J. Fluid Mech. (1977), *vol.* 82, *part* 2, *pp.* 241–253
Printed in Great Britain

An inviscid numerical simulation of vortex shedding from an inclined flat plate in shear flow

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(Received 12 July 1976)

Two-dimensional vortex shedding behind an inclined flat plate in uniform shear flow is numerically investigated by means of an inviscid discrete-vortex approximation. The points of appearance of the vortices are fixed in the plane of the plate at a short distance downstream of the edges of the plate. The strengths of the vortices are determined from the Kutta condition. On the assumption that the steadily periodic flow patterns are independent of initial conditions, the numerical calculations are performed for an inclined flat plate immersed in an incompressible fluid which is set in motion impulsively from rest with the velocity profile of uniform shear flow. The results of analysis show that the Strouhal number of vortex shedding and the time-averaged values of other hydrodynamic characteristics of the flow such as the outer-edge velocity of the separated shear layers, the convective velocity of the shear layers and the drag force exerted on the plate vary closely linearly with the shear parameter of the approaching shear flow. A linear relation between the Strouhal number and the shear parameter is confirmed by an air-tunnel experiment. The effects of the shear parameter on the calculated vortex patterns in the wake are also presented.

1. Introduction

The vortex shedding from two-dimensional bluff bodies placed in a uniform stream is of great practical importance and has been extensively studied for many years. Excellent reviews of the subject were published by Morkovin (1964) and Berger & Wille (1972), among others. There are, however, a number of practical cases in which the flow approaching the body is not uniform but is sheared, a typical example being a structure in the turbulent planetary boundary layer on the earth. Since structural oscillations can be caused by the vortex shedding from such a body, it is important to know whether the presence of shear in the approaching stream can have much effect on the mechanism by which the vortices are shed.

Very little work has been reported on the effect of shear on the vortex shedding. Furthermore, as far as the authors are aware, most of the previous investigators were concerned with a free-stream velocity varying in the axial direction of a cylindrical body. The flow over the body in this situation is pseudo-two-dimensional or weakly three-dimensional. A good list of papers in this category can be found in Maull & Young (1973). The main results of these investigations may be summarized as follows: the Strouhal number defined in terms of the vortex-shedding frequency, a representative length of the body and the local velocity in the free stream corresponding to the point of measurement is constant along the axis of the body within an error of a few per cent

(Chen & Mangione 1969; Maull & Young 1973); the vortex shedding from a bluff body in a shear flow can occur in spanwise cells, the frequency of vortex shedding being constant in each cell (Maull & Young 1973; Stansby 1976).

In addition to axial non-uniformity in the free stream, there exists another typical two-dimensional case: that in which the free-stream velocity is uniform in the axial direction of the body but varies in the direction normal to it. The planetary boundary-layer flow over long structures such as overhead railways or bridges which are parallel to the ground or water surface will be the most familiar examples. In some of these applications, the neighbouring boundary may exert a considerable influence on the kinematic and dynamic properties of the flow over the body, including the vortex-shedding characteristics. However, in order to understand the effect of the free-stream non-uniformity on the characteristics of the flow, it is reasonable to neglect that of the neighbouring boundary in the interests of simplicity for the time being. Apart from the practical applications, this problem deserves attention in its own right as one of the fundamental problems in fluid mechanics. It is rather surprising that, within the authors' knowledge, almost nothing is known about the vortex-shedding and related hydrodynamic characteristics of a two-dimensional body placed in such a shear flow.

From this point of view, the present paper describes a theoretical investigation of the vortex-shedding and related properties of an inclined flat plate placed in a uniform shear flow which has a linearly varying velocity profile. A uniform shear flow has been employed here in order to make the problem theoretically tractable. The choice of an inclined flat plate will be justified in what follows in conjunction with the theoretical model. The relation between the vortex-shedding frequency and the free-stream non-uniformity obtained theoretically will be compared with the result of an air-tunnel experiment.

2. Method of analysis

At present one of the most powerful theoretical tools which permit calculation of unsteady separated flow over two-dimensional bluff bodies at sufficiently large Reynolds number is the inviscid discrete-vortex model. In this model, the shear layers emanating from the separation points are approximated by an array of discrete vortices introduced into the wake at appropriate time intervals at some points in the vicinity of the separation points. The motion of the shear layers is then represented by the evolution of the arrays of vortices. An extensive review of the investigations based on the inviscid discrete-vortex model was written by Clements & Maull (1975), and demonstrated the limitations and usefulness of the model.

