$$x + iy = \frac{U}{K}(x^* + iy^*) \tag{11}$$

$$u - iv = \frac{1}{U}(u^* - iv^*) \tag{12}$$

$$f = \phi + i\psi = \frac{1}{K} f^* = \frac{1}{K}(\phi^* + i\psi^*) \tag{13}$$

Bernoulli's equation and the condition of constant pressure on the free surface yield

$$y + \varepsilon(u^2 + v^2) = \varepsilon, \ \psi = 0, \ \phi > 0 \ . \tag{14}$$

Here ε is defined by

$$\varepsilon = \frac{U^3}{2gK} \tag{15}$$

We find it convenient to define the new function $\tau - i\theta$ by the relation

$$u - iv = e^{\tau - i\theta} \tag{16}$$

Relation (14) can now be rewritten as

$$\int_0^\phi e^{-\tau} \sin\theta d\phi + \varepsilon e^{2\tau} = 0, \ \psi = 0, \ \phi > 0 \tag{17}$$

The function $\tau - i\theta$ is an analytic function of $f = \phi + i\psi$ in the half plane $\psi < 0$. On $\psi = 0$, its real part is the Hilbert transform of its imaginary part, thus we have

$$\tau(\phi) = \frac{1}{\pi} \int_{-\infty}^{+\infty} \frac{\theta(\Phi)}{\Phi - \phi} d\Phi \tag{18}$$

Here $\tau(\phi)$ and $\theta(\phi)$ denote respectively $\tau(\phi, 0_-)$ and $\theta(\phi, 0_-)$. The integral in (18) is to be interpreted in the Cauchy principal value sense. The kinematic condition on the body yields

$$\theta = 0, \qquad \psi = 0, \qquad \phi < -1 \tag{19}$$

$$\theta = g(\phi), \quad \psi = 0, \quad -1 < \phi < -b \tag{20}$$

$$\theta = \frac{\pi}{2}, \qquad \psi = 0, \qquad -b < \phi < 0 \tag{21}$$

Here the constant b and the function $g(\phi)$ define the shape of the body. Relation (21) implies that the body is vertical for $-b < \phi < 0$. Our aim is to identify particular values of b and ε and a particular function $g(\phi)$ for which no waves are present of the free surface. We shall restrict our attention to bodies with continuous slope. Therefore we impose the conditions

$$g(-1) = 0 \tag{22}$$

$$g(-b) = \frac{\pi}{2} \tag{23}$$

Substituting (19)-(21) into (18) we get

$$\tau(\phi) = \frac{1}{2} \ln \left|\frac{\phi}{b + \phi}\right| + \frac{1}{\pi} \int_{-1}^{-b} \frac{g(\Phi)}{\Phi - \phi}\, d\Phi + \frac{1}{\pi} \int_{0}^{\infty} \frac{\theta(\Phi)}{\Phi - \phi}\, d\Phi \tag{24}$$

For given ε, b and $g(\phi)$ the problem reduces to finding a function $\tau(\phi) - i\theta(\phi)$ satisfying the nonlinear integro-differential equation defined by (17) and (24). A numerical scheme to solve this equaiton is described in the next subsection.

3.2 Numerical Results

We choose

$$g(\phi) = \frac{\pi}{2} \frac{(\phi + \lambda)^2 - (\lambda - 1)^2}{(\lambda - b)^2 - (\lambda - 1)^2} \tag{25}$$

This function satisfies the condition (22) and (23). The parameter λ in (25) will be adjusted to remove the waves on the free surface.

We introduce the N mesh points ϕ_I given by

$$\phi_I = -1 + (I - 1)E, \quad I = 1,\ldots,N$$

Here E is the interval of discretization. We also introduce the N corresponding unknowns

