Control of Separated Flow Behind a Cylinder Using Discrete Suction

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Nomenclature

a = base length of a suction patch
b = height of a suction patch
C_m = suction coefficient, mass suction rate/density of air/$(D \times L \times U)$
D = diameter of cylinder
L = length of a cylinder over which suction is applied
U = freestream mean velocity

I. Background

THE wake of a bluff body such as a cylinder is characterized by the formation of vortices at a wide range of flow conditions. The upstream feedback of the vortices induces an oscillatory force on the body, leading to problems such as flow-induced oscillation. The near-field wake of the cylinder can be viewed as consisting of two free shear layers with opposing senses of vorticity. When the development of the shear layers is altered, the characteristics of the wake may be controlled.

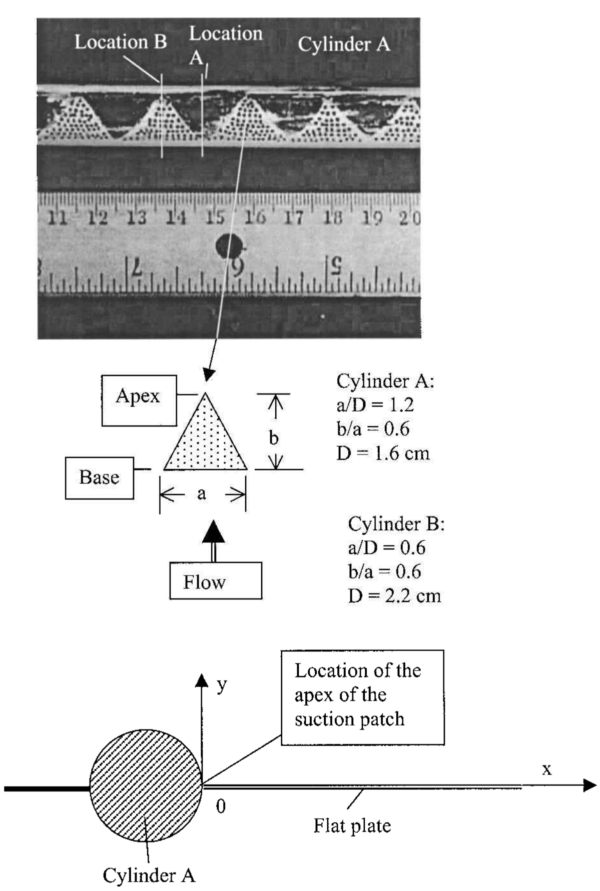

Fig. 1 Model dimensions.

A free shear layer is subjected to several instabilities, such as the Kelvin–Helmholtz instability, that lead to the formation of spanwise vortices. The computational study by Pierrehumber and Widnell[1] identified a broadband fundamental instability that leads to a streamwise vorticity concentration. Lin and Corcos[2] showed computationally that a spanwise, periodical perturbation can lead to the formation of streamwise counter-rotating vortex pairs in a plane stagnation flow. Lasheras et al.[3] demonstrated experimentally that streamwise vortices of substantial strength can be generated by triggering this instability in a free shear layer using a small cylinder upstream. Counter-rotating vortex pairs form in between spanwise vortices and merge downstream to form hair-pin vortex structures.

The focus of the previous studies was on the role of the instability in the development of a free shear layer. These studies established

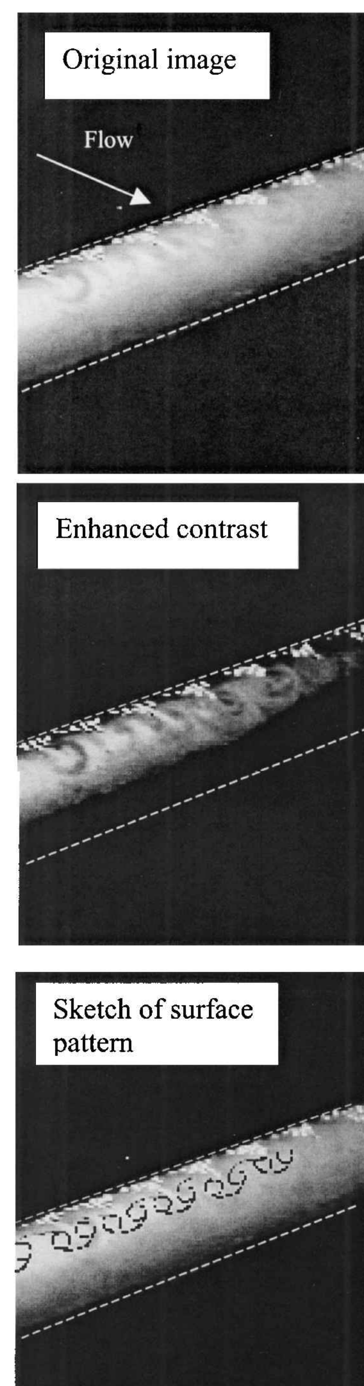

Fig. 2 Surface flow visualization of formation of counter-rotating flow structures downstream of the suction patches on cylinder A, with observed pattern noted.

