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A TIME-DOMAIN PANEL METHOD FOR ANALYSIS OF FOILS IN UNSTEADY MOTION AS OSCILLATING PROPULSORS

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ABSTRACT

Study of oscillating propulsors requires a method that accounts for the flexibility of these structures in addition to their oscillatory motion. This paper describes a two-dimensional constant potential panel method that was written to calculate the forces developed by an oscillating foil. Output from this program was compared with linear, two-dimensional, small-amplitude theory for a harmonically oscillating rigid foil. Computations were made for a foil that was flexible in the chordwise direction; the results were compared with predictions for rigid foils.

INTRODUCTION

Huge amounts of work have been done on the application of panel, or boundary element, methods to problems in aerodynamics. The background theory to methods has, for example, been covered in text books by Moran (1984) and Katz and Plotkin (1991), and the latter include a brief history of panel codes. The use of panel methods to predict forces on unsteady lifting bodies has been achieved by applying the method in the time domain (e.g. Blair and Williams, 1989; Maskew, 1991; Kinnas and Hsin, 1992).

Study of oscillating propulsors, such as the naturally-occurring flukes of cetaceans, the tail fins of some fast-swimming fish and possible man-made propulsors, requires a method that accounts for the flexibility of these structures in addition to their oscillatory motion. Large amplitude flexibility of these hydrofoils occurs in both chordwise and spanwise directions. Here a two-dimensional time domain panel method for a chordwise flexible foil is described which was written as the first step towards developing a time domain method for a three-dimensional flexible wing.

Katz and Weihs (1978), Kudo et al. (1984) and Yamaguchi (1992) studied the effect of passive chordwise flexibility on hydrodynamic propulsion from two-dimensional aerofoils; that is the deformations of the foil were a function of the hydrodynamic loading and the structural characteristics of the foil. These studies showed that flexibility increases propulsive efficiency, but reduces thrust. In addition, Kudo et al. (1984) and Yamaguchi (1992) showed that for a given thrust, a flexible foil has a higher propulsive efficiency than a rigid foil. For most naturally-occurring oscillating propulsors, the structural properties are not homogeneous or well documented (Felts, 1966; Purves, 1969). Predicting deflections for a certain loading is speculative and to avoid this the present work predicts propulsive performance for a postulated chordwise flexibility. Eventually, following an extensive parametric study on the effects of flexibility on performance, it may be possible to advantageously design man-made propulsors with defined flexible characteristics.

METHOD

The flow around the foil and its wake was considered to be inviscid, incompressible and irrotational. From Green's formula (e.g. Lighthill, 1986, equation 282), an integral equation can be set up for the unknown potential values, ϕ, on the surface of the foil in terms of the boundary condition on the foil, $\partial\phi/\partial n$, where $\mathbf{n}$ is the normal to the foil surface. For example, for two-dimensional flows this has been described by Katz and Plotkin (1991, p.57). Taking the velocity potential, ϕ, to represent the perturbation potential (i.e. that due to the disturbance of the flow around the body), the total velocity, $\mathbf{u}$, of the flow around the foil in a uniform flow, $\mathbf{u}_\infty$, is $\mathbf{u} = \mathbf{u}_\infty + \nabla\phi$; and the boundary condition on the surface of a moving foil (such that the normal component of the fluid and body velocities are equal) is $\mathbf{n}\cdot\nabla\phi = \mathbf{n}\cdot(\mathbf{u}_B - \mathbf{u}_\infty)$, where $\mathbf{u}_B$ is the velocity of the foil. The integral equation for the potential, ϕ_p, at a point in the flow is

$$\phi_p = \int_{foil}(\mathbf{n}\cdot\nabla\phi)\phi_s \mathrm{d}S \;-\; \int_{foil}\phi(\mathbf{n}\cdot\nabla\phi_s)\mathrm{d}S \;-\; \int_{wake}\Delta\phi(\mathbf{n}\cdot\nabla\phi_s)\mathrm{d}S \quad (1)$$

where ϕ is the strength of the doublet distribution over the surface, S; ϕ_s is the potential of a two-dimensional source and $\Delta\phi$ is the jump in potential over the wake (Moran, 1984). The boundary condition information is contained in the strength of the source terms (see the section on Dirichlet boundary condition (Katz and Plotkin, 1991, p. 240)).

