Experimental Thermal and Fluid Science 35 (2011) 1325–1333

Contents lists available at ScienceDirect

Experimental Thermal and Fluid Science

journal homepage: www.elsevier.com/locate/etfs

Proper orthogonal decomposition of wall-pressure fluctuations under the constrained wake of a square cylinder

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ARTICLE INFO

Article history:
Received 14 January 2011
Received in revised form 19 April 2011
Accepted 1 May 2011
Available online 5 May 2011

Keywords:
Wake
Wall-pressure fluctuations
Vortex shedding
Wall proximity
Proper orthogonal decomposition

ABSTRACT

The proper orthogonal decomposition (POD) analysis of the wall-pressure fluctuations below the constrained wake of a two-dimensional square cylinder in proximity to a plane wall was made on two systems, i.e., $G/D = 0.25$ and 0.5, which corresponds to the wakes with and without suppression of the vortex shedding, respectively. Here, G is the gap distance and D is the width of the square cylinder. Synchronized measurements of wall-pressure fluctuations were made using a microphone array. For the system $G/D = 0.5$, the first two energetic modes contribute 34.7% and 23.4% to the total fluctuation energy, respectively; however, the fluctuation energy corresponding to the third mode are relatively small and less than 10%. This sharp variation in eigenvalue is due to the presence and dominance of the Karman-like vortex shedding. However, for the system $G/D = 0.25$, the considerable reduction in the eigenvalues of the first several modes is due to the suppression of the Karman-like vortex shedding. The spatial wavy pattern of the first several energetic eigenmodes was shown to be a good reflection of convective vortices superimposed in the wakes. The spectra of the POD coefficients determined the frequency of the dominant structures. Based on the coherence of the POD coefficients, an effective method of determining the number of POD modes for reconstruction of the low-order wall-pressure field was proposed. Accordingly, the low-order wall-pressure fluctuations in the systems $G/D = 0.5$ and 0.25 were reconstructed by using the first four and five POD modes, respectively. The coherence and cross-correlation analysis of the reconstructed wall-pressure fluctuations, which excluded the influence of the small-scale structures and background 'noise', gave an insight view of the footprints of the dominant flow structures, which otherwise could not be effectively captured by using the original wall-pressure fluctuations.

1. Introduction

Previous studies of the constrained wake behind bluff body with wall proximity, which has found its place in various practical flow situations like suspension bridge, heat exchanger, oil pipe near seabed and chimneys near tall buildings [4], have established that the vortex shedding process would be suppressed when the gap width (G) between the body and the wall is below a critical one [1,15]. Durao et al. [8] and Shi et al. [16,17] showed that reducing the gap width results in considerable variations of the time-mean flow pattern, instantaneous flow behaviors and the wake dynamics. The transport phenomena, heat and mass transfer, and dynamic loading on the body are closely related to unsteady characteristics of the flow structures buried in the wake. Accordingly, rapid and effective identification of the energetic flow structures and elucidation of its convective features is highly desirable.

The critical gap width below which the vortex shedding is suppressed by the presence of the nearby plane wall was measured to $G/D \approx 0.35$ [8] by inspecting the velocity spectrum, which was determined from measurement results of a two-component laser Doppler velocimeter. Flow visualizations by Bosch et al. [5] showed that there is not a single critical width but a transition over the width range ($G/D = 0.35$–0.5) in which the fraction of the time when periodic shedding occurs changes from zero to one. Subsequently, Bailey [1] claimed the suppression of vortex shedding at $G/D < 0.4$, which was caused by complete reattachment of the lower shear layer on the lower side of the square cylinder. By measuring the wall-pressure fluctuations on the body surfaces, Martinuzzi et al. [15] classified the flow regimes from the changes in the cylinder surface pressure distributions, by which the critical gap width was measured to $G/D = 0.3$. In addition, the influence of wall proximity on heat transfer from a rectangular cylinder was reported by Chakrabarty and Brahma [7].

Shi et al. [16] employed the high-image-density Particle Image Velocimetry (PIV) and Time-Resolved Particle Image Velocimetry (TR-PIV) to obtain detailed information of the instantaneous wake flow at $Re_D = 2250$; four systems, e.g., $G/D = 0.1$ (no vortex shedding), 0.2 (no vortex shedding), 0.4 (vortex shedding) and 0.8 (vortex shedding), were chosen for comparison. The difference in

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doi:10.1016/j.expthermflusci.2011.05.001