Received 20 July 1999; revision received 28 September 2000; accepted for publication 3 October 2000.

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two necessary elements for streamwise vortex formation: 1) a stagnation velocity distribution and 2) a three-dimensional perturbation. These elements can be provided through different means. In a free-shear layer, a stagnation velocity distribution exists naturally between the spanwise vortices. A stagnation condition, however, also exists naturally during separation. In a previous study[4] the instability was used to successfully control the leading-edge separation of an airfoil. The present effort will focus on another aspect of the phenomenon. The streamwise vortices suppress the formation of spanwise vortices. Thus, the control can potentially be used to alleviate unsteady vortex shedding and associated problems. Applications include flow-induced oscillation, fluttering, cavity flow, jet noise, and dynamic stall.

II. Experimental Setup

An image of the cylinder models is shown in Fig. 1. Each cylinder was hollow, and the suction pattern was formed by 1-mm (0.039-in.)-diam holes on the surface. Both cylinders were about 60 cm (23.6 in.) long, with suction applied through about 50 cm (19.7 in.) of the length and the base of the suction patch located at 70 deg from the windward stagnation line. Additionally to cylinder-alone setups, tests were performed with a flat splitter plate placed at the trailing edge of cylinder A. In this case, the suction patch apex was located at the trailing edge.

Most of the tests were performed in a 3×3 ft (0.92×0.92 m) low-speed wind tunnel, with some supplementary tests being conducted in the Eidetics 24×36 in. (61×61 cm) water tunnel. For the wind tunnel, the freestream turbulence level (determined using a hot-wire anemometer) was about 0.3%, whereas for the water tunnel the level was less than 2% (based on measurements performed by Eidetics). Tests to be reported include surface flow visualization in the wind tunnel using fluorescent dye and hydrogen-bubble visualization in the water tunnel. The wind-tunnel experiment was conducted at a tunnel dynamic pressure of 0.24 kPa (5 psf), a Reynolds number of about 3.7×10^4 based on the diameter, and a C_m of 6×10^{-3}. The water-tunnel tests were performed at speeds ranging from 7.5 to

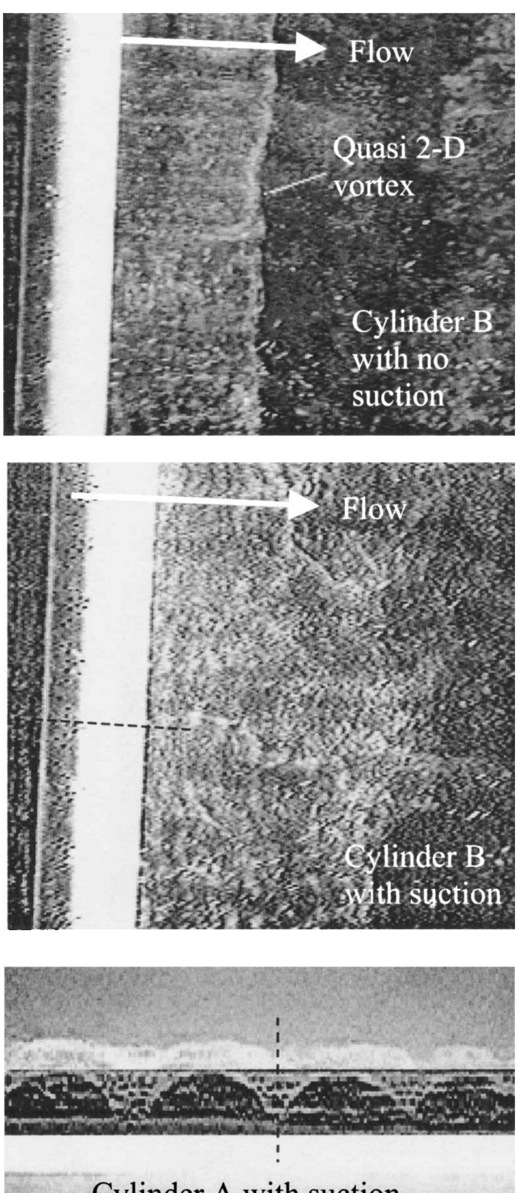

Fig. 3 Hydrogen bubble visualization of shear layer behind a cylinder; view from the top for cylinder B and from downstream of cylinder A (flow in the out-of-page direction), where dotted line indicates position B of the suction patch.

