simple changes as well as combined changes. Normal shocks are shown to occur from the supersonic portion of these loci to the subsonic portion in a manner analogous to simple-change behavior. Normal shocks change the $M = 1$ state for all values of C_2/C_1 except $C_2/C_1 = 1$. This state change in turn affects the maximum change the flow can sustain without changing the initial flow conditions.

References

[1]Shapiro, A. H., *The Dynamics and Thermodynamics of Compressible Fluid Flow,* Vol. 1, Wiley, New York, 1953.

[2]Chapman, A. J., and Walker, W. F., *Introductory Gas Dynamics,* Holt, Rinehart and Winston, New York, 1971.

[3]Zucrow, M. J., and Hoffman, J. D., *Gas Dynamics,* Wiley, New York, 1976.

[4]Saad, M. A., *Compressible Fluid Flow,* Prentice-Hall, Englewood Cliffs, NJ, 1985.

[5]Hodge, B. K., "Process Path for Simple Mass Addition in One-Dimensional Compressible Flow," *International Journal of Applied Engineering Education,* Vol. 7, No. 1, 1991, pp. 51–55.

[6]Benedict, R. P., and Stelz, W. G., *Handbook of Generalized Gas Dynamics,* Plenum, New York, 1966.

[7]Beans, E. W., "Computer Solutions to Generalized One-Dimensional Flows," *Journal of Spacecraft and Rockets,* Vol. 7, No. 12, 1970, p. 1460.

[8]Hodge, B. K., "Generalized One-Dimensional Compressible Flow Techniques," *International Journal of Applied Engineering Education,* Vol. 7, No. 1, 1991, pp. 56–63.

[9]Hodge, B. K., and Young, F. M., "Simple Mass Addition Processes in One-Dimensional Compressible Flow," AIAA Paper 93-0487, Jan. 1993.

Subharmonic and Harmonic Forced Response of the Wake of a Circular Cylinder

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Nomenclature

A = amplitude of splitter plate oscillation normalized by cylinder diameter
Cd_{norm} = drag of cylinder with splitter plate normalized by drag of cylinder without splitter plate
d = diameter of the cylinder
F = frequency of oscillation of splitter plate
f = von Kármán shedding frequency
S = Strouhal number, fd/U_o
S_f = forced Strouhal number, Fd/U_o
U_o = freestream velocity

Introduction

CAPABILITY to control frequency of vortex shedding from bluff bodies has applications ranging from wind engineering to altering of acoustic signatures of submerged vessels. Similarly, drag reduction of such bodies has always been a great concern of design engineers. A major effort in research on bluff body wakes has therefore been directed toward two aspects, namely, control of the shedding frequency and increase in base pressure. An excellent discussion of the various passive techniques to control vortex shedding can be found in a review paper by Zdravkovich.[1] Various mechanisms like base bleed, base cavity, and v grooves for increasing base pressures have also been explored by researchers.[2] Attention has also been directed toward active control of the wake width and vortex shedding frequency[3] by influencing the wake by either transverse vibrations or rotational oscillations of the cylinder or by acoustic energy input in the wake.

Monkewitz et al.[4] more recently used a linearized version of the complex Ginzburg-Landau equation to predict the global mode instability and used transverse vibrations of the cylinder as the actuator in a constant gain feedback control system to modify the wake. Their study, which was limited to S/S_f of 1.089 due to the cylinder material, concluded the ineffectiveness of the method beyond a Reynolds number of 90. However, by using an acoustic source as the actuator in a feedback control system, Ffowcs and Zhao[5] had shown that wake modification was possible at higher Reynolds numbers ($\sim 12 \times 10^3$).

The present research was motivated by the need to evaluate other practical wake modification devices having a potential of being placed in a closed-loop control system for controlling the wake. In this experimental investigation, an oscillating splitter plate located at the attachment line of a two-dimensional circular cylinder was tested as a candidate active of a feedback control system. Pertinent results of this investigation are presented.

