Conclusions

The use of a noninertial coordinate transformation leads to a successful finite difference simulation of accelerating rigid-wall boundaries in a viscous fluid. The technique is verified by application to a cylinder oscillating in a still fluid and also oscillating parallel to and normal to a uniform stream. Two dimensional computations for Reynolds numbers between 1 and 100, with amplitude ratios from 0.1 to 2.0 are in reasonable agreement with available data. Drag, lift, and inertia effects extracted from the computations are shown to be strongly dependent upon Reynolds number, oscillation amplitude, and driving frequency.

The model in its present form is limited to the simulation of low Reynolds number flows by computer run time requirements. This limit could be extended by the use of large vector processing computers, which in the authors' experience can reduce the run times quoted here by as much as twenty times, or through the use of a smaller dedicated computer system. The utility of this technique is not as a design tool but once completely verified, as a source of very complete basic data. The entire flow field is reproduced synoptically which allows study of the fluid structure interaction phenomenon in a level of detail not possible with experimental techniques.

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References


R. D. Bleivins

The authors are to be congratulated on their numerical flow solution for vortex shedding. It is an extraordinary difficult problem and their solution is by far the most complete that has been generated. It could be a landmark to the advance of numerical fluid mechanics.

A few years back at an ASME symposium on numerical fluid mechanics, I heard one speaker remark, "Some day we will be glad that we have wind tunnels, we will need a place to store our computer output!" My first question to the authors is where do you store the 30-hours worth of output that some of the runs produced and how was that much data reduced?

R. D. Bleivins

1 General Atomic Co., San Diego, Calif. 92138.
On a more serious side, I would request that the authors clarify a few points. The single most fascinating aspect of vortex shedding is the ability to convert a uniform flow about a stationary cylinder into a periodic flow. It is well known that periodic vortex shedding from a stationary cylinder in a cross flow begins at Reynolds number of about 40. There is no vortex shedding from a stationary cylinder at lower Reynolds numbers although there can be fixed vortices in the wake. The paper reports only results with cylinder motion. Have you been able to produce periodic vortex shedding from a cylinder without encouraging the shedding by cylinder motion or other seed? If so, how does the shedding frequency compare with experimental results.

In the paper results for lift force coefficient are reported. The lift force is taken as the force perpendicular to the flow. For the practically important problem of vortex-induced motion of elastic cylinders, the lift force that excites cylinder motion is not the total force perpendicular to the flow; the existing force is that component of lift that acts in phase with the cylinder velocity. The portion of the lift that acts in phase with cylinder displacement and acceleration is transverse added mass.

It has been found that this added mass is nearly equal to the displaced mass of fluid regardless of cylinder motion amplitude. The exciting lift force, on the other hand, only produces net excitation for cylinder amplitudes less than about 1.6 diameters at synchronization. Outside of synchronization or at amplitudes greater than 1.6 diameters the exciting force is a damping force and it supresses motion. The upshot of all this is that, to the best of my knowledge, no one has ever observed vortex-induced vibration of cylinders at amplitudes greater than about 1.6 diameters. Can the authors correlate their results with this observed behavior?

C. Dalton^2

The authors have treated an interesting and important problem. I am impressed with their computational results which correctly predict lock-in when the frequency of the shed vortices and the cylinder oscillation frequency are approximately the same. However, there are several points which the authors could address so that their results could be better understood.

The Fourier-averaging technique is one of the more common methods of determining the drag and inertia coefficients. This method was used by Keulegan and Carpenter^3 in their classic paper on the force acting on a structural member exposed to an oscillating flow and also by Sarpkaya in his numerous descriptions of the same problem. (See references [3, 17] of the authors’ paper.) Why do the authors not consider the Fourier-averaging technique as a means of determining the force coefficients? A further comment relates to the maximum-value method described by the authors. This procedure was the earliest used to determine the force coefficients. However, it is now realized that the maximum-value method is not an accurate means of describing the force coefficients. Could the authors comment on using the maximum-value method and not using the more-accepted Fourier-averaging method?

The authors state that their calculated drag coefficient approaches the steady flow drag coefficient as the Reynolds number and $A/D$ value increase. This conclusion is puzzling since the maximum Reynolds number for which calculations were done was 100 and the maximum $A/D$ was 2.0. Neither of these values are sufficient to simulate a steady flow situation in an oscillating flow.

