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Flow Through Very Porous Inclined Screens

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FLOW THROUGH VERY POROUS INCLINED SCREENS

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Abstract

The steady, inviscid flow through and around a screen inclined at a uniform angle to the incoming flow was investigated. For a screen placed in an infinite flow field, an asymptotic analysis for small resistance coefficients was performed, and the effects of inclination were determined. The velocity at first order in the asymptotic expansion was nonuniform along the screen. This nonuniformity caused the wake behind the screen to contain distributed vorticity at second order. These effects therefore occurred at one order lower than for normal screens.

Introduction

A screen is a device that can be used to modify the velocity distribution of a fluid flow in a controlled manner. When fluid passes through a screen, the static pressure of the flow is reduced and the oncoming streamlines are deflected toward normal to the screen. These properties have prompted researchers to treat a screen as a surface of discontinuity in the flow.

The first analysis of the flow around a very porous screen was carried out by Taylor (1963). He modeled the screen as a sheet of uniformly distributed sources. Although only the flow field outside the wake can be determined with his model, Taylor's formula for the drag coefficient agrees with experiment for values of the resistance coefficient k up to approximately 4.

This distributed source analysis was later extended by Koo and James (1973). In their mathematical model, a wake is introduced by making certain assumptions about the streamline pattern behind the screen. Along with numerical solutions to their model, Koo and James also presented some closed-form results for both normal and inclined screens. However, their analytical results are solutions not to their model but to an approximate form of their model. Although Koo and James' solutions are at best formally accurate to the same degree as Taylor's, viz, $O(k)$, their expression for the drag coefficient agrees with experimental values for k as large as 10.

A formal solution to the governing equations for steady and oscillatory flows through a normal screen has recently been given by Durbin and Muramoto (1985). They carried out an asymptotic expansion accurate to $O(k^2)$ and found that at this order the effects of tangential drag and wake vorticity have entered into the solution. A Padé approximant to their drag formula also agrees with experiment for k as large as 10. In this paper, the analysis of Durbin and Muramoto is extended to consider the steady flow through a screen inclined to the oncoming flow. Only the special case of a finite screen in an infinite flow field is considered.

Governing Equations

Following Durbin and Muramoto (1985), nondimensional variables will be used. Thus, the fluid density, the projected screen half-height, and the far-upstream velocity are assumed to be unity. For steady, inviscid, incompressible flow, the continuity and momentum equations are

$$\left.\begin{aligned} &\frac{\partial u}{\partial x} + \frac{\partial v}{\partial y} = 0 \\ &u\frac{\partial u}{\partial x} + v\frac{\partial u}{\partial y} = -\frac{\partial P}{\partial x} \\ &u\frac{\partial v}{\partial x} + v\frac{\partial v}{\partial y} = -\frac{\partial P}{\partial y} \end{aligned}\right\} \qquad (1)$$

These governing equations must be solved, subject to the following jump and boundary conditions. The pressure drop across the screen $[P]$ is generally expressed by a dimensionless resistance coefficient k (Taylor, 1963), defined by

$$[P] = \frac{1}{2}kU^2 \qquad (2)$$

where U is the velocity normal to the screen. Since mass flow through the screen must be conserved,

$$[U] = 0 \qquad (3)$$

Because the screen deflects the streamlines, there is a jump in the tangential velocity $[V]$, given by

$$[V] = BV_+ \qquad (4)$$

where B is the tangential resistance coefficient and V_+ is the tangential velocity on the upstream side of the screen. If we consider a screen placed in a uniform flow field, the upstream boundary condition is $u \to 1$ and $v \to 0$ as $x \to -\infty$. Note that lower case u and v refer to x,y components, while upper case refers to normal and tangential components.

Asymptotic Analysis

Let the location of the screen be given by the equation $s = x(y)$. Here we will take

$$x = \operatorname{sgn}(y)ay \quad -1 \leq y \leq 1 \qquad (5)$$

and thus depending on the sign of a taken, both forward-tilting ($a > 0$) and backward-tilting ($a < 0$) screens can be considered. According to equation (5), the unit vectors normal and tangent to the screen are, respectively,

$$\left.\begin{aligned} \hat{n} &= \frac{\hat{i} - \operatorname{sgn}(y)a\hat{j}}{\sqrt{1 + a^2}} \\ \hat{t} &= \frac{a\hat{i} + \operatorname{sgn}(y)\hat{j}}{\sqrt{1 + a^2}} \end{aligned}\right\} \qquad (6)$$

