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Sensitivity of the damping controlled fluidelastic instability threshold to mass ratio, pitch ratio and Reynolds number in normal triangular arrays

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ABSTRACT

Sensitivity of the damping controlled fluidelastic instability threshold of normal triangular tube arrays has been investigated through a theoretical-CFD hybrid methodology without the need for experimental data. The quasi-unsteady model with a theoretical model of the memory function was used to predict the critical velocity with the static fluid force coefficients obtained from steady RANS simulations. Five normal triangular tube arrays with pitch to diameter ratios of 1.25, 1.30, 1.32, 1.375 and 1.44 were investigated. Pressure on the tube surface for the $P/d = 1.32$ array, predicted by the CFD, was compared with empirical measurements from the literature. Force coefficients obtained with the validated numerical model, were used to predict stability thresholds for the $P/d = 1.25$ and $P/d = 1.375$ tube arrays and the results were compared with previously published experimental critical velocities. The validated theoretical-CFD hybrid methodology was used to analyze and quantify the critical velocity specific dependence on three parameters: mass ratio, Reynolds number and pitch ratio. As expected, the pitch ratio has the most effect on the critical velocity. It was found that increased Reynolds number increases the stability threshold over the whole range of mass-damping parameters, but mass ratio has only a very minor effect, and this is confined to high mass-damping values.

1. Introduction

Flow-induced vibration (FIV) can be a major problem in large heat exchangers leading to shut down or even decommissioning. While turbulent buffeting and the associated wear represents a limit on the long term integrity of these assemblies, fluidelastic instability (FEI) can lead to failure in the short term. As a result, FEI represents a limitation on the operational parameters of the unit. One particular mechanism of FEI, so-called damping controlled instability, can occur when a single flexible tube is subjected to cross flow, even within an otherwise rigid array. It is this mechanism which is the focus of the current study. An exhaustive review of the literature on damping controlled fluidelastic instability in normal triangular tube arrays is beyond the scope of this paper, but a comprehensive introduction to FEI in tube arrays can be found in, for example, Chapter 5 of Paidoussis et al. (2011) and a review of available models for specifically for damping controlled fluidelastic instability is given by Price (1995). Broadly speaking, any of the available models require some experimental input or tuning. For example, even one of the most theoretical the framework proposed by Lever and Weaver (1986) requires the gross flow path between adjacent tubes, and when it is extended to predict damping controlled instability (Yetisir, 1993) an empirical delay function is necessary.

Previous models of FEI and schemes for collapsing experimental data sets of critical velocity have assumed that the Reynolds number and mass ratio have no effect on levels of critical velocity. However, there is some experimental evidence that this may not be the case (Mewes and Stockmeier, 1991). Price (2001) in his discussion of the applicability of the Connors equation noted that a complete model of FEI should also include a Reynolds number dependency. Mahon and Meskell (2012) have shown that a Reynolds number dependency is necessary to achieve agreement between the Connors type equation and the quasi-steady model. Harran (2014) pointed out the influence of the mass ratio, in an asymptotic approach for the theoretical situation of an undamped structure.

The viability of using CFD, computational fluid dynamics, to obtain non-dimensional force coefficients, as well as other previously empirically determined quantities, and then introduce them into a theoretical framework to obtain stability thresholds, has been investigated by several authors. Harran et al. (2010) investigated pitch to diameter ratio and Reynolds Number effects on critical velocity for in-line tube arrays by obtaining coefficients for a unsteady the semi-empirical model framework of Chen (1983) from numerical simulations. Khalifa

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et al. (2013) investigated the interaction between tube vibrations and flow perturbations at lower reduced velocities and Reynolds numbers, coupling numerical predictions of the phase lag and the semi-analytical wavy wall model (Lever and Weaver, 1986; Yetisir, 1993) to predict the reduced critical velocity. Anderson et al. (2014) developed a model to account for temporal variations in the flow separation for in-line arrays. These types of study offer an interesting alternative to experimental testing which is limited for physical and economical reasons, allowing more extensive investigation of parameter effects in the reduced critical velocity.

This study will use steady CFD calculations of the fluid force coefficients on a displaced tube within an array to predict the critical velocity, using the quasi-unsteady model of Granger and Paidoussis (1996) with the memory function obtained from the wake model proposed by Meskell (2009). The approach is applied to single-phase flow, but it is conceivable that the approach could be adapted to two-phase flow if an appropriate model of two-phase damping is adopted, and an equivalent parameter to Reynolds number could be well defined.

Gillen and Meskell (2009) completed a preliminary study using a similar approach, demonstrating that the scheme was promising. However, that study had significant flaws: the simulations suffered from flow instability in the far wake; only two geometries were simulated; and the range of parameters investigated was small. It is important to note that the objective in this study is not to advance a method of determining the critical velocity *per se*. Rather, the goal of the current study is to investigate the dependence of the critical velocity on mass ratio and Reynolds number.

2. Methodology

Consider a single flexible tube in an otherwise rigid array. It will be assumed that the this tube is free to move only in the transverse direction (i.e. perpendicular to the mean bulk flow) and that the structure can be represented by a single degree of freedom model. This excludes the possibility of (coupled mode) stiffness controlled instability. In addition, streamwise instability is not possible.