The determination of the positions of appearance and strengths of the vortices is one of the crucial points in a calculation based on this model. Kuwahara (1973), in his calculation of the vortex shedding behind an inclined flat plate, determined the strengths of the nascent vortices from the Kutta condition. The nascent vortices were introduced at two fixed points near the edges of the plate. Further examination of Kuwahara's method was undertaken by Kiya & Arie (1977, hereafter referred to as K & A), who calculated in detail the kinematic and dynamic properties of flow over an inclined flat plate by systematically changing the distance between the points of appearance of the nascent vortices and the edges of the plate. Clements & Maull (1975) used the same method in some of their calculations of the vortex shedding behind a square-based body. Sarpkaya (1975) was also concerned with the inclined flat plate but used the Kutta condition in a different way. He determined the positions of the nascent vortices from the Kutta condition after computing their strengths in terms of the average of the transport velocities of four vortices in each shear layer. The number of disposable parameters is reduced to a minimum in Sarpkaya's method and in this sense it may be better than Kuwahara's method. Sarpkaya argues that oscillation of the positions of the nascent vortices is essential to the continuation of oscillations in the drag force exerted on the plate and is coupled with the manner in which the vortex sheets roll up. However, as was shown in K & A, oscillation of the position of the nascent vortices is not essential to the continuation of the drag-force oscillation. Although it is true that Sarpkaya's method predicts values of the Strouhal number and the time-averaged drag force in better agreement with experiments than does Kuwahara's method, the latter is far easier to apply and less time consuming in view of the programming procedure and computer run time. Since an established computer program based on the method of Kuwahara is available to the authors, it will be used in the present investigation with a few modifications required to incorporate the effect of the free-stream shear.

The Strouhal number which is calculated by Kuwahara's method for a plate at an incidence of 60° placed in a uniform free stream is 22–36 % smaller than that observed experimentally, when the distance a_s between the locations of the nascent vortices and the edges of the plate is taken as $a_s/(2a) = 0{\cdot}0125$, $2a$ being the half-height of the plate. The time-averaged drag force exerted on the plate is 70 % larger than the experimental value. A few plausible reasons for these differences between the theory and experiments have been described in K & A. On the other hand, the calculated mean velocity at the outer edge of the separated shear layers is smaller by only 3 % than the experimental result. The vortex pattern in the wake calculated by Kuwahara's method is more consistent with a few photographs taken by flow-visualization techniques than that calculated by Sarpkaya's method. One may naturally expect that the calculated values of the Strouhal number, the time-averaged drag coefficient and other relevant hydrodynamic characteristics of a plate placed in a uniform shear flow will include errors of the same order of magnitude as those in a uniform flow. Therefore it is an assumption of the present investigation that the general tendency of changes in the kinematic and dynamic characteristics of the flow over the plate with changes in the free-stream non-uniformity is correctly predicted by the calculation based on the method of Kuwahara, qualitatively at least. The nature of the plausible reasons for the errors described in K & A seems to permit this assumption. In view of the fact that almost nothing is yet known about the vortex-shedding characteristics in the shear flow considered here, even this sort of preliminary information will play an important role in the setting up of a more detailed study in the future.

In passing it should be mentioned that a two-dimensional body with salient edges must be employed in this method of vortex-shedding calculation, because the Kutta condition is used to determine the strengths of the nascent vortices. Admittedly an inclined flat plate is the most fundamental shape of such a body both hydrodynamically and mathematically.

One takes the x axis in the direction of the free stream and the y axis normal to it, the corresponding velocity components being denoted by u and v. The centre of an inclined flat plate coincides with the origin of the x, y plane. The free-stream velocity is described by a uniform shear flow

$$(u_\infty, v_\infty) = (U_\infty + Gy, 0), \tag{1}$$

where U_∞ is the velocity at infinity corresponding to the centre of the plate and G is the velocity gradient, or shear, of the free stream.

A stream function ψ is introduced by the definition

$$\partial\psi/\partial y = u, \quad \partial\psi/\partial x = -v. \tag{2}$$

Thereby the equation of continuity is automatically satisfied and Euler's equations of motion for an incompressible fluid reduce to

$$\Delta\psi = G, \tag{3}$$

where $\Delta = \partial^2/\partial x^2 + \partial^2/\partial y^2$. If ψ is subdivided into two parts

$$\psi = \tfrac{1}{2}Gy^2 + \Psi, \tag{4}$$

Ψ satisfies the Laplace equation

$$\Delta\Psi = 0. \tag{5}$$

Accordingly, by the introduction of a harmonic function Φ which is related to Ψ by the Cauchy–Riemann equations, the complex function

$$W = \Phi + i\Psi \tag{6}$$

becomes an analytic function of $z = x + iy$. Uniform shear flow around a two-dimensional body can thus be treated by potential flow theory. It should be remarked here that the terminology in the present paper is the same as that in K & A, unless otherwise stated.

A transformation plane $Z = X + iY$ will be introduced by the definition

$$z = ie^{-i\alpha}(Z - a^2/Z), \tag{7}$$

where a and α are real constants. The circle of radius a with centre at the origin of the Z plane is transformed in the physical plane into an inclined flat plate of length $4a$ at an incidence angle α to the free stream. The leading and trailing edges of the plate, which will hereafter be referred to by the suffixes 1 and 2, are located at $Z_1 = ai$ and $Z_2 = -ai$ respectively in the Z plane.

