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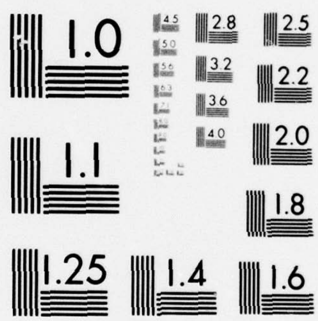

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LIFT, DRAG AND MOMENT FOR A HYDROFOIL OPERATING NEAR THE FREE SURFACE AND UNDER TRANSVERSE GRAVITY

V.S. Bakhshi

Report No. ONR-75-1

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BY

V.S. Bakhshi

K.M. Agrawal
(Principal Investigator of the Project)

June 1975
Virginia State College
Mathematics Department
Petersburg, Virginia 23803

Abstract

Using linear theory, expressions for lift, drag and moments are obtained for hydrofoil operating near the free surface and under transverse gravity. Existing results are easily obtainable for special cases when gravity is neglected, and/or depth below the free surface approaches infinity. Numerical calculations are performed and results are shown by figures.

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CONTENTS

1. Introduction

Since the renewal of the interest in hydrodynamics of hydrofoils because of their potential advantages when used on small craft [1]* variety of papers have appeared dealing with different aspects of supercavitating flow. A complete solution to the supercavitating flow is the analysis of the flow in three dimensions, when hydrofil, is operating near the surface under the effect of transverse gravity. This problem has not been solved in its generality though various simplified versions in two dimensions, have been solved. Most of the work has been done by considering two dimensional models because of readily availability of technique of analytic function theory for such problems. Tulin [2] studied the hydrofoil and its associated cavity as a slender body and used techniques similar to Biot [3], Stewart [4] and others. For limited range of cavitation numbers, Tulin used this theory to calculate the forces on a flate plate hydrofoil operating at small angle of attack. Wu [5] represented an extension of the classical free stream line theory of Helmholtz and Kirchoff and also [6] extended the linearized theory to include the effects of camber upon the forces on a profile in a cavity flow. These results when compared with experiments [7] show certain small but symmetric discrepancies for the circular arc and the flat plate profile in fully cavitating flow. It may be noted that in all above mentioned studies, effect of gravity and free surfaces are neglected. Parkin [8] studied the cavity flow under gravity, possibility to account for the discrepancies observed in Wu [5, 6] theoretical and Parkin [7] experimental results.

* Number in brackets designate references which are listed at the end of this work.

Supercavitating flows under gravity has also been studied by Acosta [9], Lenau and Street [10], Street [11] and others. Problem involving free surface for uniform folw is treated by Auslaender [12] and for non-uniform flow by Hsu [14]. Untill now problem involving gravity and free surface has not been discussed. In the present work such a problem is undertaken.

2. Formulation of the Problem

Consider an inviscid steady two-dimensional uniform fluid flow of density ρ . Suppose the flow is disturbed by introducing a flat plate of unit length, inclined at an angle δ to the direction of the flow. (The unit length body is used without loss of generality, since its use is equivalent to normalizing the problem on actual length of the plate). The upstream velocity far from the plate is U and the origin of the x, y-coordinate system is taken at the leading edge of the plate. The supercavitating hydrofoil at a finite depth, h , below the free surface is shown in figure 1. It is assumed that :

(a) Hydrofoil and cavity are equivalent to a long slender body which causes only small pertubations in the flow that is uniform far from the body.

(b) The cavitation number is zero

Accordingly the velocity components are assumed to be

$$U\ (1+ u,v) \qquad\qquad ---- (1)$$

where the components of the perturbation velocity (u,v) and their first partial derivatives are "small", in the sense that their square and product are negligible. These components may be combined into the total complex velocity $W(z)= U(1+w(z))$, which is an analytic function of z. In this expression the complex velocity of small perturbation w(z) is given by

$$w(z) = u - iv$$

As is discussed by Auslaender [12] and Smith [15], the simply connected (Fig.2) polygon $A_\infty B_\infty B'_\infty$ E F C_∞ can be mapped into the lower half of the ζ plane (Fig. 3) by the conformal transformation

$$z = a A\left[\frac{\zeta}{a} - \log\left(1+ \frac{\zeta}{a}\right)\right] \qquad --- \quad (2)$$

where $-\pi < \arg z < 0$

$$\frac{1}{A} = 1 - a \log\left(\frac{1+a}{a}\right)$$

and $aA\pi = h$

The above relations have been obtained by using the constraints that x = 0 and x = 1 corresponds to $\xi = 0$, and $\xi = 1$ respectively.