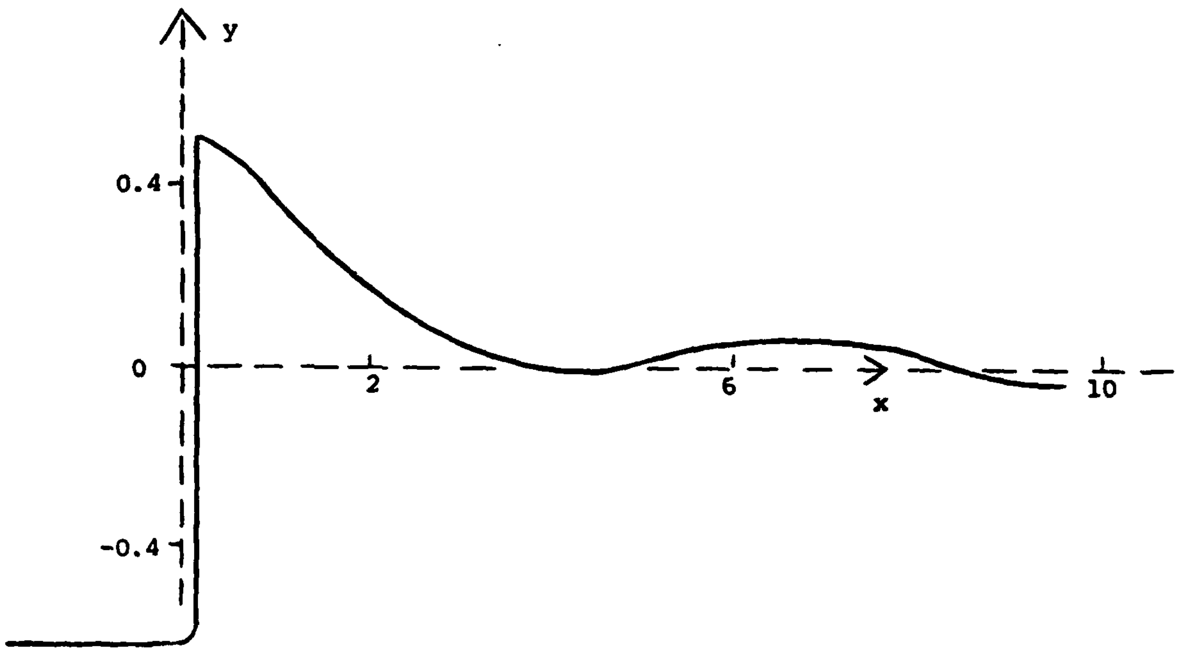

Figure 5: Computed body profile and free surface profile for $\lambda = 0.3$ and $\varepsilon = 0.5$.

$$\theta_I = \theta(\phi_I), \quad I = 1,\ldots,N$$

We find it convenient to define E as

$$E = 1/M$$

where M is an integer. With this particular choice

$$\phi_{M+1} = 0$$

We shall also use the $N - 1$ intermediate mesh points

$$\phi_{I+1/2} = \frac{1}{2}(\phi_I + \phi_{I+1}), \quad I = 1,\ldots,N-1$$

From (19)-(21) we see that θ has a jump discontinuity at $\phi = 0$ with $\theta(0_-) = \frac{\pi}{2}$ and $\theta(0_+) = 0$. Therefore the values of θ at $\phi = \phi_{M+1} = 0$ are known. In addition $\theta_1 = 0$, so only $N - 2$ of the θ_I are unknown. From

(20)-(21) we obtain $M - 1$ equations for

$$\theta_I = \theta(\phi_I), \quad I = 2,\ldots,M \tag{26}$$

We now compute

$$\tau_{I+1/2} = \tau(\phi_{I+1/2})$$

in terms of θ_I and b by applying the trapezoidal rule to the integral in (24) with the mesh points ϕ_I. The symmetry of the discretization enables us to compute the Cauchy principal value as if it were an ordinary integral. The error inherent in approximating the integral by an integral over a finite interval was found to be negligible for NE large enough. We now use the values of $\tau_{I+1/2}$ and θ_I to satisfy (17) at the mesh points $\phi_{I+1/2}$, $I = M + 2,\ldots,N - 1$. The integral in (17) was computed by the trapezoidal rule. Thus we obtain $N - M - 2$ equations for the $N - 2$ unknowns θ_I, $I = 2,\ldots,N$. Relation (26) provides $M - 1$ extra equations. Therefore we have $N - 3$ equations for the $N - 2$ unknowns. θ_I.

The last equation is obtained by expressing θ_{M+4} in terms of $\theta_{M+1} = 0$, θ_{M+2} and θ_{M+3} by an extrapolation formula. This equation is motivated by the work of Vanden-Broeck and Tuck (1977) and Vanden-Broeck, Schwartz and Tuck (1978). These authors showed that special care had to be taken near the stagnation point to insure convergence of the numerical scheme.

For given values of ε, b and λ, the $N - 2$ equations are solved by Newton method with the initial guess

$$\theta_I = g(\phi_I), \quad I = 2,\ldots,M$$

$$\theta_I = 0, \qquad I > M + 2$$

Once a solution was obtained the profiles of the bow and of the free surface were obtained by numerically integrating the identities

$$\frac{\partial x}{\partial \phi} = e^{-\tau}\cos\theta \tag{27}$$

$$\frac{\partial y}{\partial \phi} = e^{-\tau} \sin \theta \tag{28}$$

For most values of ε, b and λ, waves are present on the free surface. Moreover many values of ε, b and λ lead to unacceptable body profiles which cross themselves. This is due to the fact that the profile of the body is obtained in the parametric form $x(\phi)$, $y(\phi)$ $-1 < \phi < -b$. Therefore the mathematical formulation does not prevent unacceptable crossing of the profile.