We seek a solution to the problem by expanding the dependent variables in powers of k, that is

$$\left.\begin{aligned} u &= u_0 + ku_1 + k^2u_2 + \dots \\ v &= v_0 + kv_1 + k^2v_2 + \dots \\ P &= P_0 + kP_1 + k^2P_2 + \dots \end{aligned}\right\} \quad (7)$$

Similarly, we will assume that B can be written in the form

$$B = kB_1 + k^2B_2 + k^3B_3 + \dots \quad (8)$$

By inspection, the zeroth-order solution is simply

$$u_0 = 1,\ v_0 = 0,\ P_0 = 0 \quad (9)$$

Proceeding to the first-order problem, a formal solution must be obtained to the following equations:

$$\frac{\partial u_1}{\partial x} + \frac{\partial v_1}{\partial y} = 0 \quad (10a)$$

$$-\frac{\partial P_1}{\partial x} = \frac{\partial u_1}{\partial x} \quad (10b)$$

$$-\frac{\partial P_1}{\partial y} = \frac{\partial v_1}{\partial x} \quad (10c)$$

with $[U_1] = 0$, $[V_1] = B_1V_0$, $[P_1] = 1/2\ u_0^2$. Integration of equation (10b) yields

$$u_1 = -P_1 + f_1(y) \quad (11)$$

where $f_1(y)$ is an arbitrary function of y, except for a jump across the screen. Now since P_1 satisfies Laplace's equation, we may introduce the harmonic function Q_1 conjugate to P_1. Therefore, by the Cauchy-Riemann equations and the boundary conditions to the problem

$$v_1 = Q_1 \quad (12)$$

To determine the unknown quantities $f_1(y)$ and $[Q_1]$, the jump conditions on U and V at the screen will be used. Substituting equations (11) and (12) into (3) and (4) gives the following pair of algebraic equations:

$$\left.\begin{aligned} [f_1(y)]n_x + [Q_1]n_y &= [P_1]n_x \\ [f_1(y)]t_x + [Q_1]t_y &= [P_1]t_x + B_1V_0 \end{aligned}\right\} \quad (13)$$

where $n_x = \hat{n}\cdot\hat{i}$, $n_y = \hat{n}\cdot\hat{j}$, $t_x = \hat{t}\cdot\hat{i}$, and $t_y = \hat{t}\cdot\hat{j}$. Substituting $[P_1] = n_x^2/2$ and $V_0 = t_x$ and after using equation (6) for $\hat{n}$ and $\hat{t}$ gives the solution to the system of equations (13):

$$[f_1(y)] = \frac{1 + 2a^2B_1}{2(1 + a^2)} \quad (14)$$

$$[Q_1] = \frac{aB_1\ \mathrm{sgn}(y)}{1 + a^2} \quad (15)$$

Since the jumps $[P_1]$ and $[Q_1]$ are now known, the sectionally analytic function $P_1 + iQ_1$ can be determined according to the Plemelj formulas (Roos, 1969):

$$\begin{aligned} P_1 + iQ_1 &= \frac{1}{2\pi i}\int_S \frac{[P_1]}{z' - z}\,dz' + \frac{1}{2\pi i}\int_S \frac{i[Q_1]}{z' - z}\,dz' \\ &= \frac{1}{4\pi i(1 + a^2)} \ln\left[\frac{z - (a + i)}{z + (-a + i)}\right] \\ &\quad + \frac{aB_1}{2\pi(1 + a^2)} \ln\left(\frac{z^2 - 2az + 1 + a^2}{z^2}\right) \end{aligned} \quad (16)$$

where the branch cuts of the logarithms are along the screen. Hence, by equations (11) and (12),

$$\begin{aligned} u_1 - iv_1 &= -\frac{1}{4\pi i(1 + a^2)} \ln\left[\frac{z - (a + i)}{z + (-a + i)}\right] \\ &\quad - \frac{aB_1}{2\pi(1 + a^2)} \ln\left(\frac{z^2 - 2az + 1 + a^2}{z^2}\right) \\ &\quad - C(a)f(y) \end{aligned} \quad (17)$$

where

$$C(a) = \frac{1 + 2a^2B_1}{2(1 + a^2)} \quad (18)$$

and

$$f(y) = \begin{cases} 0, & x < ay \\ 0, & x > ay,\ |y| > 1 \\ 1, & x > ay,\ |y| < 1 \end{cases} \quad (19)$$

Note here that the velocity given by equation (17) has logarithmic singularities at the edges of the screen $z = 0$, $a \pm i$. As in the case of a normal screen, vorticity is absent inside the wake at this order because f is constant there: vorticity is confined to a sheet at $|y| = 1$. On the other hand, an inclined screen generates a first-order velocity whose normal component is not constant along the screen.