The complex velocity potential W consists of four parts, i.e.

$$W = W_u + W_v^{(N)} + W_v^{(0)} + W_s, \tag{8}$$

in which W_u represents the potential flow over a plate placed in a uniform flow of velocity U_∞, $W_v^{(N)}$ represents the flow induced by a system of vortices in the wake, $W_v^{(0)}$ represents the flow induced by the nascent vortices and W_s is needed to satisfy the boundary condition on the plate surface owing to the rotational component $\tfrac{1}{2}Gy^2$ in (4). The first three components are exactly the same as those described in K & A. The last component will now be determined. Since the velocity vector on the surface of the plate should be tangential to it, the boundary condition can be written as

$$\tfrac{1}{2}Gy_p^2 + \Psi_{sp} = 0, \tag{9}$$

where the suffix p implies the value on the surface of the plate and Ψ_s is the imaginary part of W_s. Another transformation plane $s = \lambda + i\mu$ in introduced through

$$s = i(Z-a)/(Z+a), \tag{10}$$

which maps the region outside the circle of radius a in the Z plane onto the upper half of the s plane. The ordinate of the plate is thus transformed into the real axis of the s plane. Accordingly, an analytic function whose imaginary part on the boundary is described by (9) is given in the s plane by

$$W_s = \frac{G}{2\pi}\int_{-\infty}^{+\infty} \frac{y_p^2(\lambda^*, 0)}{s-\lambda^*}\, d\lambda^*, \tag{11}$$

in which

$$y_p(\lambda, 0) = 4a \sin(\alpha)\,\lambda/(\lambda^2+1). \tag{12}$$

Substituting (12) into (11) and performing the integration, one finally obtains

$$W_s = -iGa^2 \sin^2\alpha(1-a^2/Z^2). \tag{13}$$

The strengths of the nascent vortices can be determined from equations (12a,b) of K & A except that $B(Z)$ is replaced by

$$B(Z) = -\left(\frac{dW_u}{dZ}+\frac{dW_s}{dZ}+\frac{dW_v^{(N)}}{dZ}\right). \tag{14}$$

The velocity of any one of the vortices in the wake is given by

$$u_{jk}-iv_{jk} = Gy_{jk}-ie^{i\alpha}\frac{Z_{jk}^2}{Z_{jk}^2+a^2}(U_{jk}-iV_{jkj})+(-1)^{j+1}e^{i\alpha}\frac{\Gamma_{jk}}{2\pi}\frac{a^2 Z_{jk}}{(Z_{jk}^2+a^2)^2}, \tag{15}$$

where

$$U_{jk}-iV_{jk} = \left(\frac{d}{dZ}\left\{W-(-1)^{j+1}i\frac{\Gamma_{jk}}{2\pi}\log(Z-Z_{jk})\right\}\right)_{Z=Z_{jk}} \tag{16}$$

The oscillating force exerted on the plate can be calculated from the generalized Blasius theorem, which in the case of uniform shear flow becomes

$$\tilde{D}-i\tilde{L} = \tfrac{1}{2}i\rho\oint (dW/dz)^2 dz + i\rho\frac{\partial}{\partial t}\oint W^* dz^* + \tfrac{1}{2}\rho G\oint (z\,dW - z^*\,dW^*). \tag{17}$$

On substituting (8) into (17) together with the expressions for W_u, $W_v^{(N)}$, $W_v^{(0)}$ and W_s and carrying out the integrations, one obtains

$$\begin{aligned}\tilde{D}-i\tilde{L} = &-4\pi i\rho G U_\infty a^2\sin^2\alpha + \sum_{j=1}^{2}(-1)^{j+1} i\rho \sum_{k=0}^{N_j}\Gamma_{jk}(u_{jk}-iv_{jk})\\ &- i\rho a^2\sum_{j=1}^{2}(-1)^{j+1}\sum_{k=0}^{N_j}\Gamma_{jk}\left(\frac{e^{2i\alpha}}{Z_{jk}^2+a^2}(Gy_{jk}+u_{jk}+iv_{jk})+\frac{Gy_{jk}+u_{jk}-iv_{jk}}{Z_{jk}^{*2}+a^2}\right)\\ &-\rho G a^2\sin^2\alpha\sum_{j=1}^{2}(-1)^{j+1}\sum_{k=0}^{N_j}\Gamma_{jk}\left(\frac{1}{Z_{jk}}-\frac{1}{Z_{jk}^*}\right).\end{aligned} \tag{18}$$

In the same manner as in a uniform free stream, there is no force acting along the plate.

3. Results and discussion

In the present calculation the fluid is assumed to be set in motion impulsively from rest with the velocity distribution (1). Although in the case of a uniform velocity distribution ($G = 0$) this condition may easily be realized by moving the plate impulsively from rest in an otherwise stationary fluid, it will be next to impossible to obtain such a velocity profile as (1) experimentally at the instant of the start of flow. However,

