Vortex- and Wake-Induced Vibrations of Two and Three Cylinders Arranged In-line

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ABSTRACT

Vortex-induced vibrations (VIV) and galloping effects are studied for the case of two cylinders in tandem arrangement. Both cylinders are allowed to move in X and Y directions and rigidity is kept the same for both directions. The cross-flow around moving cylinders is computed using a specifically designed numerical method which has been thoroughly verified and validated with manufactured solutions and systematic comparisons between numerical and available experimental results. It consists of a monolithic finite element method for solving fluid-structure problems. After validation results, we present configurations for a center-to-center distance $L/D = 4$ and reduced velocities ranging from 4 to 16 at a laminar Reynolds number of 200.

KEY WORDS: vortex-induced vibrations; wake-induced vibrations; galloping; circular cylinder; tandem arrangement; XY vibrations.

INTRODUCTION

We study vortex-induced vibrations (VIV), interference and galloping phenomena occurring when two and three circular cylinders arranged in-line are placed in a uniform flow. If VIV for single circular cylinders are well documented, VIV, interference and galloping phenomena studies for arrays of cylinders remain sparse since Bokaian and Geoola (1984) and Zdravkovitch (1985). Recent experiments by Germain et al. (2006) showed that wake-induced vibrations occur for reduced velocities far beyond than 10. In Germain et al. (2006) peak displacements of the rear cylinder are much larger than one diameter transversely and it is also shown that in-line peak vibration amplitudes may be larger than one diameter. Available numerical studies on XY-oscillating in-line cylinders in cross-flow depict results below reduced velocities of 7 [see Fregonesi et al. (2001); Mittal and Kumar (2001, 2004); Potanza et al. (2005)].

In Etienne (2008), we presented results till values of 10 of the reduced velocity. To shed light on wake-induced vibrations and reveal some of the features highlighted in the work by Germain et al. (2006), much larger reduced velocities shall be studied. In this work the range of studied reduced velocities is extended to values of 16. These configurations are studied with a numerical method based on the finite element method.

We have performed a parametric study with respect to the reduced velocity $U_r = U/fD$, with $U$ the uniform flow velocity, $f$ the natural frequency of cylinders in still water, and $D$ their diameter. $k$ is the rigidity of the spring that supports a unit length cylinder and $m$ is its mass per unit length. The non-dimensional center-to-center distance $L/D = 4$ is kept constant throughout this study. Values of the reduced velocities $U_r$ are in the range 4 to 16.

Note that the reduced velocity can be expressed as $U_r^* = U/(f_n D)$, with $f_n$ the natural frequency of cylinders in still water. The relation between the two formulas $U_r$ and $U_r^*$ is such that:

$$U_r^* = \sqrt{(m^* + 1/m^*) U_r^1}$$

with $m^* = m/m_0$, the mass ratio and $m_0 = D^2/4$.

A Reynolds number value of 200 has been selected for all computations presented here. This work is handled in a two-dimensional frame of reference. This is justified by the low value of the Reynolds number considered here. At this low value of the Reynolds number the flow is laminar. Also with cylinder vibrations, the correlation length of the flow vortical structures is increased. We assume that under these assumptions the flow remains mainly two-dimensional. All variables are expressed in terms of unit length in the $3^\text{rd}$ direction.

We have chosen to enrich the solution map with computations for the case of an array of 3 in-line two-degree of freedom cylinders to highlight wake-induced vibrations phenomena. The motivation to explore the behaviour of 3 in-line two-degree of freedom cylinders in cross-flow stems from the fact that the second cylinder undergoes larger vibrations on a larger reduced velocity range than the first one. This induces impacting wake characteristics that are radically different on the third cylinder than on the second one. Thus, one could expect an amplification of vibrations of the third cylinder compared to the second one on the selected range of reduced velocities ($U_r = 4$ to 16).

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