Also it has been shown that

$$\text{when } h \longrightarrow 0, \quad \begin{cases} a \longrightarrow 0 \\ A \longrightarrow 1 \\ x - i0 \longrightarrow \xi, \quad \xi > 0 \end{cases} \qquad - (3)$$

$$\text{when } h \longrightarrow \infty \quad \begin{cases} a \longrightarrow \infty \\ A \longrightarrow 2a \\ x + i0 \longrightarrow \xi^2, \quad \xi < 0 \\ x - i0 \longrightarrow \xi^2, \quad \xi > 0 \end{cases} \qquad - (4)$$

3. Lift, Drag and Moments Coefficients

By normalizing the expression for lift with respect to $1/2 \rho U^2$, the lift coefficient is

$$C_L = \int_0^1 \frac{\Delta P}{\frac{1}{2}\rho U^2} \cdot \frac{dx}{d\xi} \cdot d\xi$$

where ΔP is the pressure difference between the face and back of the hydrofoil.

By using equation (2) and Bernoulli's equation, we get

$$C_L = -2\left[\int_0^1 \bar{u}(\xi)\frac{A\xi}{\xi+a} \cdot d\xi + \frac{g}{U^2}\int_0^1 y_0(x)\,dx\right]$$

Since the lower surface of the hydrofoil is a flat place ($y_0(x)=-\delta x$) the above equation reduces to

$$C_L = -2\int_0^1 \bar{u}(\xi)\frac{A\xi}{\xi+a}\,d\xi + \frac{g\delta}{U^2} \qquad --- \quad (5)$$

To find the value of $\bar{u}(\xi)$, we use the relation between $\bar{v}(\xi)$ and $\bar{u}(\xi)$ as discussed by Tulin and Burkart [16], we have

$$\bar{v}(\xi) = \frac{1}{\pi}\int_0^1 \frac{\bar{u}(\xi)}{\xi-\xi'}\,d\xi' \quad , \qquad \text{where } 0 \leq \xi \leq 1$$

The inversion of this integral equation was shown by Munk [17] to be

$$\bar{u}(\xi) = -\frac{(1-\xi)^{1/2}}{\pi\xi^2} \cdot \int_0^1 \frac{\xi'^{1/2}\cdot \bar{v}(\xi')\,d\xi'}{(1-\xi')^{1/2}(\xi-\xi')} \quad , \qquad -- (6)$$

$$0 \leq \xi \leq 1$$

It may be noticed that

(a) Velocity must be tangential to the bottom surface of the hydrofoil, therefore

$$\frac{dy_0}{dx} \cong v$$

(b) Angles are not affected by the transformation, therefore

$$\frac{dy_0}{dx} = v(x) = \bar{v}(\xi)$$

(c) For the flat plate $\frac{dy_0}{dx} = -\delta$

Using these observations, equation (6) become

$$\bar{u}(\xi) = \frac{\delta(1-\xi)^{1/2}}{\pi \xi^{1/2}} \cdot \int_0^1 \frac{\xi'^{1/2} \cdot d\xi'}{(1-\xi')^{1/2} \cdot (\xi - \xi')}$$

or

$$u(\xi) = -\frac{\delta(1-\xi)^{1/2}}{\xi^{1/2}} \qquad ----(7)$$

substituting value of $u(\xi)$ as given by the equation (7) in equation (5) we get

$$C_L = \frac{\delta h}{a}\left[(1+a)^{1/2} - a^{1/2}\right]^2 + \frac{g\delta}{U^2} \qquad --(8)$$

By using equations (4) and (8) give

$$C_L = \begin{cases} \delta\pi + \frac{g\delta}{U^2}, & h = 0 \\ \frac{\delta h}{a}\left[(1+a)^{1/2} - a^{1/2}\right]^2 + \frac{\delta g}{U^2}, & 0 < h < \infty \\ \frac{\pi\delta}{2} + \frac{g\delta}{U^2}, & h = \infty \end{cases} \qquad -(9)$$

In the special case, when the effect of gravity is neglected, equation (9) gives the same result as given by Auslaender [12]. Also for infinity depth and without gravity effect, equation (9) gives the same result as given by Parkin [8] which is also a linearized version of the result given by Lamb [18].