The fluidelastic force E that a tube in an array is subjected to, can be expressed by the governing equation of motion

$$m_s\ddot{y} + c_s\dot{y} + k_s y = F_y(\ddot{y},\dot{y},y,U_0) \tag{1}$$

The quantities m_s,c_s and k_s are the structural mass, damping and stiffness respectively. The effects of both turbulent buffeting and vortex shedding have been omitted as it is assumed that they do not change the stability behaviour of this model. This superposition effectively assumes that the dependency of the fluid force on the tube displacement is linear at low amplitudes (i.e. at the onset of instability). Note that if the post-stable behaviour was of interest (i.e. the limit cycle amplitude) then a more sophisticated approach would be needed, but as the focus of this study is the onset of instability, the simplification of a linear relationship with displacement is acceptable. Meskell and Fitzpatrick (2003) demonstrated that the fluidelastic stiffness and damping were cubic in displacement and tube velocity respectively. As a result, the onset of dynamic instability will be governed by the linear parameters. This is generally true in non-linear system dynamics, for example see Chapter 3 of Virgin (2000). Furthermore, these assumptions are widely made in models of fluidelastic instability. For example, Price and Paidoussis (1984) and Lever and Weaver (1986) implicitly assume that the only fluid force is due to tube displacement.

As the full detail of the fluidelastic force function, F_y, is unknown, various models have been developed. One such model used the quasi-steady approach (Price and Paidoussis, 1984), which assumes the force on the oscillating tube at any moment in time is equal to the force it would experience at that static displacement, but subject to a time lag. This model was later improved upon by Granger and Paidoussis (1996), by replacing the time lag as a function spread over time. In this quasi-unsteady model, the relationship between the instantaneous fluid forces and the static lift and drag force coefficients is

$$F_y(t) = -\frac{1}{2}\rho d^2 L C_M \ddot{y} + \frac{1}{2}\rho U^2 L d\left(\frac{dC_L}{dy}h*y - C_d\dot{y}\right) \tag{2}$$

The terms of this equation consist of tube diameter, d, and length, L; the fluid density ρ; freestream velocity, U; and the mass, lift and drag coefficients (C_M,C_L and C_D respectively). The tube displacement y is convolved with the delay function h. The drag, which would normally only be considered for forces in the x direction is included due to the quasi-steady assumption which rotates the fluid force system to be aligned with the instantaneous apparent flow direction. It is worth noting that the strict requirement for the application of the quasi-steady assumption as stated by Van Oudheusden (1995) is that it is possible to "define a steady situation (in which the structure is in rest with regard to some suitably chosen reference frame) which is aerodynamically equivalent to the unsteady situation". But this cannot be met in a tube array because of the proximity of the neighbouring tubes. Nonetheless, it is clear that there should be a positive damping associated with the fluid which will be modified by flow, and so the quasi-steady assumption is included as an imperfect model of this stabilizing effect as its influence is smaller when compared to the influence of the time delayed lift. The convolution integral can be represented as

$$h*y = \int_0^\tau h(\tau-\tau_0)y(\tau_0)d\tau_0 \tag{3}$$

with h representing the memory function

$$h(\tau) = \frac{d\Phi}{d\tau} \tag{4}$$

where $\tau = \frac{tU}{d}$ is the non-dimensional time. The convolution can also be thought of as a low pass filter and so that any response to any vortex shedding and most turbulent excitation will be attenuated, further justifying the assumption in Eq. (1) to ignore these excitation mechanisms. The transient evolution of this memory function, which is essential for damping controlled FEI, is determined by the function Φ. This transient function converges monotonically towards 1 as τ approaches infinity (Granger and Paidoussis, 1996). Without loss of generality, it can be represented this as a series of decaying exponentials:

$$\Phi = \left(1-\sum_{i=1}^{N}\alpha_i e^{-\beta_i\tau}\right)H(\tau) \tag{5}$$

Granger and Paidoussis (1996) quantified the parameters α_i and β_i by fitting the model response to experimental data of critical velocity in a normal triangular array subject to cross flow. Li and Mureithi (2016) have quantified these parameters for a parallel triangular array, also by comparison with experimental data, although the main focus of their study was the development of a frequency domain formulation, equivalent to a Theodorsen function. However, Paidoussis et al. (2011) pointed out that using experimental data to determine the detail of the memory function increased the need for empirical data, largely negating the benefit of a model. Meskell (2009) has proposed a wake model to predict theoretically the values of α_1 and β_1 for a first order model, i.e. $N = 1$ in Eq. (5).

This wake model approach assumes that the memory function is the normalized instantaneous bound circulation on the tube. The wake is modeled as a discretized vortex sheet. The convection of the shed vorticity is assessed in an idealized velocity field based only on the enforcement of the continuity equation along the gap between tubes. The resulting one dimensional relationship for the temporal variation in lift force on the tube is an integro-differential equation which cannot be solved analytically (Price et al., 1992), but a first order model of the memory function is quantified by numerical quadrature. The non-dimensional values obtained in that study and used here are $\alpha_1 = 1.0$ and $\beta_1 = 0.1572$. In principle, this approach can be applied to any tube array