To avoid a nonuniformity in the asymptotic expansion at the edge of the wake, we will follow the method used by Durbin and Muramoto (1985) and replace $f(y)$ by $f[y - \mathrm{sgn}(y)s(x)]$ with $s = ks_1 + k^2s_2 + \dots$ so that the wake boundary lies on $y = 1 + s(x)$. This transformation does not affect the first-order solution given by equations (17) to (19).

Moving on to next order, the following second-order equations may be derived:

$$\frac{\partial u_2}{\partial x} + \frac{\partial v_2}{\partial y} = 0 \quad (20a)$$

$$-\frac{\partial P_2}{\partial x} = \frac{\partial u_2}{\partial x} + C(a)\frac{ds_1}{dx}\left|\frac{\partial f}{\partial y}\right| + u_1\frac{\partial u_1}{\partial x} + v_1\frac{\partial u_1}{\partial y} \tag{20b}$$

$$-\frac{\partial P_2}{\partial y} = \frac{\partial v_2}{\partial x} + u_1\frac{\partial v_1}{\partial x} + v_1\frac{\partial v_1}{\partial y} \tag{20c}$$

To eliminate the singularity at $|y| = 1$ associated with the $\partial u_1/\partial y$ term in equation (20b), we are required to take $v_1(x,1) = ds_1/dx$. From equation (17), the first-order wake boundary is

$$\begin{aligned} y_{wake} &= 1 + ks_1(x) \\ &= 1 + k\left(-\frac{1}{8\pi(1+a^2)}\left\{(x-a)\ln\left[\frac{(x-a)^2}{4+(x-a)^2}\right]\right.\right. \\ &\quad \left. + a\ln\left(\frac{a^2}{4+a^2}\right) - 4\left[\tan^{-1}\left(\frac{x-a}{2}\right) + \tan^{-1}\left(\frac{a}{2}\right)\right]\right\} \\ &\quad + \frac{aB_1}{2\pi(1+a^2)}\left[(x-a)\tan^{-1}\left(\frac{2}{x-a}\right) - a\tan^{-1}\left(\frac{2}{a}\right)\right. \\ &\quad - 2x\tan^{-1}\left(\frac{1}{x}\right) + \ln\left(\frac{4+(x-a)^2}{1+x^2}\right) \\ &\quad \left.\left. - \ln(4+a^2)\right]\right) \end{aligned} \tag{21}$$

If we let $H_2 = P_2 + 1/2(u_1^2 + v_1^2)$, the second-order momentum equations (20) can be written in the form

$$-\frac{\partial H_2}{\partial x} = \frac{\partial u_2}{\partial x} \tag{22a}$$

$$-\frac{\partial H_2}{\partial y} = \frac{\partial v_2}{\partial x} + C(a)u_1\frac{\partial f}{\partial y} \tag{22b}$$

Equation (22a) can be integrated immediately to yield

$$u_2 = -H_2 + f_2(y) \tag{23}$$

where $f_2(y)$ has a jump across the screen. From equation (22) it is evident that H_2 satisfies Laplace's equation everywhere except for a jump across the vortex sheets of

$$\langle H_2\rangle = C(a)u_1(x,|y| = 1)\,\mathrm{sgn}(y) \tag{24}$$

where the angular brackets denote a jump across the sheets and $u_1(x,|y| = 1)$ stands for the average of the velocities above and below $|y| = 1$. It follows from equation (17) that

$$\langle H_2\rangle = -C(a)\left[\frac{1}{2}C(a) + P_1(x,1)\right]\mathrm{sgn}(y) \tag{25}$$

In a manner analogous to what was done at first order, we introduce the function R_2, the harmonic conjugate to H_2. By the Cauchy-Riemann equations, one can easily show that

$$v_2 = R_2 \tag{26}$$

The jump of R_2 across the vortex sheets can be determined after removing the nonuniformity appearing in the equations at third order. Thus, to remove the nonuniformity, it is necessary to take

$$v_2 = \frac{ds_2}{dx} + u_1\frac{ds_1}{dx} - s_1\frac{\partial v_1}{\partial y} \tag{27}$$

Using equation (26) in (27), the jump of R_2 across the upper vortex sheet is just

$$\begin{aligned} \langle R_2\rangle &= \langle u_1\rangle\frac{ds_1}{dx} \\ &= C(a)v_1(x,1) \\ &= C(a)Q_1(x,1) \end{aligned} \tag{28}$$

since none of the other terms on the right side of equation (27) have jumps. A similar expression can be derived for the jump across the lower sheet.