The drag coefficient can be obtained from the consideration that for a fully cavitating flow past the flat plate, the local pressure is everywhere normal to the plate [5]. Therefore, the drag coefficient (C_D) and C_L satisfy the relation $C_D / C_L = \tan\delta \cong \delta$ - - -(10)

using equations (9) and (10), we get

$$C_D = \begin{cases} \pi\delta^2 + \dfrac{g\delta^2}{U^2}, & h = 0 \\ \dfrac{\delta^2 h}{a}\left[(1+a)^{1/2} - a^{1/2}\right]^2 + \dfrac{g\delta^2}{U^2}, & 0 < h < \infty \\ \dfrac{\pi\delta^2}{2} + \dfrac{g\delta^2}{U^2}, & h = \infty \end{cases} \qquad -(11)$$

Moment about the leading edge :

By dividing the usual expression for moments about the leading edge by $1/2\ \rho U^2$, we get the coefficient of moment C_M.

$$C_M = -\frac{2}{\rho U^2}\int_0^1 \Delta P \cdot x \cdot dx$$

By using Bernoulli's eqations and equations (2) and (10)

$$C_M = -\frac{2}{3}\frac{g\delta}{U^2} - 2aA^2\delta\left[\frac{1}{a}\int_0^1 \frac{\xi^{3/2}(1-\xi)^{1/2}}{a+\xi}\, d\xi - \int_0^1 \frac{\xi^{1/2}(1-\xi)^{1/2}}{a+\xi}\,\ln\left(1+\frac{\xi}{a}\right) d\xi\right]$$

By carring out the integration, we get

$$C_M = \frac{A^2 \delta}{a}\left[\frac{\pi}{16}(2a-1) - a^2\left\{\frac{2a+1}{2} - \pi\sqrt{a^2+a}\right\}\right] - \frac{2}{3}\frac{g\delta}{U^2} \qquad --(12)$$

Equations (8), (11) and (12) give us the expressions for C_D, C_L and C_M. These expressions can be given in terms of the Froude number $F = u/(gh)^{1/2}$, based on the hydrofoil depth, h, as follows :

$$C_L = \frac{\delta h}{a}\left[(1+a)^{1/2} - a^{1/2}\right]^2 + \frac{\delta}{F^2 h}$$

$$C_M = \frac{A^2 \delta}{a}\left[\frac{\pi}{16}(2a-1) - a^2\left\{\frac{2a+1}{2} - \pi\sqrt{a^2+a}\right\}\right] - \frac{2}{3}\frac{\delta}{F^2 h}$$

4. Numerical Calculations and Results

Before making any numerical calculations, it may be mentioned that equations (9) and (12) conform with the known observation that gravity has a significant contribution, when velocity is small and its effect may be neglected for large velocity.

Numerical calculations were carried out on IBM 370/125 and results are shown in figures 4 and 5. The effect of Froude number is shown in figure 4 where the variation in the ratio of the lift-coefficient at depth h, to the lift coefficient at infinity depth, i.e., C_L/C_{L_∞} with respect to F is plotted for several values of h. It may be noted that for hydrofoil operating at a depth greater than 1/2 of the chord length, the value of C_L/C_{L_∞} remains practically unchanged, when the value of F decreases from large values to F= 3.