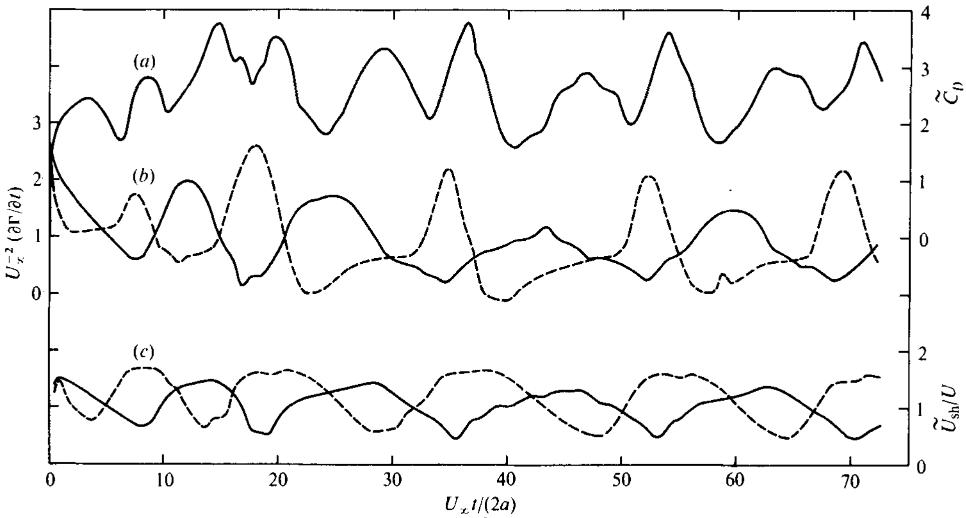

FIGURE 1. Wave forms of (*a*) the drag coefficient $\tilde{C}_D$,(*b*) the rate of shedding $U_\infty^{-2}(\partial\Gamma/\partial t)$ of vorticity into the shear layers from the leading and trailing edges of the plate and (*c*) the convective velocity $\tilde{U}_{sh}/U$ of the shear layers. $\alpha = 60°$, $4aG/U_\infty = -0{\cdot}08$. In (*b*) and (*c*): ——, leading edge; ---, trailing edge.

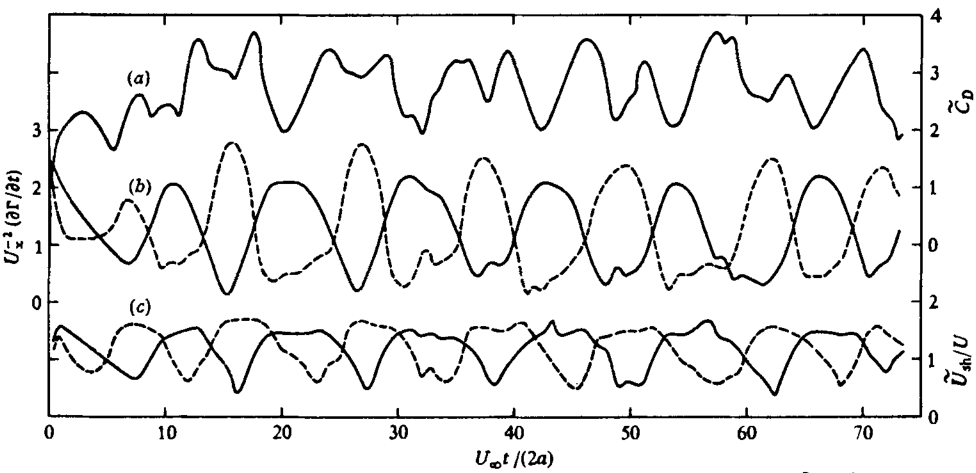

FIGURE 2. Wave forms of (*a*) the drag coefficient $\tilde{C}_D$, (*b*) the rate of shedding $U_\infty^{-2}(\partial\Gamma/\partial t)$ of vorticity into the shear layers from the leading and trailing edges of the plate and (*c*) the convective velocity $\tilde{U}_{sh}/U$ of the shear layers. $\alpha = 60°$, $4aG/U_\infty = 0{\cdot}10$. In (*b*) and (*c*): ——, leading edge; ---, trailing edge.

since it is the state of steadily periodic vortex shedding that most practical appplications are concerned with, this physical difficulty with the initial conditions will not pose any problem. The kinematic and dynamic characteristics of the flow in the steadily periodic vortex shedding will not be influenced by the initial conditions.

Numerical calculations were performed for an inclined flat plate at an incidence of 60° by systematically changing the shear parameter $4aG/U_\infty$. The distance between the points of appearance of the nascent vortices and the leading and trailing edges of the plate was chosen as $a_s/(2a) = 0{\cdot}0125$ in view of the results obtained in K & A.

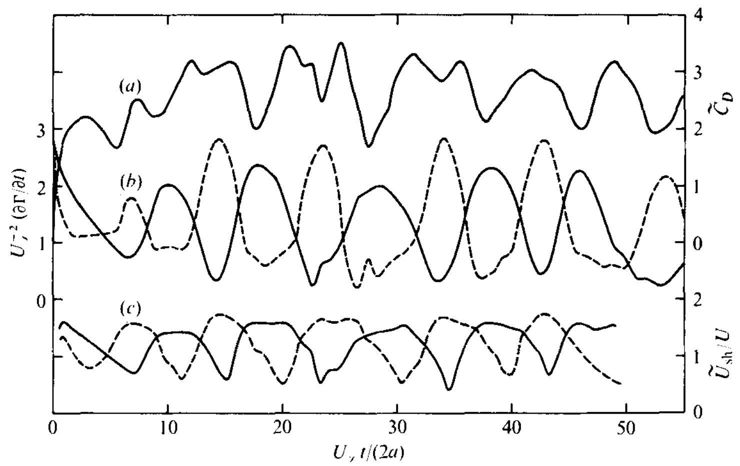

FIGURE 3. Wave forms of (*a*) the drag coefficient $\tilde{C}_D$, (*b*) the rate of shedding $U_\infty^{-2}(\partial\Gamma/\partial t)$ of vorticity into the shear layers from the leading and trailing edges of the plate and (*c*) the convective velocity $\tilde{U}_{sh}/U$ of the shear layers. $\alpha = 60°$, $4aG/U_\infty = 0{\cdot}20$. In (*b*) and (*c*): ——, leading edge; ---, trailing edge.