The jumps of H_2 and R_2 across the screen can also be found in a straightforward fashion. The result for H_2 is

$$\begin{aligned} [H_2] &= [P_2] + \frac{1}{2}\left[u_1^2\right] + \frac{1}{2}\left[v_1^2\right] \\ &= U_0U_1 + u_{1s}[u_1] + v_{1s}[v_1] \\ &= u_{1s}n_x^2 + v_{1s}n_xn_y + u_{1s}B_1t_x^2 + v_{1s}B_1t_xt_y \\ &= \left(\frac{1+a^2B_1}{1+a^2}\right)u_{1s} + \left(\frac{B_1 - 1}{1+a^2}\right)a\,\mathrm{sgn}(y)v_{1s} \end{aligned} \tag{29}$$

where u_{1s} and v_{1s} denote the average of the velocities in front of and behind the screen. By equation (17), u_{1s} and v_{1s} are functions of y. Inserting equations (23) and (26) into the two jump conditions (3) and (4) provides two algebraic equations for the unknowns $[f_2(y)]$ and $[R_2]$:

$$\left.\begin{aligned} &[f_2(y)]n_x + [R_2]n_y = [H_2]n_x \\ &[f_2(y)]t_x + [R_2]t_y = [H_2]t_x + B_1V_{1+} + B_2V_0 \end{aligned}\right\} \tag{30}$$

Hence,

$$[f_2(y)] = 2C(a)u_{1s} + \left(\frac{2B_1 - 1}{1+a^2}\right)a\,\mathrm{sgn}(y)v_{1s} + \frac{a^2\left(B_1^2 + 2B_2\right)}{2(1+a^2)} \tag{31}$$

$$[R_2] = \frac{\text{sgn}(y)}{1 + a^2}\left[B_1[au_{1s} + \text{sgn}(y)v_{1s}] + \frac{1}{2}a\left(B_1^2 + 2B_2\right)\right] \qquad (32)$$

Because u_{1s} and v_{1s} are functions of y, so is f_2. Since the downstream profile is given by $u_\infty = 1 - [f_1]k - ([f_2] - \langle H_2\rangle_{x=\infty})k^2 - \ldots$, the wake at second order contains distributed vorticity. This should be contrasted with the normal screen result, where there is no vorticity in the wake until third order in the asymptotic expansion (Durbin and Muramoto, 1985).

By applying the Plemelj formulas, one can in principle determine a sectionally analytic function $H_2 + iR_2$ with jumps (25), (28), (29), and (32) and then find $[P_3]$. Because a Padé approximant to a two-term asymptotic expansion provides a very good representation of the drag coefficient over a large range of k (Durbin and Muramoto, 1985), we will not be concerned here with calculating these higher order contributions. The total drag and lift coefficients based on the projected area of an inclined screen are, respectively,

$$\begin{aligned} C_D &= \int_s \left\{[P]\cos\alpha + U[V]\sin\alpha\right\} ds \\ &= \cos\alpha \int_{-1}^{1}\left\{k[P_1] + k^2[P_2] + \ldots\right\} \\ &\times \sqrt{1 + a^2}\, dy + \sin\alpha \\ &\times \int_{-1}^{1}\left\{kU_0[V_1] + k^2(U_0[V_2] + U_1[V_1]) + \ldots\right\} \\ &\times \sqrt{1 + a^2}\, dy \end{aligned} \qquad (33)$$

$$\begin{aligned} C_L &= 2\int_{\frac{1}{2}s} \left\{-[P]\sin\alpha + U[V]\cos\alpha \, ds\right\} \\ &= -2\sin\alpha \int_{0}^{1}\left\{k[P_1] + k^2[P_2] + \ldots\right\} \\ &\times \sqrt{1 + a^2}\, dy + 2\cos\alpha \\ &\times \int_{0^+}^{1}\left\{kU_0[V_1] + k^2(U_0[V_2] + U_1[V_1]) + \ldots\right\} \\ &\times \sqrt{1 + a^2}\, dy \end{aligned} \qquad (34)$$