This result is similar to the theoretical results of Hough and Moran [13] and the experimental result of Strandhagen and Seikel [19] . The main difference being that in the range $10 > F > 3$, which corresponds to the most foil operating conditions, C_L/C_{L_∞} does not decrease as rapidly with decreasing F, as is determined by Hough and Moran [13] . For example, when h= 0.5 and F decreases from 10 to 3, the decrease in value of C_L/C_{L_∞} at F=3 is only 2.9% of the value of C_L/C_{L_∞} at F=10. It may also be seen that when hydrofoil is operating near the surface (h=0.1), there is a sharp increase of 34.6% in the value of C_L/C_{L_∞} when F increases from 0.2 to 7 and when F increases from 7 to 10, the increase in value of C_L/C_{L_∞} is less than 1%. It can also be safety concluded that for all practical purposes, the value of C_L/C_{L_∞}, for large value of F is the same as its value in the neighborhood of F=5, when hydrofoil is operating at a depth greater than 1/2 of the chord length. The variation of C_L/C_{L_∞} with h for fixed F can be easily calculated. It is clear that when F increases from 5 to 10 the increase in value of C_L/C_{L_∞} is only 0.73%, 0.38%, 0.16%, 0.08% respectivity at h=0.5, h=1, h=2 and h=3 . This again confirms that for all practical purposes, values of C_L/C_{L_∞} for large value of F is the same as at F=5. It is interesting to note that for fixed F (= 5), the value of C_L/C_{L_∞} decreases steady by nearly 1.4% for each increment of 0.1 in value of h, as h increases steady from 0.1 to 1.2 . There is a sharp decline in the value of C_L/C_{L_∞} of 5.5% as h increases from 1.2 to 1.5, when h increases further, value of C_L/C_{L_∞} levels off with its value close to h=1.5 . Similar pattern follows for other fixed values of F .

The results for the variation of C_M/δ with respect to F, for fixed h are shown in figure 5. Figure 5 indicates practically no change in value of C_M/δ as F decreases from large values to 3 or 4, a gradual decrease in value of C_M/δ, as F decreases from 4 to 2, and a sharp decline as F decreases beyond 2. For example, when h=0.97, the decrease in value of C_M/δ is 2.8% (of its value at F= 10) when F decreases from 10 to 4, the decrease in value is 12.26% (of its value at F= 4) when F decreases from 4 to 2 and the decrease in value is 42.9% (of the value at F= 2) when F decreases from 2 to 1.

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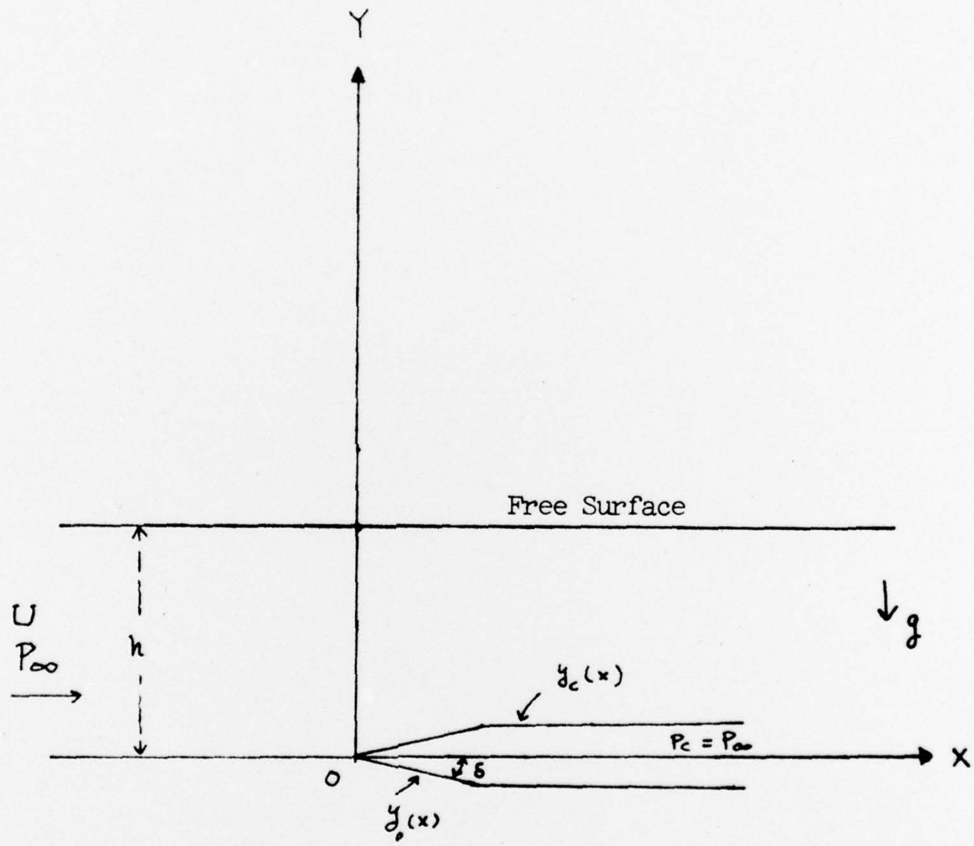

