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Drag Reduction and Vibration Suppression of a D-Section Structural Member Through Momentum Injection

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ABSTRACT

Fluid effects on bluff structures include higher drag force as well as vortex resonance and galloping instabilities. Vibrations of tall buildings, bridges, smokestacks, etc. have been of interest to scientists and engineers. Recent advances in material science and design have led to structures with reduced stiffness, making them prone to wind and earthquake as well as ocean waves and current-excited oscillations. This paper addresses this issue fundamentally through a comprehensive study aimed at the Moving Surface Boundary-layer Control (MSBC) of the classical D-section type bluff geometry which is susceptible to the above-mentioned instabilities. Extensive wind-tunnel and flow-visualization studies suggest that the MSBC concept represents a versatile tool for drag reduction and vibration control of the D-section.

LIST OF SYMBOLS

C_D : drag coefficient, $D/(1/2)\rho U^2(2R)$
C_L : lift coefficient, $L/(1/2)\rho U^2(2R)$
C_Y : lateral force coefficient, $-(C_L + C_D \tan \alpha) \sec \alpha$
D, L : mean drag and lift forces, respectively
N : cylinder rotational speed
R : radius of D-section
S : circumferential length along D-section contour
U : free-stream wind speed
U_C : rotating cylinder surface speed
α : angle of attack
ρ : density of air

INTRODUCTION

A bluff body immersed in a stream of fluid is susceptible to vortex resonance as well as galloping instabilities. A structure experiences vortex resonance if its natural frequency coincides with the vortex-shedding frequency. Galloping is a form of self-excited vibrations, where the body generates an aerodynamic force aiding the motion, which can build up into large-amplitude, low-frequency vibrations. The catastrophic collapse of the Tacoma Narrows Bridge in 1940, in the United States, is all too well-known. Such vibrations have been regularly reported for tall buildings, suspension bridges, smokestacks, bundles of tubes in nuclear reactors, submarine periscopes, ice-covered transmission lines, and similar bluff bodies. A vast body of literature accumulated over the years has been reviewed by several authors including Roshko (1954), Marris (1964), Parkinson (1971), Berger and Wille (1972), Bearman (1984), and Modi and Welt (1988) and others.

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KEY WORDS: Drag reduction, vibration suppression, momentum injection, D-section.

Recent advances in computer-aided engineering and material science have led to structures with reduced mass and stiffness, making them prone to wind and earthquake as well as ocean waves and current-excited oscillations. The 21st century will witness super-tall buildings (>1000 m) and extra-long span bridges (>2000 m), as pointed out by Kubo et al. (1993, 1995). The conventional approach to vibration control is through increased structural damping, using, tuned mass or nutation dampers. Zdravkovich (1981), Every, King and Weaver (1982), as well as Modi, Welt, and Seto et al. (1994) have summarized literature pertaining to various devices employed for vibration control of structures. Approximately 1% of the structure weight is necessary for such devices to be effective. Of course, there is a limitation as to how large the weight can be as the structure grows taller. The alternate approach to vibration suppression is to modify the forces responsible for the vibrations. One way to achieve this objective is to prevent, or at least delay, separation of the boundary-layer from the wall of the structure. A moving wall attempts to accomplish this in two ways:

1. It retards the growth of the boundary-layer by minimizing relative motion between the surface and the free stream.
2. It injects momentum into the boundary-layer.

Using rotating cylinders as momentum-injecting elements, wind-tunnel tests with several two-dimensional bluff geometries and a family of airfoils have shown the Moving Surface Boundary-layer Control (MSBC) to be remarkably successful in delaying separation of the boundary-layer (Modi, 1990, 1991, 1993). Results showed significant reduction in the drag of two-dimensional flat plate and rectangular prisms. Kubo et al. have extended application of the MSBC concept to control vortex resonance and galloping oscillations associated with two-dimensional (1993) as well as three-dimensional (1995) square prisms representing tall buildings.

As is well recognized, the D-section has a front flat face and a semicircular afterbody. An interesting toy known as Lanchesters's *aerial tourbillion* (Den Hartog, 1956) has the D-shaped cross-section and exhibits autorotation (Lugt, 1983). The D-section is susceptible to both the vortex resonance and galloping instabilities. Being a hard oscillator due to the nonlinear character of the sys-