The limit of this equation, as the point p approaches a point on the foil surface, was solved by discretizing the foil surface into panels following a cosine spacing over chord, thus concentrating panels at the leading and trailing edges, and assuming a constant value of the doublet potential and source strength over each panel. The discretization was similar to that given by Moran (1984, p.270–271) except that further terms were included for the source strength terms and the wake and Kutta condition were treated in a different manner. Influence coefficients for unit doublet and source distributions over a panel are given by Moran (1984) and Katz and Plotkin (1991).

The solution for the potential of the flow at each time step is unique for a given wake and depends only on the instantaneous velocity boundary condition on the foil surface(e.g. Batchelor, 1967, p. 104 and 112). All memory effects are included in the foil wake which contains the shed vorticity from the foil, but at a given time step this is fixed. The calculation proceeded in a series of time steps and the wake was made up of segments, or panels, that represented conditions over each time step. The strength of the shed vorticity was determined from a Kutta condition applied at the trailing edge. The wake panels were left in the fluid flow where they were formed. No attempt was made to allow the wake to move with the local induced flow; though for low reduced frequencies this restriction was not expected to lead to large errors. The first wake panel was assumed to leave the trailing edge along the bisector of the trailing edge angle. The value of the potential on each wake panel was taken to be the mean of the values of $\Delta\phi$ obtained at consecutive time steps either side of the wake panel under consideration, except that a linear variation of potential was applied on the wake panel immediately behind the trailing edge. This is similar to the method applied by Kinnas and Hsin (1992) and was applicable for the same reason: the linear variation of potential on the first wake panel made the calculation relatively insensitive to the time step size.

Moran (1984), following Morino and Kuo (1974), used a Kutta condition with the constant potential panel method defining the circulation around the aerofoil as $\Gamma = \Delta\phi = \phi_N - \phi_1$ where ϕ_N and ϕ_1 are the doublet potential values on the upper and lower panels immediately adjacent to the trailing edge, respectively. While this worked for steady flows at small angles of attack, differences in the pressure coefficient were obtained at the upper and lower surfaces at the trailing edge if the foil either had large camber and/or was operating at large angles of attack. In unsteady flow, there were always large differences in the pressure coefficient at the trailing edge with this Kutta condition.

In unsteady flow the pressure is a function of the velocity squared and the rate of change of potential (Bernoulli's equation in unsteady irrotational flow (e.g. Lighthill, 1986, equation 178)). Kinnas and Hsin (1992) used an iterative Kutta condition, starting with the condition that $\Gamma = \phi_N - \phi_1$ at the given time step and using a Newton-Raphson scheme to ensure pressure equality at the trailing edge. The implementation of this method here showed slow convergence and a method based on a linearised pressure coefficient was used instead. A 'dummy' doublet potential value ϕ_{N+1} was introduced at the upper surface at the trailing edge. The linearised pressure coefficient was included as an $N+1$th equation and solved with the sytem of linear equations for the potential values (there were N panels on the foil surface arranged in a manner similar to that used by Moran (1984, p.269)). The pressure coefficient in unsteady flow is $C_p = 1 - \left(\frac{q}{V}\right)^2 - \frac{2}{V^2}\frac{\partial\phi}{\partial t}$ where q is the local fluid velocity and V is the velocity of the free stream. This was linearised as

$$\left(\frac{\phi_{2p}-\phi_{1p}}{d_1^2} + \frac{2(\mathbf{u}_\infty\cdot\mathbf{t})_1}{d_1}\right)(\phi_2-\phi_1) + (\mathbf{u}_\infty\cdot\mathbf{t})_1^2 + \frac{2}{\Delta t}(\phi_1-\phi_{1p}) = \left(\frac{\phi_{(N+1)p}-\phi_{(N-1)p}}{d_{N-1}^2} + \frac{2(\mathbf{u}_\infty\cdot\mathbf{t})_N}{d_{N-1}}\right)(\phi_{N+1}-\phi_{N-1}) + (\mathbf{u}_\infty\cdot\mathbf{t})_N^2 + \frac{2}{\Delta t}(\phi_{N+1}-\phi_{(N+1)p}) \quad (2)$$

where the ϕ's are the values of the potential on the panels; the d's are the distances between control points for the panel indicated by the subscript and the panel with the next higher index value; $\mathbf{t}$ is the unit tangential vector at the panel control point; the subscript p denotes the value from the previous time step and Δt is the time step. A 1st order differentiation was used for the term $\partial\phi/\partial t$. The actual difference in pressure coefficient between the upper and lower surfaces at the trailing edge was calculated after each step. In most situations this value was small at the first iteration, but if it was larger than a pre-set value (0.005 was used routinely), the calculated values of potential, ϕ, were used as the 'previous' values and a second solution was obtained. Unless the pitching amplitude, and hence pitching velocity, was large, this process converged rapidly within a couple of iterations.