Figure 1. Supercavitating Flow Near A Free Surface

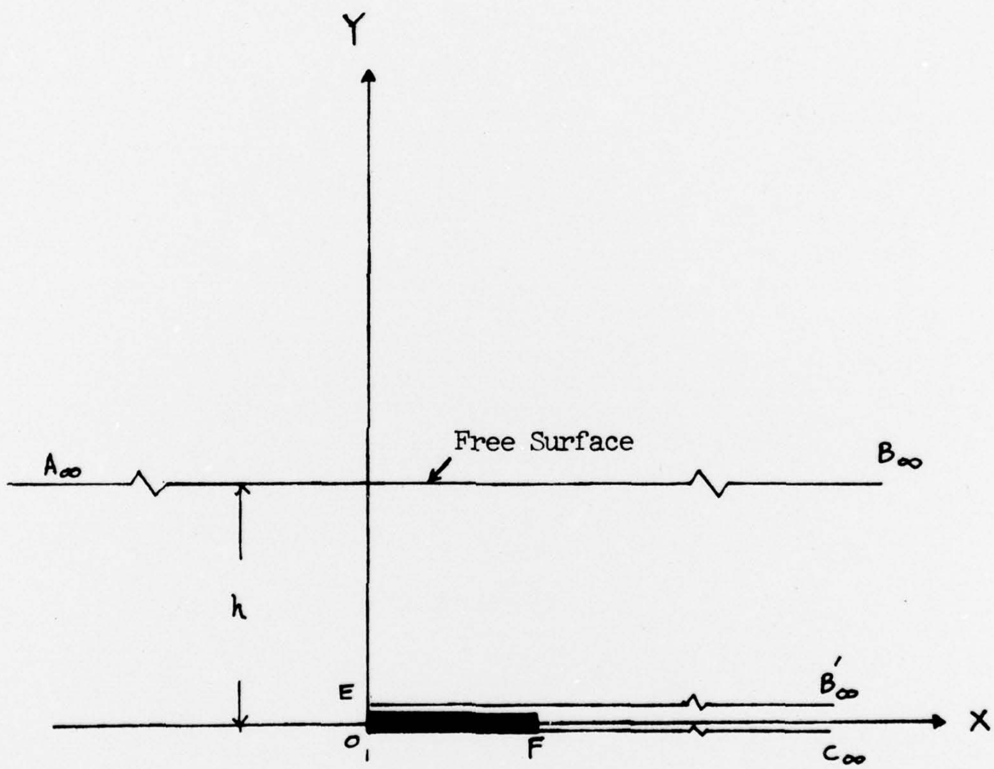

Figure 2. Hydrofoil Plane (z= x +iy)

