Journal of Fluids and Structures 72 (2017) 80–95

Contents lists available at ScienceDirect

Journal of Fluids and Structures

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

An algebraic expansion of the potential theory for predicting dynamic stability limit of in-line cylinder arrangement under single-phase fluid cross-flow

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ARTICLE INFO

Article history:
Received 11 October 2016
Received in revised form 10 March 2017
Accepted 7 April 2017

Keywords:
Fluid structure interaction
Fluidelastic instability
Cylinder arrangement
Potential flow theory

ABSTRACT

Flow-induced vibration in square cylinder arrangement under viscous fluid incompressible cross-flow is investigated in the present work. The purpose is to contribute to better modeling and understanding external fluid loads exerted on long thin cylinders inducing flow perturbations. Due to high flow confinement, thin cylinders may be subjected to strong vibrations, which may lead to dynamic instability development. A theoretical approach is developed to determine a stability criterion of the dynamical system. The influence of geometric, mechanical and flow parameters such as reduced velocity and pitch ratio is investigated.

The proposed model is derived from the potential flow theory and enhanced through an algebraic phase lag model in order to predict the critical limit of the reduced velocity for a square cylinder arrangement submitted to an external in-line cross flow. A theoretical formulation of the total damping, including added damping in still fluid, the damping due to fluid flow and the damping derived from the phase shift between the fluid load and the tube displacement, is expressed. A function depending on fluid and structure parameters, such as reduced velocity, pitch ratio and Scruton number is thus obtained. It is shown that this function provides a prediction of the dynamic stability limit of the system for several ranges of the major parameters to be considered. The results are compared to experimental reference solutions and to those provided by other theoretical models.

This work proposes a consistent original model based on a potential flow theory enriched by using an algebraic formulation based on standard physical assumptions from literature. The major advantage of this model is due to the fact that it is in the same time robust and very user-friendly from a computational point of view thanks to the potential framework. In order to describe fluid and solid dynamics in the domain, terms coming from the potential flow theory are estimated by using a finite element method and complementary terms acting on damping are obtained through an algebraic formulation. Therefore this is a convenient way to propose a hybrid numerical / algebraic model for predicting dynamic instability limit in cylinder arrangements.

1. Introduction

Fluidelastic instability is one of the most critical mechanisms involved in flow-induced vibrations of heat exchanger cylinder arrangements (Connors, 1980; Price, 1995). Indeed, in presence of high flow confinement, the thin cylinders

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http://dx.doi.org/10.1016/j.jfluidstructs.2017.04.004

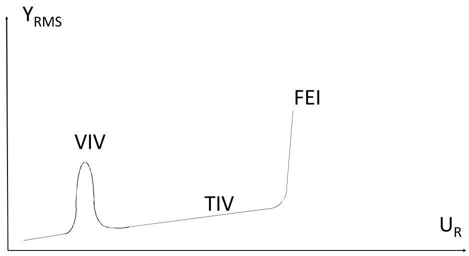

Fig. 1. Idealized response of a cylinder in an in-line array under single-phase fluid cross flow with solid displacement versus reduced velocity exhibiting three main areas. VIV Vortex-Induced Vibration: response to periodicity at lockin with synchronization of vibration and vortex shedding frequencies. TIV Turbulence-Induced Vibration: non resonant buffeting response with displacement magnitude increasing with Reynolds number. FEI Fluid Elastic Instability: sudden increase of response magnitude above a critical reduced velocity.

may be subjected to strong vibrations leading to instability development and therefore to a risk of damage. Several authors address the problem of fluidelastic instability in cylinder arrangements through both experimental and theoretical approaches (Tanaka et al., 2002; Price and Paidoussis, 1989; Paidoussis, 1980). However, all the contributions of the various geometrical, fluid and solid parameters involved are not always simultaneously taken into account.

Authors usually try to separate the phenomena for better understanding the mechanism. The potential flow approximation is used in this context. However, it seems that inviscid flow theory is inadequate for stability analyses of cylinder arrays under cross-flows (Price, 1995). Therefore an algebraic expansion is formulated and proposed for stability analysis in cylinder arrays. The model includes a damping term describing still fluid viscous effect, fluid velocity-depending effect and phase lag shift between load and solid response.

After a brief recall on standard fluidelastic models, the present article describes the method and its application to elementary configurations. The model robustness is evaluated through comparisons to results from the literature using experiments and existing models. Fluid–structure interaction and flow-induced vibration in square cylinder arrangement under cross flow are investigated and the influence of key parameters on fluid–solid dynamics interaction may be quantified.

2. Modeling fluidelastic instability

As far as cylinder arrangements are concerned, the major vibration types are usually called vortex-induced vibration, turbulent buffeting, acoustic resonance and fluidelastic instability. The damage due to turbulent buffeting is long term. On the contrary, the damage due to fluidelastic instability occurs within a very short time. Therefore unsteady models are required for prediction. Most important parameters, namely, orientation, mass, damping, pitch ratio, natural frequency of each cylinder and flow velocity are involved for modeling fluidelastic instability.

Both the galloping and the flutter instabilities involve either an asymmetry in the associated geometry or/and the interaction with an incident flow with dynamically changing the angle of attack. Figure 1 shows an idealized response of a cylinder from an array under the various excitation mechanisms (Païdoussis, 1983). The mathematical models of fluidelastic instability can be categorized based on the physical assumptions and methodologies used to derive it, namely, jet switch models, quasi-static models, quasi-steady models, semi-analytical models and unsteady models.

Until the 60's, the flow-induced vibrations due to the fluidelastic instability are attributed to the vortex shedding resonance. In its work (Roberts, 1962) discovers the self-excitation mechanism in a staggered row of cylinders under cross flow, for the vibration in inflow direction. A theoretical development for predicting the critical flow velocity is proposed, which is based on a jet switching phenomenon (Roberts, 1966). The flow jet, which is formed due to the cylinder arrangement, oscillates at a relatively lower frequency than the cylinder natural frequency. Later, (Connors, 1978) proposes a relatively simple dependency of the critical flow velocity on the structural parameters, i.e. on the mass-damping parameter. The model is developed using a single in-line row of cylinders instead of the staggered arrangement in Roberts (1962). Blevins (1974) extends the model of Connors (1970) for the tube arrays. Although the extended model incorporates the changing damping with respect to the flow velocity, the dependency on the mass-damping parameter remains in the same form. Eq. (1) is the general form of the Connors fluidelastic instability criteria:

$$\frac{u_{pc}}{f_n D} = K\left(\frac{m\delta}{\rho D^2}\right)^a \tag{1}$$

u_{pc} is the effective critical flow velocity (also called as gap or pitch or intertube velocity). f_n, m and δ represent the cylinder natural frequency, mass of cylinder per unit length and the logarithmic decrement of the cylinder free vibration decrease respectively whereas D stands for the cylinder diameter. The mechanical variables f_n, m and δ can be defined in several ways, but generally they are defined with respect to the fluid medium at rest. ρ is the fluid density. K is a constant of proportionality. a is a constant exponent. Standard values of constants are often used. A detailed historical development on the topic is reviewed in (Païdoussis et al., 2014).