The time intervals δt and δt_i and the cut-off length σ were the same as those used in K & A.

Figures 1, 2 and 3 show the oscillation wave forms of the drag coefficient $\tilde{C}_D$, the rate of shedding $\partial\Gamma/\partial t$ of vorticity into the shear layers and the convective velocity $\tilde{U}_{sh}$ of the shear layers, the shear parameter being chosen as $4aG/U_\infty = -0{\cdot}08$, $0{\cdot}10$ and $0{\cdot}20$ respectively. The shear parameter is defined as positive if the free-stream velocity corresponding to the leading edge of the plate is higher than that corresponding to the trailing edge and vice versa. It is immediately evident that the frequency of vortex shedding increases with increases in the shear parameter. Since, as may be most clearly seen in the wave forms of $\partial\Gamma/\partial t$, the vortex-shedding interval changes a little in an irregular manner from one cycle to another, the Strouhal number St is determined as the arithmetic average over all the intervals after the second peaks of $(\partial\Gamma/\partial t)_1$ and $(\partial\Gamma/\partial t)_2$.

Figure 4(*a*) shows the ratio of the Strouhal number of the plate in the shear flow to that in uniform flow, i.e. St/St_0, where St_0 is the Strouhal number in the uniform flow, as a function of the shear parameter. In these Strouhal numbers the representative velocity is U_∞. The relation between the Strouhal-number ratio and the shear parameter is closely approximated by a straight line of the form

$$St/St_0 = 1 + c(4aG/U_\infty), \tag{19}$$

in which c is a constant of proportionality whose value is about 2·4. The experimental data obtained by Abe (1976), which are also included in figure 4(*a*), confirm a linear relationship between the Strouhal-number ratio and the shear parameter, the constant c taking a value of about 1·3 in the experiment. The authors could not find plausible explanations for the rather large difference between the theoretical and experimental values of c. It would be interesting to repeat the same calculation by means of Sarpkaya's method (1975), because his method yields a Strouhal number which compares well with experiments in the case of a uniform free stream.

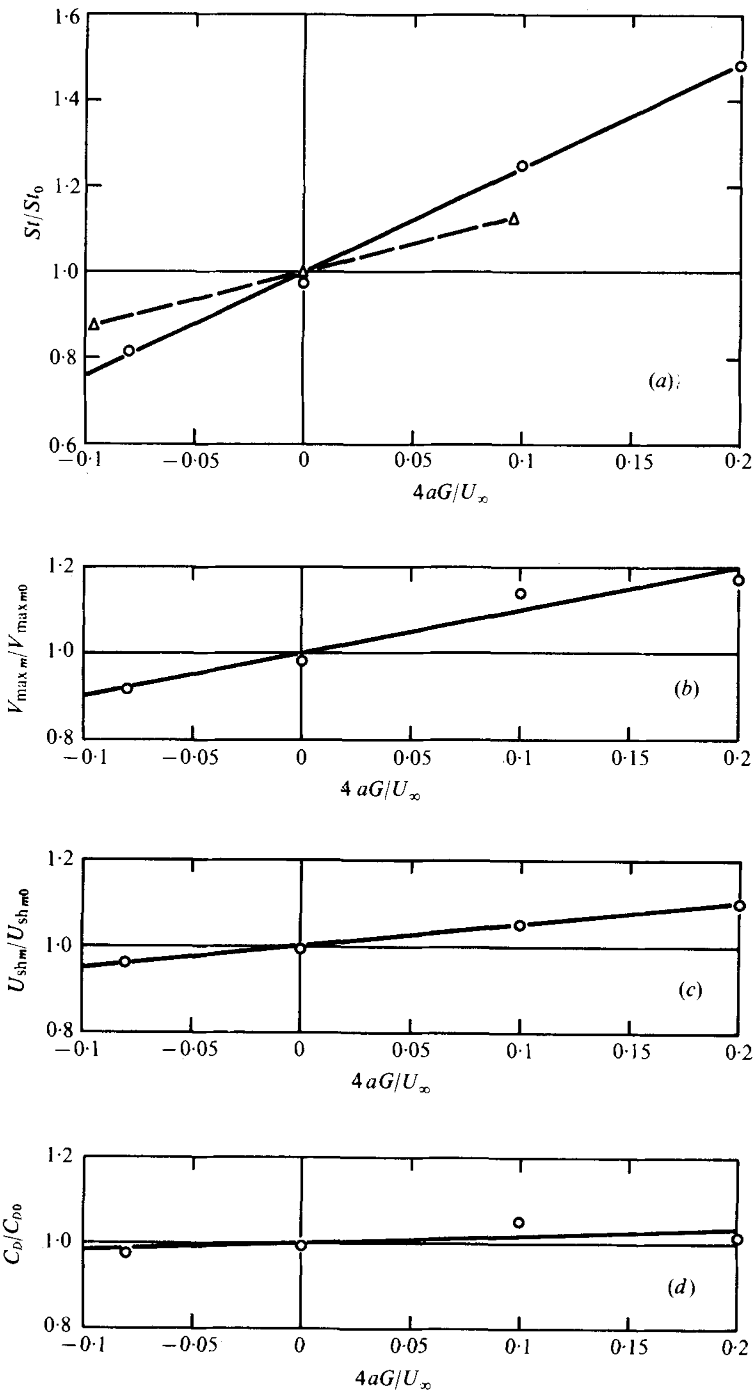

FIGURE 4. Variation of (a) Strouhal number, (b) outer-edge velocity of shear layers, (c) convective velocity of shear layers and (d) drag coefficient with respect to the shear parameter. ○, present calculation; ——, best-fit straight line; —△—, experiment by Abe (1976). $\alpha = 60°$.

