

Effect of Momentum Injection on the Drag Reduction and Flow-Induced Instabilities of a Square Prism

S. R. Munshi and V. J. Modi*

Department of Mechanical Engineering, The University of British Columbia, Vancouver, Canada

T. Yokomizo

Department of Mechanical Engineering, Kanto Gakuin University, Yokohama, Japan

ABSTRACT

Fluid flow effects on bluff structures include higher drag resistance as well as vortex resonance and galloping type of instabilities. Vibrations of tall structures such as buildings, bridges, chimneys, offshore platforms, marine risers and a wide variety of other configurations have been of interest to engineers and scientists. Recent advances in material science and computer-aided design have led to structures with reduced stiffness, making them prone to wind and earthquake as well as ocean waves and current-excited oscillations. A structural member with square cross-section is frequently encountered in such civil, mechanical and ocean engineering applications. The present study assesses the effectiveness of the Moving Surface Boundary-layer Control (MSBC) with reference to the drag reduction and vibration suppression of a two-dimensional square prism. To begin with the effects of the momentum injection parameter U_C/U (U_C , cylinder surface velocity; U , free stream velocity) and angle of attack on the surface pressure distribution, resultant forces and wake characteristics are evaluated using an organized wind-tunnel static test investigation. Next, dynamic studies are undertaken to assess its effectiveness in suppressing both vortex resonance and galloping type of instabilities. Finally, the wind-tunnel test results are complemented by an extensive flow visualization study. The results suggest that the boundary-layer control through momentum injection can significantly reduce drag and effectively control flow-induced instabilities.

LIST OF SYMBOLS

C_P : mean pressure coefficient, $(p-p_\infty)/(1/2)\rho U^2$
 C_{PB} : mean base pressure coefficient
 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
 $2R$: frontal diameter of square prism
 Re : Reynolds number, $(2R)U/\nu$
 S : circumferential length along contour of square prism
 St : Strouhal number, $f_V(2R)/U$
 St_p : Strouhal number based on projected height normal to flow, $f_V h/U$
 Su : universal Strouhal number, St_p/k_1
 U : freestream wind speed
 U_C : rotating cylinder surface speed
 U_C/U : momentum injection parameter
 V : nondimensional wind speed, $U/(2R\omega_n)$
 V_C : critical wind speed necessary to initiate galloping
 Y : nondimensional transverse amplitude, $y/(2R\omega_n)$
 \dot{Y} : nondimensional transverse velocity, dY/dt
 f_n : structure natural frequency
 f_V : frequency of vortex shedding
 h : projected height normal to flow
 k : stiffness

k_1 : base pressure parameter, $\sqrt{1 - C_{PB}}$
 l_1 : length of bluff body
 m : structure mass per unit length
 p : pressure at any point in flow
 p_∞ : free stream pressure
 r : system damping ratio
 t : time
 y : coordinate direction transverse to freestream
 \dot{y} : transverse velocity, dy/dt
 α : angle of attack
 ρ : density of air
 τ : nondimensional time, $\omega_n t$
 ν : kinematic viscosity of air
 ω_n : circular natural frequency, $2\pi f_n$

INTRODUCTION

The phenomenon of flow separation and the associated turbulent vortex wake is the most characteristic feature of an incompressible flow past a bluff body over a wide range of Reynolds numbers ($1 \leq Re \leq 10^7$). At the point of separation the thickness of the shear layer abruptly changes from $O(Re^{-1/2})$ upstream to $O(1)$ downstream in case of laminar separation (Brown and Stewartson, 1969). The recirculating region downstream of the body alters the effective body shape, hence the inviscid flow around it. Such a bluff body experiences very high drag due to the low pressure in the wake.

The separated shear layers roll up into alternately shedding vortices. As postulated by Gerrard (1966), the vortex formation in the wake takes place when the separating shear layer periodically entrains fluid containing oppositely signed vorticity from the other shear layer. This mechanism is believed to also govern the frequency of vortex shedding. The separating shear layer in general is convectively unstable (Oertel, 1990). Perturbations intro-

*ISOPE Member.

Received November 29, 1995; revised manuscript received by the editors February 23, 1996. The original version (prior to the final revised manuscript) was presented at the Sixth International Offshore and Polar Engineering Conference (ISOPE-96), Los Angeles, USA, May 26-31, 1996.

KEY WORDS: Momentum injection, drag reduction, flow-induced instability, square prism.