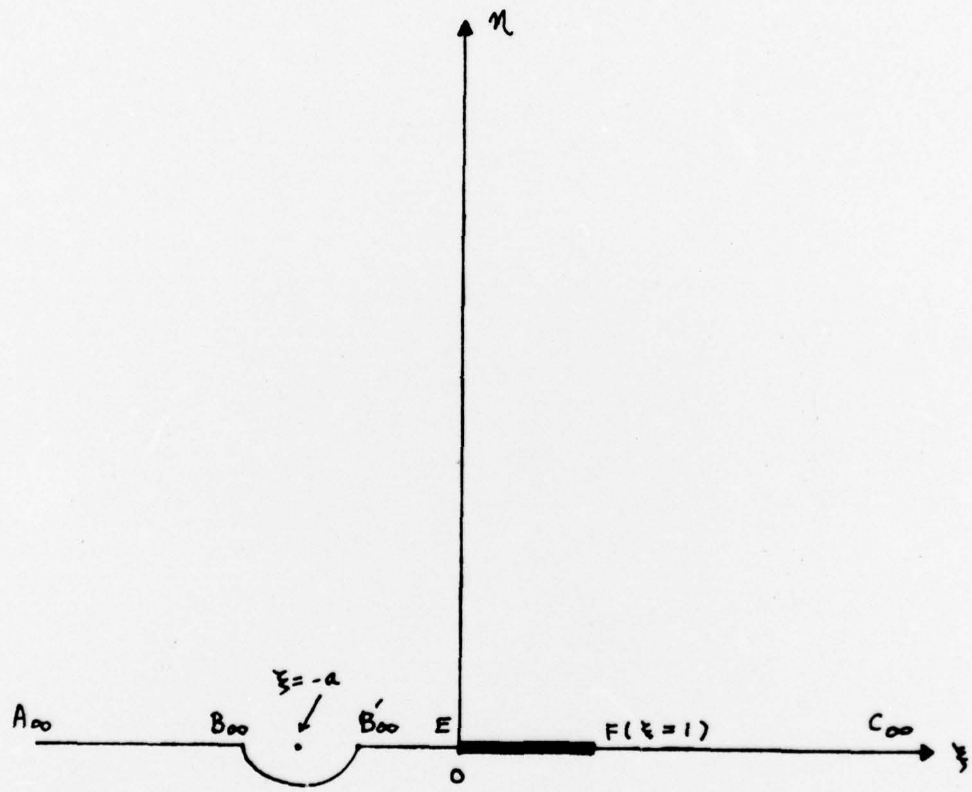

Figure 3. Air-Foil Plane ($\zeta = \xi + i\eta$)

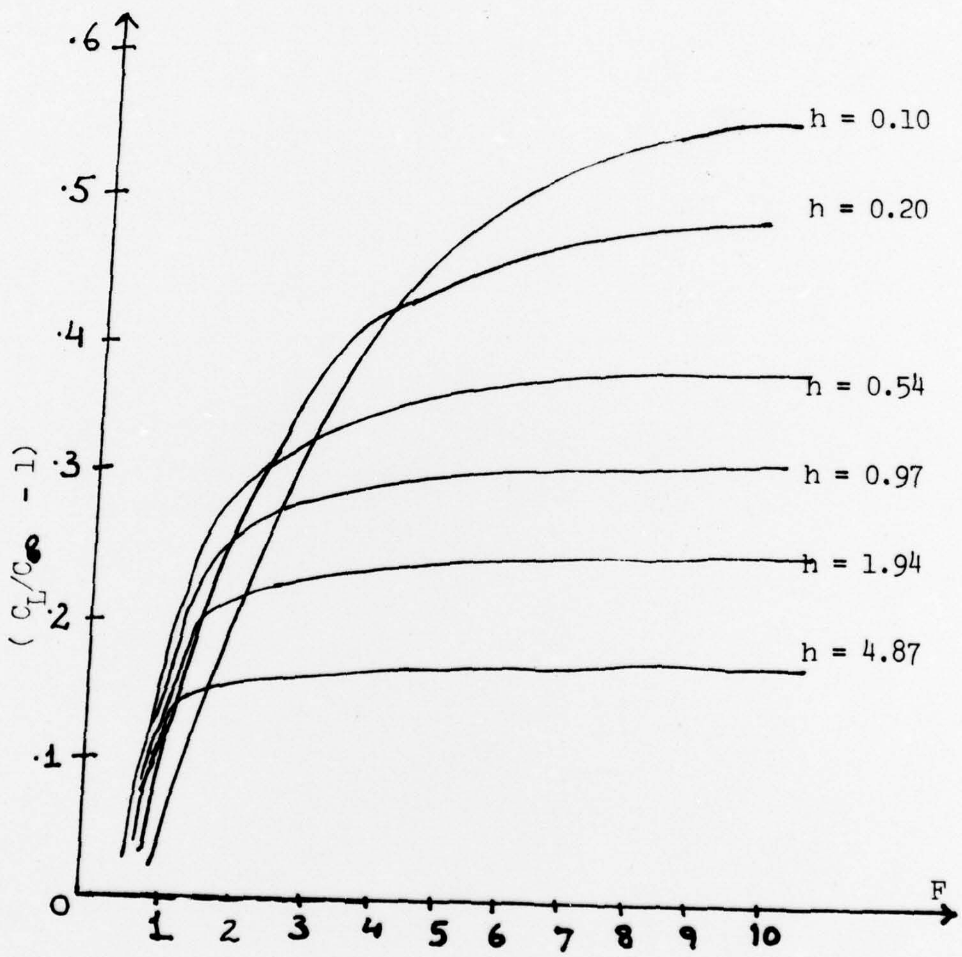

Figure 4. Effect of Froude Number on the Hydrofoil Lift.