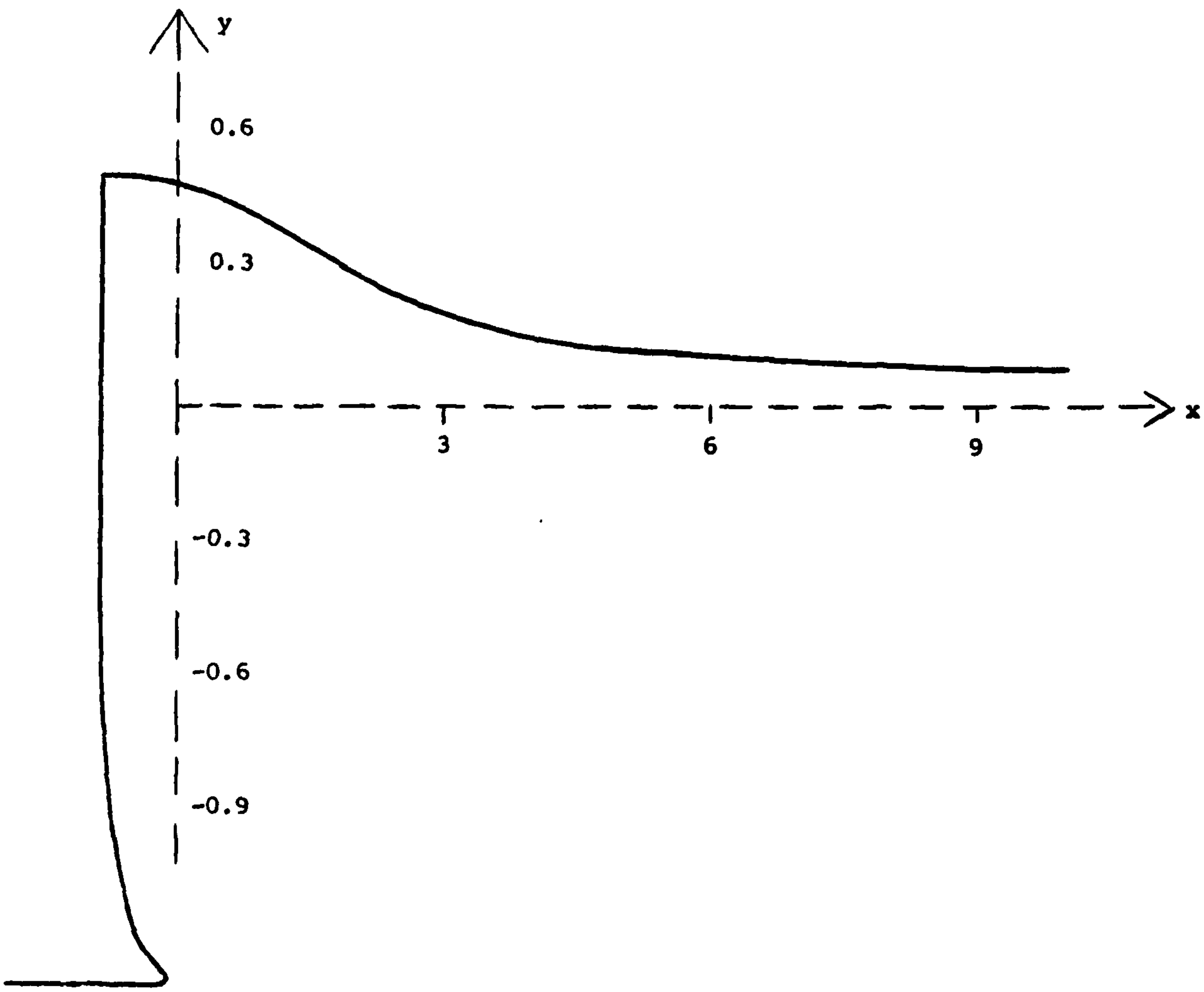

Figure 6: Computed body profile and free-surface profile for $\lambda = 0.53$ and $\varepsilon = 0.5$.

By running the scheme for many different values of ε, λ and b we were able to identify particular values of these parameters for which waveless solutions with no crossing in the profile of the bow exist.

Typical profiles for $\varepsilon = 0.5$ and $b = 0.2$ are shown in Figures 5 and 6. These solutions were computed with $E = 0.1$ and $N = 100$. To check the accuracy of our results we ran the scheme with $E = 0.05$ and $N = 200$. The results were found to be indistinguishable within graphical accuracy from those presented in Figure 5 and 6.

The profile in Figure 5 corresponds to $\lambda = 0.3$. A train of waves is present on the free surface. This profile is qualitatively similar to the solutions obtained by Vanden-Broeck and Tuck (1977) and Vanden-Broeck, Schwartz and Tuck (1978). The main difference is that the corner has now been rounded.

The profile in Figure 6 corresponds to $\lambda = 0.53$. The free surface is completely waveless. Therefore this solution (when reversed in direction) demonstrates numerically the existence of splashless bow flows in two dimensions. It is interesting to note that the profile of the bow has a definite bulbous character.

Other splashless bow flows could be obtained by using different functions $g(\phi)$ in (20). By analogy with the work of Vanden-Broeck and Tuck (1984) we expect that all the corresponding bow shapes are bulbous.

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In two-dimensional bow-like flows past a semi-infinite body, one must in general expect a free-surface discontinuity, in the form of a splash or spray jet. Similarly, if one reverses the flow direction, so generating a stern-like flow, one must expect a train of waves at infinity. For example, we have shown in previous work that there is no stern-like flow without waves (cont.)

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ABSTRACT (cont.)

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