in which $\alpha = \tan^{-1}a$. It should be pointed out that the C_L defined in equation (34) is the lift coefficient that would be measured for a half-screen located next to an infinite wall at $y = 0$. Substituting the appropriate quantities into equations (33) and (34) yields the following expressions accurate to $O(k^2)$:

$$\begin{aligned} C_D = \left(\frac{1 + 2a^2B_1}{1 + a^2}\right)k + \Bigg\{ &\frac{a^2B_1[6B_1(1 - a^2) - 8] - 1}{4(1 + a^2)^2} \\ &+ \frac{2a^2B_2}{1 + a^2} - \frac{aB_1(1 + 2a^2B_1)}{2\pi(1 + a^2)^2}\ln\left(\frac{4}{1 + a^2}\right) \\ &- \frac{a^2B_1(1 + 2B_1) + 1}{\pi(1 + a^2)^2}\left(\frac{\pi}{2} - \tan^{-1}a\right) \\ &+ \frac{2a^2B_1(1 + B_1 + a^2B_1) + 1}{2\pi(1 + a^2)^2} \\ &\times \left(\frac{\pi}{2} - 2\tan^{-1}a\right)\Bigg\}k^2 \end{aligned} \qquad (35)$$

$$\begin{aligned} C_L = \left[\frac{a(2B_1 - 1)}{1 + a^2}\right]k + \Bigg\{ &\frac{a[1 - 2B_1(1 - 3a^2) + 6B_1^2(1 - a^2)]}{4(1 + a^2)^2} \\ &+ \frac{2aB_2}{1 + a^2} + \frac{B_1(1 + 2a^2 - 2a^2B_1)}{2\pi(1 + a^2)^2}\ln\left(\frac{4}{1 + a^2}\right) \\ &+ \frac{a(1 - B_1 - 2B_1^2)}{\pi(1 + a^2)^2}\left(\frac{\pi}{2} - \tan^{-1}a\right) \\ &- \frac{a[1 + 2B_1(a^2 - B_1 - a^2B_1)]}{2\pi(1 + a^2)^2} \\ &\times \left(\frac{\pi}{2} - 2\tan^{-1}a\right)\Bigg\}k^2 \end{aligned} \qquad (36)$$

The formulas reduce to $C_D = k - k^2/2$ and $C_L = (B_1 \ln 2)k^2/\pi$ when $a = 0$.

If we assume that the deflection coefficient D_θ (Taylor and Batchelor, 1949) is independent of the angle of incidence and that the following formula can be used,

$$D_\theta = (1 + k)^{-1/2} \qquad (37)$$

then since $B = 1 - D_\theta$, for small k

$$B_1 = \frac{1}{2},\ B_2 = -\frac{3}{8} \qquad (38)$$

These values of B_1 and B_2 have been used in computing all of the curves in figures 1 to 3.

In figure 1, the second-order downstream velocity in the wake is displayed for both forward-tilting and backward-tilting screens. Actually, $u_2(x = \infty, y)$ has logarithmic singularities at $y = 0$ and $|y| = 1$. The maximum velocity in the wake occurred at the centerline for $a > 0$ and at the edge $y = 1$ for $a < 0$. Thus, the shapes of these asymptotic profiles are in qualitative agreement with those measured by Koo and James (1973). A direct comparison cannot be made, however, since the experimental data are for screens partially spanning the width of a channel. Note that the analytical solution of Koo and James yields a uniform velocity profile in the wake that is not a good approximation to the actual profile. Their numerical results are in qualitative agreement with figure 1.

In figure 2, Padé approximants formed from the two-term expansion for C_D are plotted versus k for a series of values of a. This figure shows that $C_D = C_D(k)$ is a nonsymmetric function of a; the maximum drag occurred not at $a = 0$ but at $a = -0.11$. In contrast, the drag coefficient predicted by Koo and James' analytical solution is independent of the sign of a. Finally, the lift coefficient is shown in figure 3 for various values of a. One observes that $C_L = C_L(k)$ first increases for $0.2 \gtrsim a \gtrsim -1$ and then decreases for $-1 \gtrsim a > -\infty$. For the values of B_1 and B_2 given, the maximum lift and the point of zero lift occurred at $a = -0.9$ and $a = 0.23$, respectively.