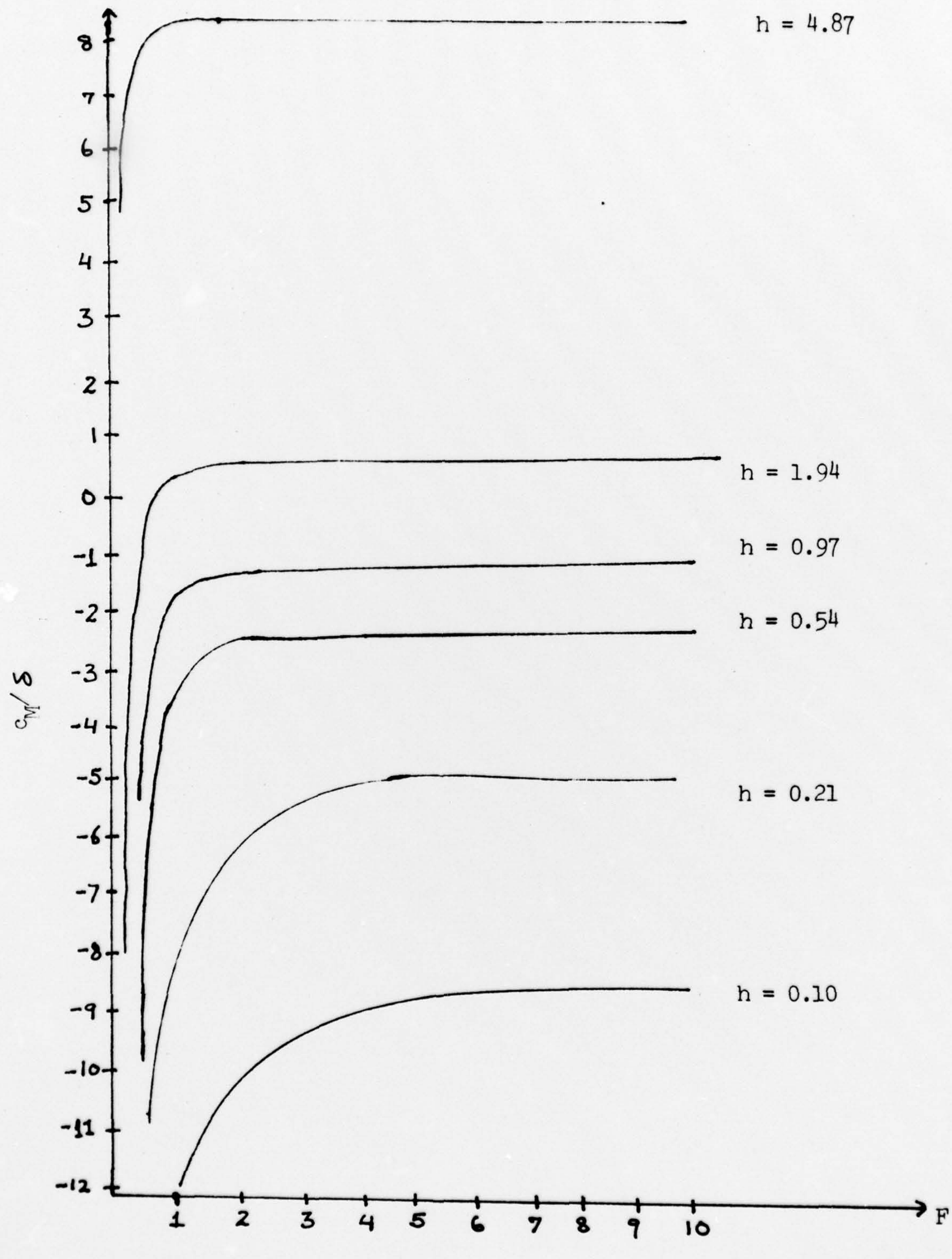

Figure 5. Variation of C_M/δ with respect to F, for fixed h .