The authors have shown plots of the cyclic variation of the shear drag in Figs. 1, 2, 3, 4, 5, and 7. Exactly how was this obtained? What kind of approximations were used in order to represent the velocity gradient at the cylinder boundary? The freestream Reynolds number at a value of 80 is not high enough for a boundary layer assumption to be invoked. Also in Fig. 7, the separation angle is shown. Exactly how was this obtained? What criterion was applied to define the separation angle?

Authors’ Closure

In response to Professor Dalton’s question, we evaluated the force coefficients by both the maximum-value and the least-squares techniques. There is only a 3 percent difference in values computed by these two methods, primarily due to the low noise in the records derived from the simulations. The Fourier-averaging technique, which is essentially equivalent to the least-squares method for nearly sinusoidal records, would have definite advantages if the force data were noiser.

Table 1 shows both the computed force coefficient of the oscillating cylinder as well as the drag coefficient for steady flow at the same Reynolds number. At $Re = 1$, the drag coefficient for small amplitude oscillation ($A/D = 0.1$) is about 3.5 times larger than the steady flow value. Similarly, at $Re = 100$, the small-amplitude drag value is 2.7 times larger than for steady flow. However, as amplitude increases to $A/D = 2.0$, the difference decreases, so that the oscillating drag is only 30 percent higher than the steady flow value. Although flow about an oscillating cylinder at $Re = 100$ and $A/D = 2.0$ does not physically resemble a steady flow field at $Re = 100$, it does appear that the drag coefficient is approaching the steady state value.

The shear drag was computed by circumferential integration of the surface shear stress, evaluated from the wall velocity gradient. The level of approximation for this procedure is the same as that of the entire solution. Its validity rests on the resolution of the boundary layer by the finite difference grid and is critical to the accuracy of the simulation as a whole. The desire to have a large number of grids within the boundary layer is balanced by the necessity of simulating an infinity condition at the outer boundary plus the timestep penalty imposed by very small grid spacings. The compromise used was a logarithmically stretched radial coordinate with a minimum of two grids within the stagnation boundary layer. The solution itself provides the velocity gradient so that no further assumptions about wall shear are needed.

The separation point was defined as the surface location where the wall shear becomes zero. The tangential velocity also goes to zero at this point, and it is numerically convenient to search the wall grid points for a change in sign of tangential velocity. The separation point was then computed by interpolation, with the separation angle referenced to the downstream axis.

We appreciate R. D. Blevins’ comments and share the feeling that this approach can advance our understanding of fluid-structure interaction problems.

The model output was generally stored on magnetic tape or disk only after steady state behavior was obtained. Hence only the last several cycles of velocity and pressure are stored and the data processed to obtain lift and drag, surface
pressure distribution, streamlines, and pressure contours. In both our results and in a previous related study of steady flow past a cylinder [36], vortex shedding does not occur in finite difference calculations (at least up to Re = 200) without a triggering mechanism. The procedure used was to run the oscillating cylinder cases until a flow field forms with standing symmetric vortices. The flow is then perturbed (in our case, with a cylinder rotation) so that asymmetric vortices appear. Shedding begins shortly thereafter, and the simulation is run until the final asymmetric flow pattern is achieved.

The Strouhal numbers for the fixed-cylinder cases run to date are slightly higher than measured values. For example, at Re = 100, $S_{v} = 0.174$ is computed, as compared to measured values of 0.14 to 0.17. The discrepancy is believed due to lack of resolution: simulations with different grids [10] indicate that $S_{v}$ decreases to an asymptotic limit as grid spacing decreases.

Since the moving-stream cases have been for a small oscillation ($A/D = 0.14$), we have not been able to assess stability for higher amplitudes or for elastically mounted cylinders. At small amplitudes, the possibility of self-excited oscillation is clearly shown by the positive imaginary lift coefficient computed for the driven cylinder. This imaginary lift component corresponds to the exciting force for vortex-induced motion.

Subsequent to the work reported here, simulations were attempted at a higher Reynolds number (Re = 200) and a larger amplitude ($A/D = 0.5$) but were not completed due to excessive computational time requirements. A simulation with the cylinder oscillating at the vortex-shedding frequency seemed to evolve into a complex asymmetric shedding pattern. An overall cycle approximately three cylinder oscillation periods long appeared to repeat itself, but computer time was insufficient to verify that this was a steady-state condition. Asymmetric shedding patterns have been reported in this parameter range by Griffin and Ramberg [37]. It is not possible to draw conclusions from such an incomplete simulation, but the results are encouraging.

### Additional References