Values of the lift coefficient were calculated as $C_l = L/\left(\frac{1}{2}\rho c V^2\right)$, where L is the lift; ρ is the density of the fluid and c is the foil chord length. In the time-domain program for oscillatory motion, the thrust force (negative drag) and work done to maintain the motion were averaged, $\overline{T}$ and $\overline{W}$ respectively, over the last cycle of the motion for which the calculation was done, by taking the mean for all time steps within the cycle. The work done at each time step was calculated from $W = -L\dot{h} + M\dot{\alpha}$, where $\dot{h}$ and $\dot{\alpha}$ were the heave and pitch velocity respectively; and the signs were dependent on the sign convention (positive lift, vertically upwards, was in the same direction as positive heave velocity, whereas positive moment, clockwise, was in the opposite direction to positive pitch velocity). The results of thrust are presented in the form of a thrust coefficient similar to that used by Lighthill (1970): $C_t = \overline{T}/\left(\frac{1}{2}\rho c\omega^2 h^2\right)$ and efficiency was calculated as $\eta = V\overline{T}/\overline{W}$; ω was the oscillation frequency and h was the heave amplitude.

RESULTS AND DISCUSSION

A variety of checks were made on the use of the time-domain program. For example, good agreement was found for constant heaving and pitching motions in comparison with classical solutions for thin wings. A calculation of the variation in lift coefficient with time for a NACA 0012 foil of 1 m chord undergoing a sinusoidal oscillation with a heave amplitude of 1 m; a reduced frequency, $\sigma = \omega c/(2V)$, of 0.2; and a feathering parameter $\theta = 0.4$ ($\theta = V\alpha/(\omega h)$ where α is the pitch amplitude) gave a steady state lift coefficient amplitude within 2.5% of the thin wing small amplitude solution. The foil was pitching about its trailing edge with pitch leading heave by $\pi/2$ rad.

Figure 1 shows the variation of lift coefficient with time for a sudden change in angle of attack of 4 deg. occurring at time 0 sec. The calculation was for NACA 0012 and 0006 airfoils with 40 panels, of 1 m chord, in a uniform stream of 1 m/sec and a time step of 0.1 sec. Also shown is the approximation to Wagner's solution for the lift coefficient (Jones, 1940) for this sudden acceleration; Wagner's actual solution for the lift coefficient is infinite at $t = 0$ and drops to exactly half of the steady state lift at $t = 0+$ (e.g. Katz and Plotkin, 1991, p.439). The calculations are sensitive to the value of the potential on the wake panels, especially the first panel behind the trailing edge. If the mean value of the wake potential between time steps is used on the first wake panel behind the trailing edge, then the lift coefficient is underpredicted over the first couple of seconds. If the mean value of the potential is used on all panels except the first panel behind the trailing edge, and on this panel the value of the potential at the present time step is used, then the results are sensitive to the time step size in the calculation. The results for a time step size of 0.1 sec are shown as o's on the plot; results found with a larger time step would be above these points and results found with a smaller time step would tend towards the more exact solution. The results presented over the full time sequence include a linear variation of potential over the first wake panel behind the trailing edge (time step of 0.1 sec), from the value at the present time step at the trailing edge to the value at the previous time step at the junction with the next wake panel. With this linear variation of potential, the results are relatively insensitive to the time step size.

Calculations were done for oscillating rigid foils and results obtained of thrust coefficient and propulsive efficiency. These are plotted in figures 2 and 3 for feathering parameters of 0.0, 0.4 and 0.8. The results are for a NACA 0012 foil, with 40 panels, oscillating with the pitch axis at the trailing edge, phase of pitch leading heave by $\pi/2$ and a ratio $h/c = 1$; thrust coefficient and efficiency were found from the third cycle of the motion. The trends in the results are similar to thin wing, small amplitude theory (e.g. Lighthill, 1970), though results of both thrust coefficient and efficiency are less than the thin wing theory results. Also shown are the results for a NACA 0006 foil at a feathering parameter of 0.4 and these show a trend towards the thin wing theory results for this thinner section.