Experimental Setup

The experiments were performed in the 0.5×0.9 m (2×3 ft) water tunnel and 0.45×0.45 m (18×18 in.) wind tunnel at the Texas A & M University. Plexiglass cylinders mounted between end plates were used as test models. A splitter plate of width $0.25d$ was pivoted between the end plates and oscillated about its trailing edge by a B & K shaker through a rigid tie-rod mechanism. A flexible seal was used to isolate the upper and lower surfaces near the attachment line of the cylinder.

The test conditions of a wind-tunnel speed of 15 m/s and water tunnel speed of 15 cm/s resulted in subcritical Reynolds numbers (based on cylinder diameter) of 3.1×10^4 and 1.4×10^4, respectively. Shedding frequency for the wind-tunnel model was estimated to be 98 Hz and for the water tunnel model to be 0.5 Hz using a Strouhal number (S) of 0.2. It was therefore decided to evaluate the subharmonic response of the wake in the wind tunnel and the higher harmonic response in the water tunnel because of limitations on the shaker.

The wake power spectra and shedding frequency were monitored using a hot-film sensor in the wake for use in the feedback loop, although for more practical applications a surface mounted sensor is envisaged (Fig. 1). For this investi-

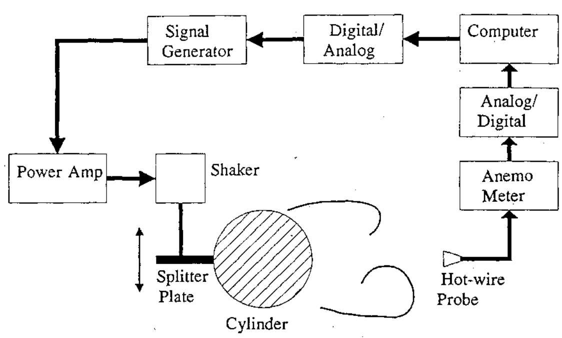

Fig. 1 Schematic of feedback control system.

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gation, the feedback system had a fixed gain. The control law logic was based on a peak counting algorithm, and as a result, the frequency with the largest amplitude was selected as an input to the shaker amplifier. Since the shedding frequency always had the highest amplitude, the feedback system remained autonomous as long as the shaker was to be excited at the shedding frequency. For other frequencies, the algorithm was modified to accept a set of desired frequencies. Measurements of mean velocities and shedding frequencies in the wind tunnel were made with a TSI hot-film probe, an A. A. Lab anemometer, and a Hewlet-Packard spectrum analyzer.

A TSI model 1210-20w hot-film probe was used in conjunction with a TSI 1050 anemometer in the water tunnel to monitor the wake. The anemometer signal was AC coupled to an Analogic, Inc., Data 6100 analyzer for wake power spectra from which the fundamental shedding frequency and its harmonics were determined. An Aerometrics laser Doppler velocimeter (LDV) system was used in the back scatter mode to measure the wake mean velocity profiles. Directional ambiguity in LDV measurements was resolved through shifting one of the beams by 40.09 MHz using a Bragg cell. The measurement volume diameter was estimated to be 80 μm.

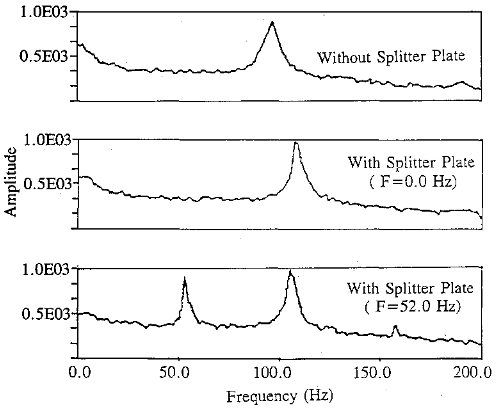

Fig. 2a Wake spectra for subharmonic response.

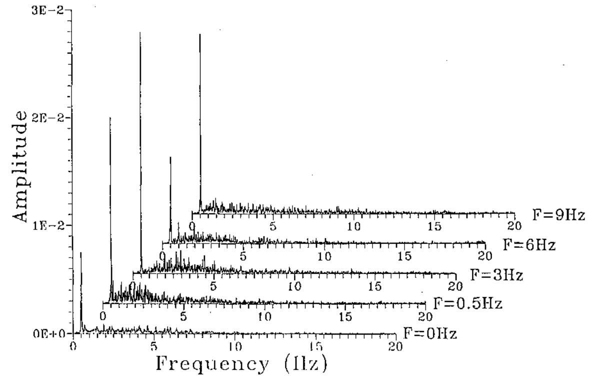

Fig. 2b Wake spectra for harmonic response.