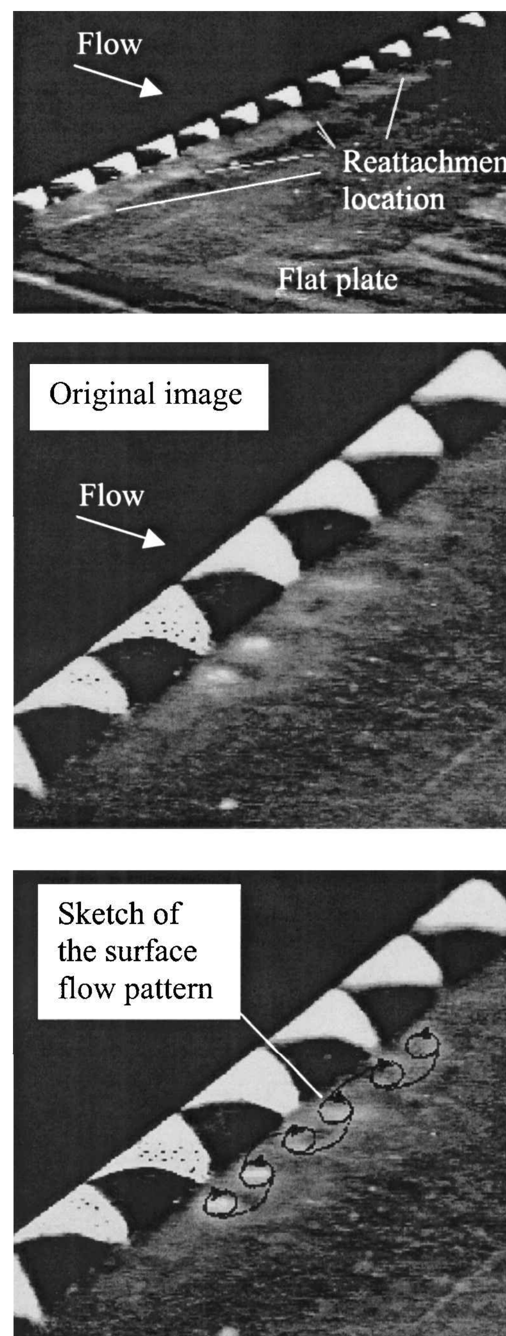

Fig. 4 Surface flow visualization of formation of counter-rotating flow structures on the flat surface downstream of the suction patches. Pattern noted.

25 cm/s (3 to 9.8 in./s), with a suction rate that was below measurable by the available instrument [resolution of 0.2 gal/min (0.0038 l/s)] in the Eidetics water tunnel.

III. Results

Because results of cylinders A and B are qualitatively similar, they will be used interchangeably in the following discussions. Figure 2 shows an example of the surface flow visualization on cylinder B in the wind tunnel and with suction. The surface oil pattern reveals steady low-speed or recirculatory regions on the surface. The result suggests the control induces a series of counter-rotating vortex structures behind the suction patches.

The phenomenon can also be seen in the water-tunnel hydrogen-bubble visualization results in Fig. 3. With no suction, the flow shows the typical quasi-two-dimensional vortex shedding behind a cylinder. When suction is turned on, a significant spanwise variation in the wake can be observed. A visual tracking of the hydrogen bubbles suggests the formation of a high-speed region along suction patch position B and a low-speed one along A. The view from downstream shows a spanwise, periodical wrinkling of the shear layer. The surface and hydrogen-bubble flow visualizations together indicate the formation of a series counter-rotating, streamwise vortex structures behind the cylinder.

Figure 4 shows results of cylinder A with a flat plate attached to the trailing edge to isolate the controlled shear layer from the opposite side flow. The main observations are that suction again leads to counter-rotating surface structures, except that the structures are formed on the flat surface immediately downstream of the cylinder. The absence of oil immediately downstream of the structures indicates that the flow has reattached at about 1 diameter downstream from the trailing edge.

IV. Summary

Results from the quasi-two-dimensional flow in the wake of a circular cylinder in a crossflow suggested that unsteady vortex shedding can be suppressed using a discrete suction control that induces the formation of stable, counter-rotating, streamwise vortices.

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