Calculations done for variations in the ratio h/c, for a rigid NACA 0012 section at a reduced frequency of 0.2 and a feathering parameter of 0.4, showed a gradually increasing thrust coefficient with reducing h/c ratio (by about 4.9% over a drop in h/c from 2.0 to 0.1); whereas the efficiency had a minimum in the range between h/c from 0.5 to 1.0 of just over 0.72. Variation of thrust coefficient and efficiency with number of panels was explored for the same condition and a value of $h/c = 1$. Thrust coefficient and efficiency increased with increase in number of panels; the rate of increase reduced as panel number was increased. Between panel numbers of 40 and 80, thrust coefficient increased by 1.4% and efficiency by 0.03%, whereas between 20 and 40 panels the values were 3.0% and 0.4%, respectively. All these results were obtained for a time step of 0.5 sec and a run time of 49 sec.

Calculations were done for a flexible NACA 0012 section at a feathering parameter of 0.4, pitching around an axis at the trailing edge, with pitch leading heave by $\pi/2$ and for a value of the ratio $h/c = 1$; 40 panels were used over the foil. The flexibility was prescribed, and consisted of a flexible rear part of the foil from the mid-chord to the trailing edge. The deflected shape was assumed to be cubic and was taken as a function of the maximum deflection at the trailing edge, δ, as a fraction of the chord length, c: i.e. δ/c. The equation of the deflected chord line of the foil was $y = 8\delta(x - 0.5)^3 \sin(\omega t)$, where x was the distance from the leading edge. From this the deflected node positions, as well as the velocities of the control points, could be found and included in the formulation of the instantaneous body shape and boundary velocities. Figure 4 shows the deflected and non-deflected foil shapes at a reduced frequency of 0.2, after 3 sec from the start of the motion on the downstroke and after 42 sec on the upstroke. Figures 5 and 6 show the variation of thrust coefficient and efficiency

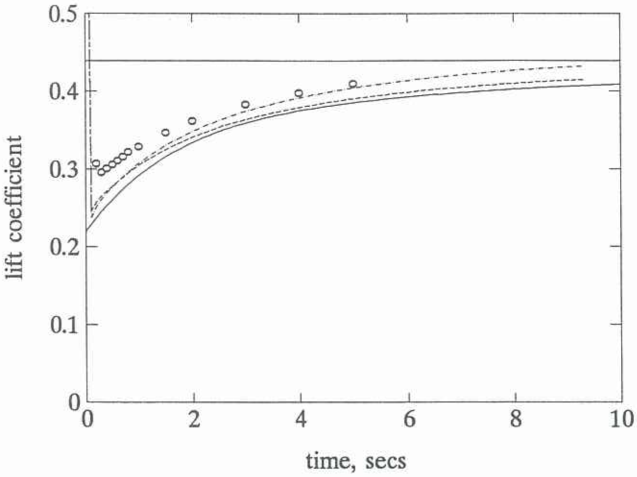
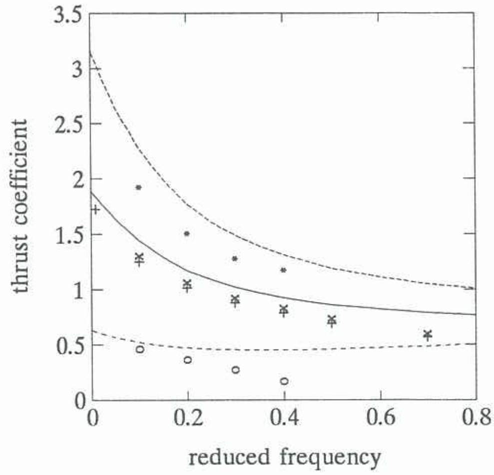


Figure 1. Variation of lift coefficient following a change in angle of attack of 4° at time=0. The chain dotted line is for section NACA 0012; the dotted line is for NACA 0006; the solid line is the approximation to Wagner's solution; the o's are for NACA 0012 with a uniform potential on the first wake panel and a time step of 0.1 sec; and the horizontal line is the steady thin wing lift coefficient at 4°.



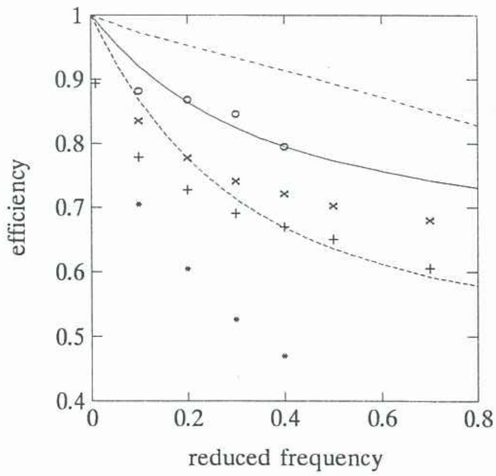


Figure 2. thrust coefficient and figure 3. propulsive efficiency for an oscillating rigid wing. The chain dotted, solid and dotted lines are the thin wing small amplitude solution for feathering parameters of 0.8, 0.4 and 0.0, respectively; the o, + and $*$ are the time domain solutions for a NACA 0012 section at the same feathering parameters, respectively. The $\times$ are the time domain solution for a NACA 0006 section at a feathering parameter of 0.4.

with reduced frequency for maximum deflections at the trailing edge, δ/c, of 0.000, 0.025, 0.050 and 0.100. For a given deflection, at a given value of reduced frequency, the thrust coefficient is reduced below the rigid foil value.