Conclusions

The inviscid flow through a very porous screen inclined to the oncoming flow has been investigated. An asymptotic analysis for small resistance coefficients showed that when the screen is submerged in an infinite flow field, the first-order velocity is nonuniform along the screen. This nonuniformity gives rise to the presence of vorticity within the wake at second order. The present method also applies to axisymmetric screens or to free surface jets flowing through infinite screens. In those cases, Green's formulas for axisymmetric flow would be used in place of the Plemelj formulas.

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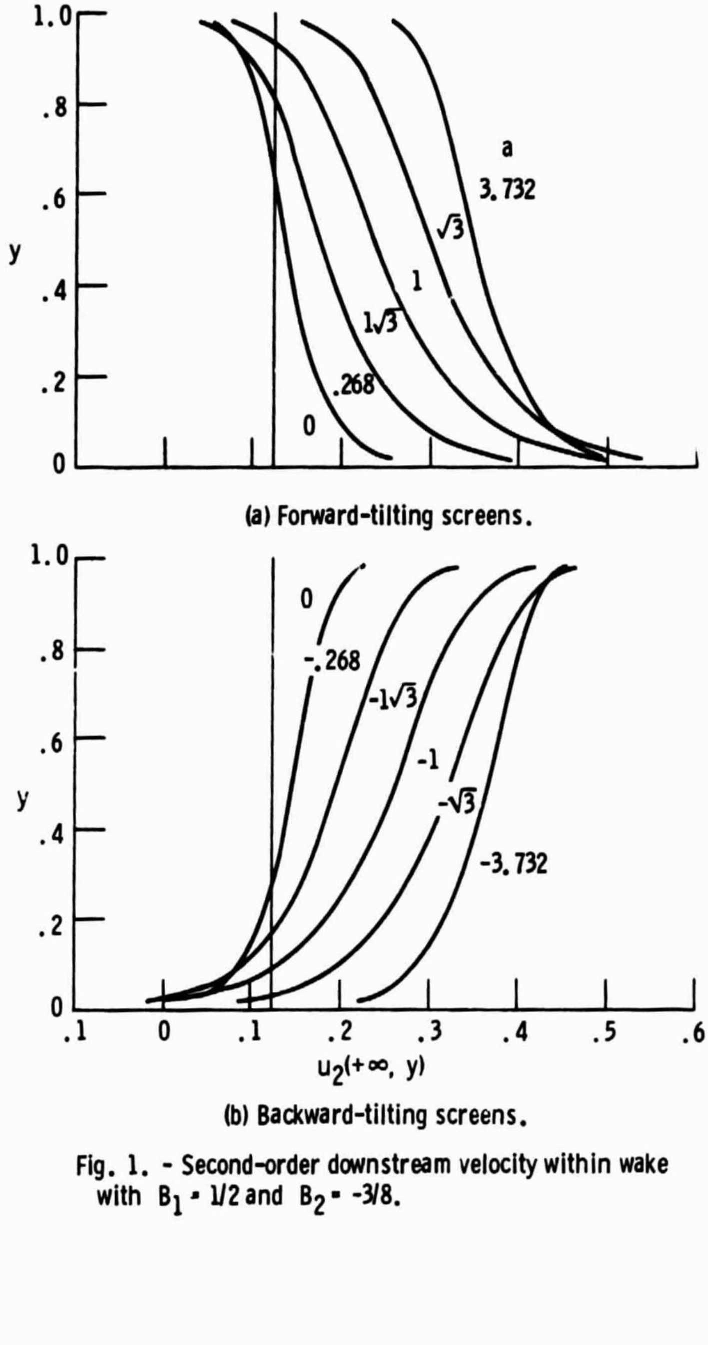

(b) Backward-tilting screens.

Fig. 1. - Second-order downstream velocity within wake with $B_1 = 1/2$ and $B_2 = -3/8$.