Figures 4(*b*), (*c*) and (*d*) show the relation between the shear parameter and the time-averaged values of the velocities at the outer edges of the shear layers emanating from both edges of the plate, the convective velocity of the shear layers and the drag coefficient, which are denoted by $V_{\mathrm{max}m}$, $U_{\mathrm{sh}m}$ and C_D respectively, in the form of the ratio to the corresponding quantities in a uniform free stream (identified by the suffix 0). Here the suffix m represents an arithmetic average of the values at the leading and trailing edges of the plate. Each ratio on the whole increases with increasing shear parameter, except for the C_D ratio corresponding to $4aG/U_\infty = 0{\cdot}2$. The best-fit lines to these data, which were obtained by means of the least-squares method, are as follows:

$$V_{\mathrm{max}m}/V_{\mathrm{max}m0} = 1+0{\cdot}99(4aG/U_\infty), \tag{20}$$

$$U_{\mathrm{sh}m}/U_{\mathrm{sh}m0} = 1+0{\cdot}50(4aG/U_\infty), \tag{21}$$

$$C_D/C_{D0} = 1+0{\cdot}17(4aG/U_\infty), \tag{22}$$

which may be applicable in the range $-0{\cdot}1 \leqslant 4aG/U_\infty \leqslant 0{\cdot}20$. An examination of (19)–(22) immediately reveals that the Strouhal number is most sensitive to the shear parameter, while the time-averaged drag coefficient is most insensitive to it. Since Abe (1976) observed experimentally that the drag coefficient of the plate was little influenced by the free-stream shear as long as the shear parameter was less than 0·1, the theoretical prediction is not necessarily inconsistent with the experiment.

A linear relationship between the Strouhal number and the shear parameter may suggest that the characteristics of the separated flow over an inclined flat plate placed in a uniform shear flow are approximately prescribed by the free-stream velocity corresponding to the leading edge of the plate. With this suggestion in mind, (19) can be derived in a simple way. Since the Strouhal number of the vortex shedding behind an inclined flat plate in a uniform flow is constant over a wide range of the Reynolds number, a small change in the free-stream velocity, say ΔU_∞, is accompanied by a small change in the vortex-shedding frequency which is proportional to ΔU_∞. In the uniform shear flow considered in this study, the free-stream velocity corresponding to the leading edge of the plate is higher by $2Ga\sin\alpha$ than that corresponding to the centre of the plate. Accordingly, the vortex-shedding frequency f in the uniform shear flow may be written as

$$f-f_0 \propto G\sin\alpha, \tag{23}$$

where f_0 is the vortex-shedding frequency in a uniform free stream whose velocity is equal to that of the approaching shear flow at the centre of the plate. On writing the constant of proportionality in (23) as c', one finally obtains

$$St/St_0 = 1+\{c'\sin\alpha/(4St_0)\}(4aG/U_\infty), \tag{24}$$

which is reduced to (19) by the choice $c = c'\sin\alpha/(4St_0)$. If the experimental values of $c = 1{\cdot}3$ and $St_0 = 0{\cdot}17$ (Fage & Johansen 1927) are employed, one obtains $c' \simeq 1{\cdot}0$.

It should be remarked that linear relationships between each flow characteristic and the shear parameter such as those given by (19)–(22) will be valid only for bluff bodies, such as an inclined flat plate, for which the leading and trailing edges can be clearly defined on physical grounds. In the case of symmetric bluff bodies such as a circular cylinder and a normal flat plate, the dynamic properties of the flow must be even functions of the shear parameter, because the two shear flows described by