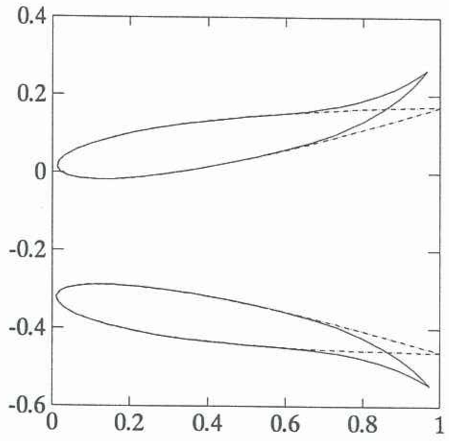
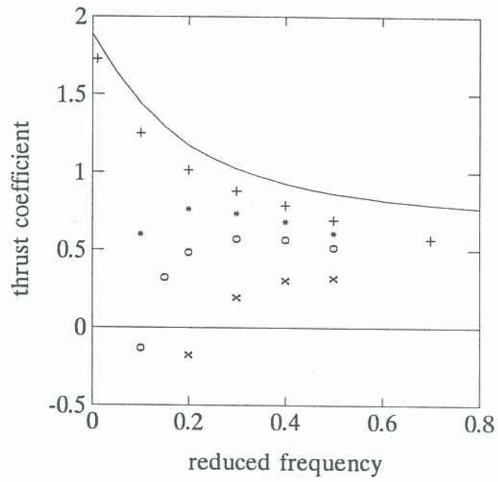


Figure 4. The rigid (chain dotted) and flexible section shapes after 3 sec on the downstroke (upper) and 42 sec on the upstroke for a NACA 0012 foil at a reduced frequency of 0.2, feathering parameter of 0.4 and $\delta/c = 0.1$.



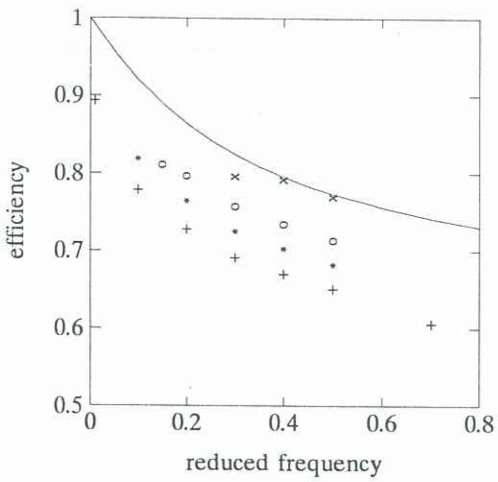


Figure 5. thrust coefficient and figure 6. propulsive efficiency for a flexible NACA 0012 section at a feathering parameter of 0.4. The lines are the thin wing rigid foil solution; the +, $*$, $\circ$ and $\times$ are the time domain solutions for a rigid foil and for deflection amplitudes at the trailing edge, δ/c, of 0.025, 0.050 and 0.100, respectively.

Also, for a given deflection, as the reduced frequency is reduced, the thrust drops to zero. In practice, for passive flexibilities, this would not actually occur as the deflection would reduce as the lift reduced, but it occurs here because the flexibility is not calculated as a function of loading on the foil. Figure 6 shows how in the same conditions, the propulsive efficiency is increased over the rigid foil result.

The paper describes a time-domain panel method that was used to calculate the propulsive thrust and efficiency of two-dimensional oscillating rigid and flexible foils. Results from this method show reduced values of propulsive thrust and efficiency for a thick wing over a similar thin wing; and reduced values of thrust, but higher efficiencies, for a flexible foil in comparison with a rigid foil.

The method used was an inviscid theory and a more complete solution should include modifications for viscous flows that would: reduce the value of leading edge suction as a result of separation, especially at high instantaneous angles of attack; modify lift at the high angles of attack that occur at high reduced frequencies; and increase the value of work done to maintain the foil motion as a result of viscous shear stresses on the foil surface.

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