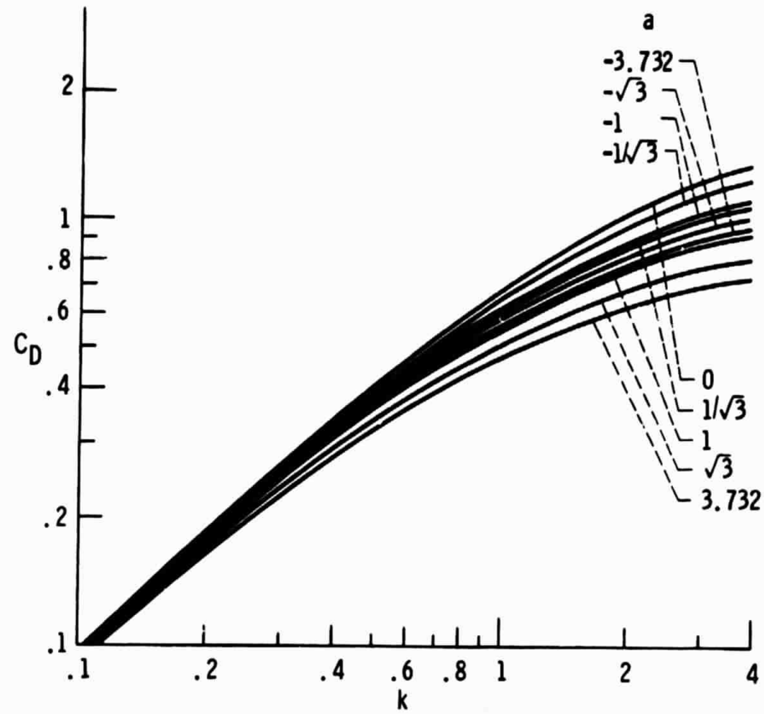

Fig. 2. - Drag coefficient as a function of resistance coefficient for various values of a with $B_1 = 1/2$ and $B_2 = -3/8$. Padé approximant formed from eq. (35).

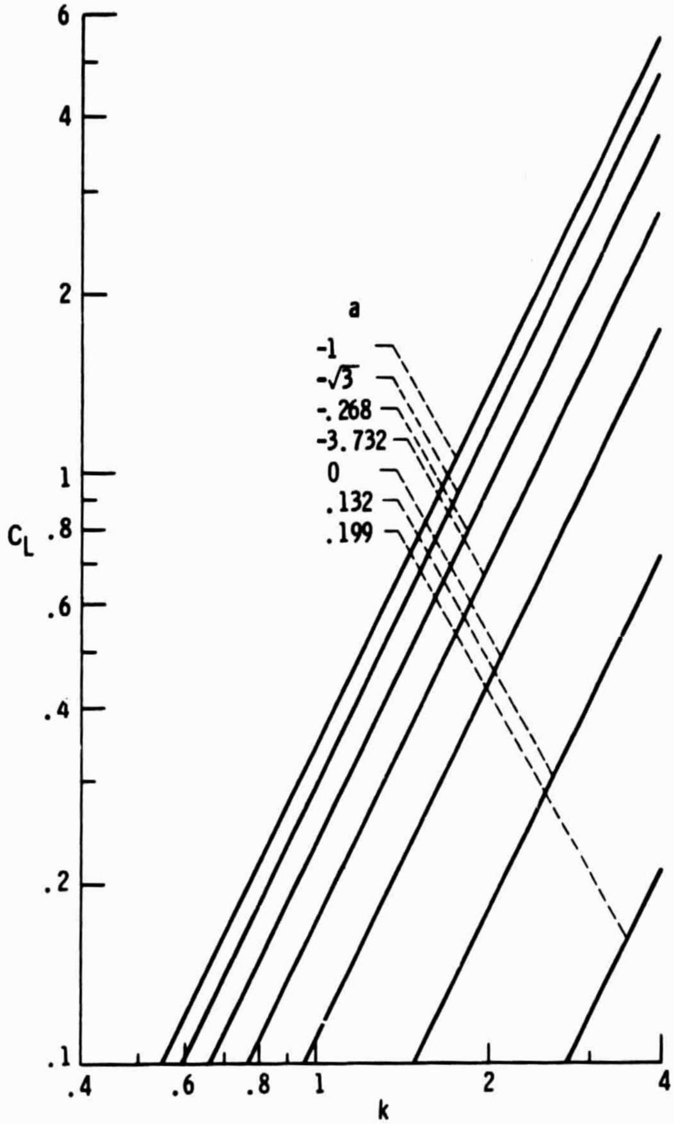

Fig. 3. - Lift coefficient as a function of resistance coefficient for backward-tilting screens with $B_1 = 1/2$ and $B_2 = -3/8$. Padé approximant formed from eq. (36).

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16. Abstract

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