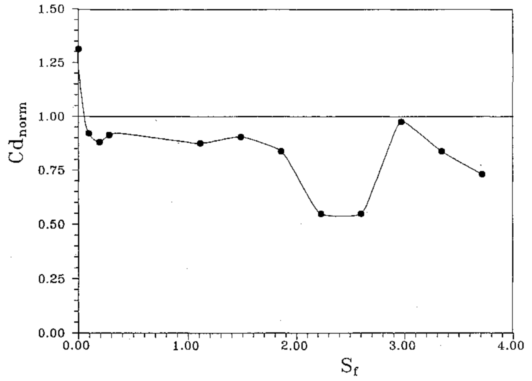

Fig. 3 Variation of drag with forced Strouhal number.

Results and Discussion

Traces of wake spectrum for the tests are shown in Figs. 2. It was observed that when the plate was oscillated at a subharmonic of the natural shedding frequency, the frequency of oscillation and its harmonics replaced the natural shedding frequency (Fig. 2a). However, unlike the subharmonic case, the forcing frequency did not replace the natural shedding frequency when the plate was oscillated at harmonic multiples of the natural shedding frequency; although some redistribution of energy in the power spectrum can be observed (Fig. 2b), especially into subharmonic of the forcing frequency, suggesting a trend from order toward breakdown of the wake. These observations are consistent with the flow visualization results.[6]

The drag of the configuration was calculated for various oscillating frequencies by integration of the wake momentum deficit. A reduction of approximately 23% in Cd_{norm} was observed for the subharmonic case. Influence of increasing amplitude of splitter plate oscillation in this frequency range could not be established due to mechanical limitation on the shaker. The mean streamwise velocity measured by the LDV for tests in the water tunnel showed that the velocity deficit was influenced by the frequency and amplitude of oscillation of the splitter plate. The drag was observed to be having an oscillatory dependence on frequency of plate oscillation. A minimum drag was observed for a S_f of 2.5. A maximum reduction in Cd_{norm} of 60% for a normalized amplitude of 0.18 was achieved (Fig. 3).

Conclusions

The forced response of the wake of a circular cylinder with an oscillating splitter plate installed near the leading-edge attachment line was measured. The results indicate that such a configuration can be effectively used to modify the wake through subharmonic interaction. At frequencies higher than the natural shedding frequency, the configuration can result in reducing the width of the wake and the drag of a bluff body. Some redistribution of power in the wake spectrum was also observed. Plate oscillation frequency and amplitude were identified as control parameters for modifying the wake of a bluff body.

References

[1]Zdravkovich, M. M., "Review and Classification of Various Aerodynamic and Hydrodynamic Means for Suppressing Vortex Shedding," *Journal of Wind Engineering and Industrial Aerodynamics*, Vol. 7, 1981, pp. 145–189.

[2]Tanner, M., "Reduction of Base Drag," *Progress in Aerospace Sciences*, Vol. 16, No. 4, 1975, pp. 369–384.

[3]Rockwell, D., "Active Control of Globally Unstable Flow," *International Symposium on Unsteady Fluid Dynamics*, ASME Fed-Vol. 92, 1990, pp. 379–394.

[4]Monkewitz, P. A., Berger, E., and Schumm, M., "The Nonlinear Stability of Spatially Inhomogeneous Shear Flows, Including the Effect of Feed Back," *European Journal of Mechanics, B/Fluids*, Vol. 10, No. 2, 1991, pp. 295–300.

[5]Ffowcs, Williams, J. E., and Zhao, B. C., "The Active Control of Vortex Shedding," *Journal of Fluids and Structures*, Vol. 3, 1989, pp. 175–122.

[6]Khan, M. J., and Ahmed, A., "Wake of a Circular Cylinder with a Leading Edge Oscillating Splitter Plate," *Symposium on Experimental and Numerical Flow Visualization*, ASME FED-Vol. 128, 1991, pp. 285–289.