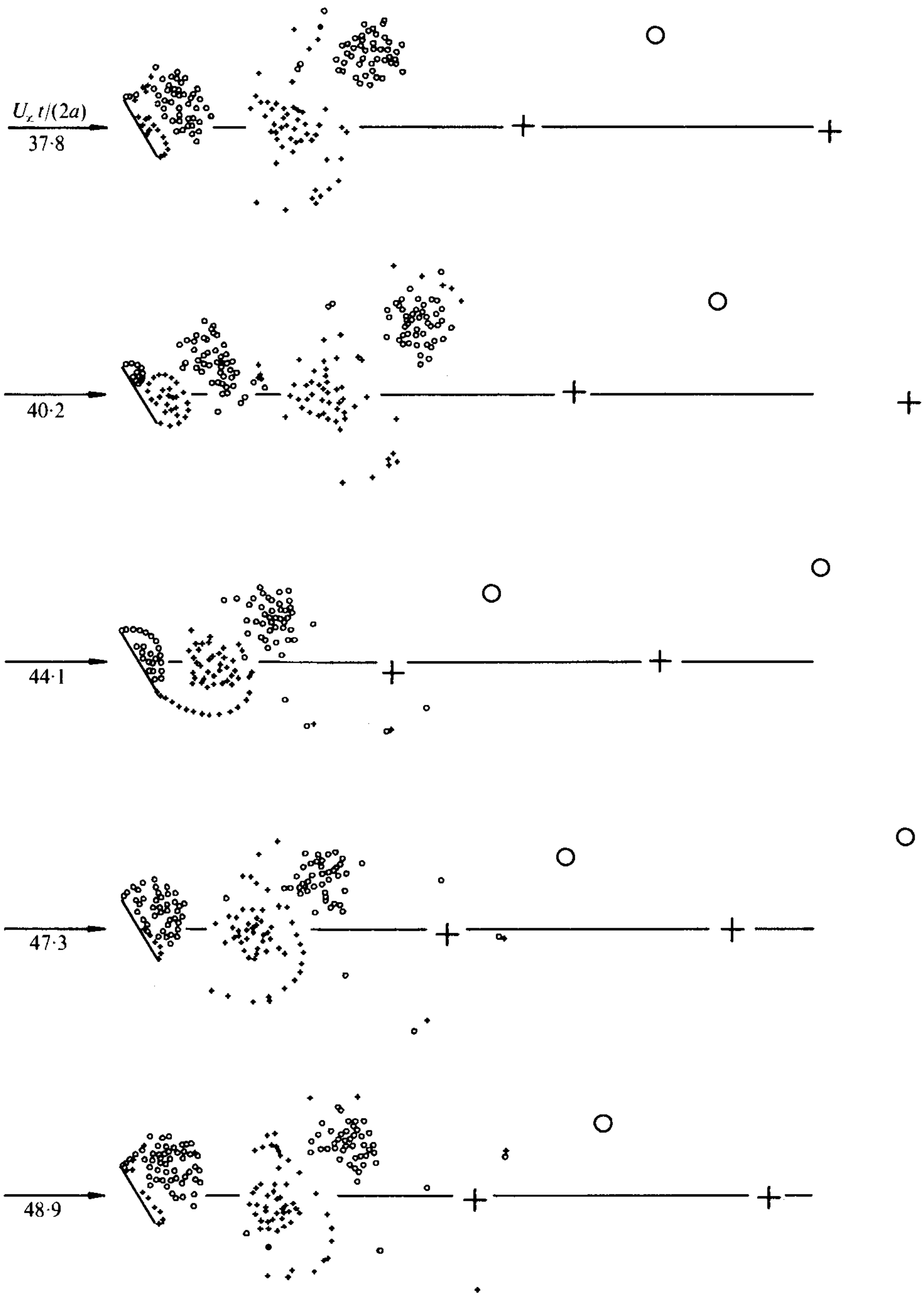

FIGURE 5. Vortex patterns over one full cycle of steadily periodic flow. ○, clockwise vortices; +, counterclockwise vortices. $\alpha = 60°$, $4aG/U_\infty = 0{\cdot}10$.

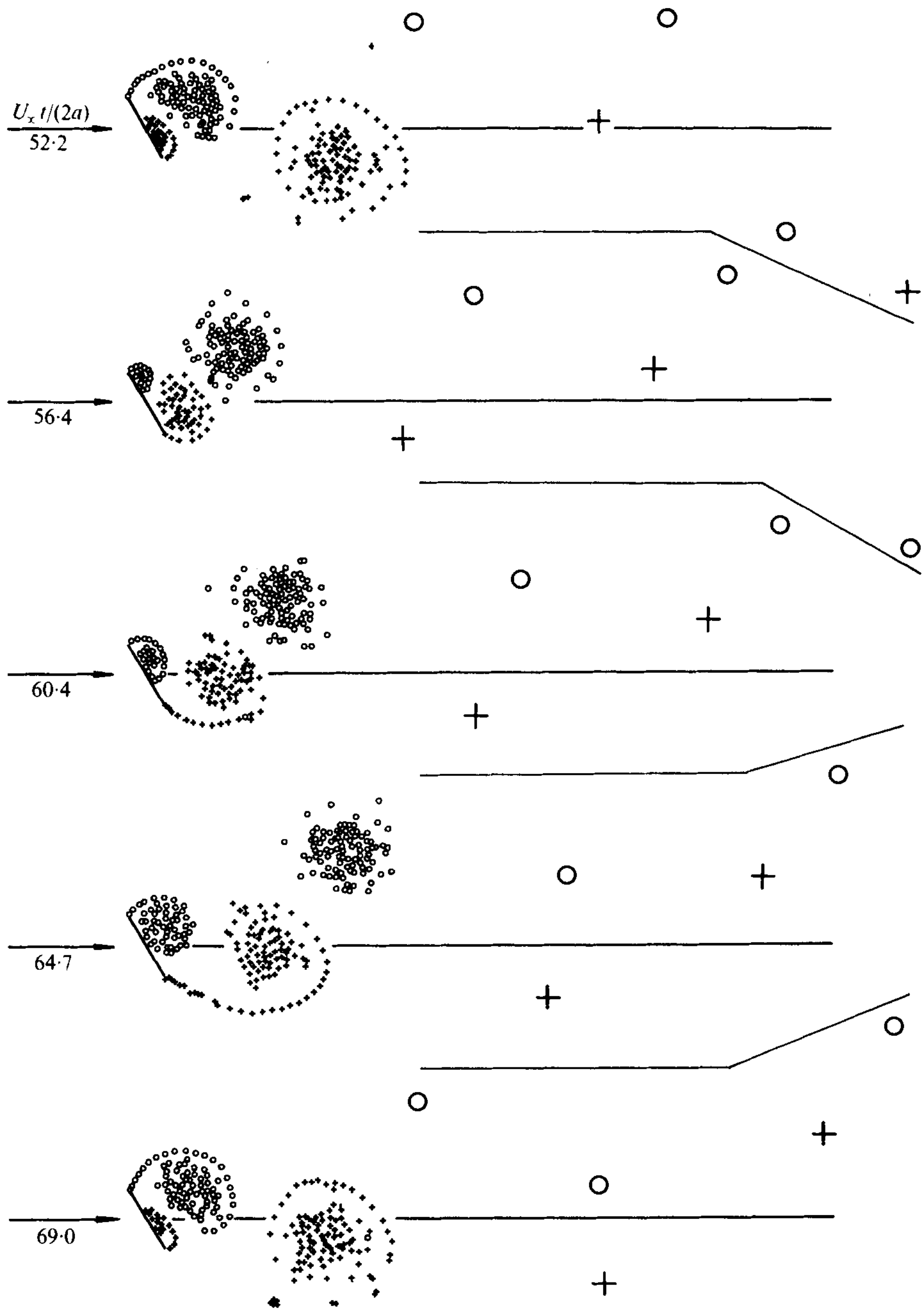

FIGURE 6. Vortex patterns over one full cycle of steadily periodic flow. ○, clockwise vortices; +, counterclockwise vortices. $\alpha = 60°$, $4aG/U_\infty = -0{\cdot}08$.

$u_\infty = U_\infty \pm Gy$ are physically equivalent in this case. Accordingly, if the shear parameter is much less than unity, the Strouhal-number ratio can be written in the form

$$St/St_0 = 1 + c_1(Gl/U_\infty)^2 + c_2(Gl/U_\infty)^4 + \ldots, \tag{25}$$

where l is a representative length of the body and c_1 and c_2 are numerical constants. Equation (25) suggests that the non-uniformities in the free stream will have much less effect on the characteristics of the flow around symmetric bluff bodies than on those for asymmetric ones, as long as the shear parameter is not very large.

Figures 5 and 6 show the vortex patterns in the wake over one full cycle of steadily periodic flow for two typical values of the shear parameter, i.e. $4aG/U_\infty = 0{\cdot}10$ and $-0{\cdot}08$. As may be seen in figure 5, the vortex patterns corresponding to $4aG/U_\infty = 0{\cdot}10$ are similar to those of an ordinary Kármán vortex street behind a symmetrical bluff body placed in a uniform free stream. The inclination of the vortex-street axis and the phase difference between the vortex shedding from the leading and trailing edges of the plate which were observed in the calculation of K & A are not evident in this case except for a small displacement of the vortex-street axis towards the high-velocity side. The general characteristics of the vortex patterns corresponding to $4aG/U_\infty = 0{\cdot}20$, which are not shown in the present paper, mainly in the interests of space, are almost the same as those corresponding to $4aG/U_\infty = 0{\cdot}10$ except that the said displacement of the vortex-street axis is much smaller. However, as may be seen in figure 6, a uniform shear flow with a negative shear parameter yields much less coherent vortex patterns behind the plate. It is hoped that a detailed experimental study in the future will confirm, or otherwise, the vortex patterns in the wake predicted by the present investigation.

4. Concluding remarks

The kinematic and dynamic characteristics of the flow over an inclined flat plate placed in a uniform shear flow have been investigated through the use of an inviscid discrete-vortex model in which the points of appearance of the vortices are fixed near the separation points and their strengths are determined from the Kutta condition. Numerical calculations were performed for an inclined flat plate at an incidence of 60° by systematically changing the shear parameter of the approaching shear flow, the shear parameter being in the range $-0{\cdot}08$ to $0{\cdot}20$.

The Strouhal number of the vortex shedding was found to increase linearly with increasing shear parameter. The linear relationship between the Strouhal number and the shear parameter was confirmed by an air-tunnel experiment except that the constant of proportionality obtained experimentally is about half the calculated one. The time-averaged values of the drag coefficient, the velocity at the outer edges of the shear layers and their convective velocities also increase linearly to fairly good approximations as the shear parameter increases. The Strouhal number was found to be most sensitive to the shear parameter, whereas the time-averaged drag force is most insensitive to it. The theoretical predictions in this respect are not inconsistent with experiment.

When the shear parameter is positive, the vortex patterns in the wake are coherent and similar to the ordinary Kármán vortex street observed behind a symmetric bluff body in a uniform flow. However, for a negative shear parameter the vortex patterns become much less coherent, which may suggest that organized vortex systems will not appear in the case of sufficiently large negative shear parameters. Detailed experimental studies will be necessary to check the predictions of the present theoretical investigation.

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