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Modelling of fluidelastic instability in a square inline tube array including the boundary layer effect

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ABSTRACT

Flow-induced vibration (FIV) is a design concern in many engineering applications such as tube bundles in heat exchangers. When FIV materializes, it often results in fatigue and/or fretting wear of the tubes, leading to their failure. Three cross-flow excitation mechanisms are responsible for such failures: random turbulence excitation, Strouhal periodicity, and fluidelastic instability. Of these three mechanisms, fluidelastic instability has the greatest potential for destruction. Because of this, a large amount of research has been conducted to understand and predict this mechanism. This paper presents a time domain model to predict the fluidelastic instability forces in a tube array. The proposed model accounts for temporal variations in the flow separation. The unsteady boundary layer is solved numerically and coupled with the structure model and the far field flow model. It is found that including the boundary layer effect results in a lower stability threshold. This is primarily due to a larger fluidelastic force effect on the tube. The increase in the fluidelastic effect is attributed to the phase difference between the boundary layer separation point motion and the tube motion. It is also observed that a non-linear limit cycle is predicted by the proposed model.

1. Introduction

Historically, heat exchangers have been among the most failure prone components in nuclear power plants (Diercks et al., 1996) and continue to be a major reliability issue as evident by recent tube degradation problems (e.g. Units 2 and 3 of the San Onofre Nuclear Generating Station, Unit 1 of Three Mile Island, Unit 1 of Arkansas Nuclear One). Most of the tube failures are due to corrosion, fatigue and fretting wear of the tubes. Fatigue and fretting wear are a result of dynamic loading caused by three cross-flow excitation mechanisms: turbulent buffeting, Strouhal periodicity and fluidelastic instability (FEI) (Weaver and Fitzpatrick, 1988). The turbulent buffeting mechanism results in long-term failures due to fretting-wear damage at the tube supports, while Strouhal periodicity and fluidelastic instability result in short-term failures due to excessive vibration of the tubes. Of the three mechanisms, FEI has the greatest potential for destruction in heat exchanger tube bundles. Because of this, a large amount of research has been conducted to characterize this mechanism.

FEI is a self excitation mechanism caused by the interaction of the flexible tubes and the fluid forces. The motion of the tubes alters the flow field which, in turn, creates fluid forces that further excite the tube. Energy is thereby transferred from the flow to the tube. Problems arise when more energy is extracted from the fluid flow than can possibly be dissipated by

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Nomenclature

$A, \overline{A}, a$	flow channel area: unsteady, steady state, perturbation
b	effective viscosity
d	tube diameter
f, f_n	frequency, natural frequency
L	length scale used to normalize position
$P, \overline{P}, p$	pressure: unsteady, steady state, perturbation
s_o, s_a, s_s	flow channel inlet, attachment point, separation point
s	position along flow channel
t, T	time, non-dimensional time
X, η	dimensionless boundary layer coordinates
$U, \overline{U}, u$	flow velocity: unsteady, steady state, perturbation
$\hat{U}, \hat{U}_o$	normalized flow velocity: current, initial
U_p, U_o	pitch velocity, inlet flow velocity
w	tube displacement
δ	log decrement
ρ	fluid density
τ	time lag

the structural damping of the tube. This causes large amplitude vibrations that can result in mid-span collisions between the tubes and accelerated wear at the tube supports. However, predicting tube response at the onset of the instability or at the pre-stability is still far from realistic. Without an estimation of the motion of the tubes, the life cycle of a heat exchanger cannot be accurately predicted. This problem is most relevant in nuclear power generation in which any leak causes a radiation hazard and the offending tubes must be plugged. Over time numerous tubes can become plugged, reducing the overall efficiency of the heat exchanger. This requires the heat exchanger to be replaced, which is very costly.

Several theoretical models have been proposed to predict the onset of fluidelastic instability in heat exchanger tube bundles, such as that of Tanaka and Takahara (1981), Chen (1983), Lever and Weaver (1982) and Price and Païdoussis (1984). These models provide vital tools for predicting the critical flow velocity. Many of these models rely on experimentally determined inputs. The model proposed by Lever and Weaver (1982, 1986) is a semi-analytical model, which requires fewer empirical coefficients. More recently Hassan and Hayder (2008) and Hassan and Mohany (2013) reformulated the Lever and Weaver (1982) model for time domain simulations, and demonstrated its validity in estimating the fretting wear analysis of loosely supported tube bundles. The original Lever and Weaver (1982) model relies on the assumption of wake independence and phase lag analogy. A uniform steady state flow channel width was assumed. This enabled them to analyze the problem utilizing basic fluid mechanics. However, when a fluid flows over the tubes, low pressure zones are formed behind each tube. These act to distort the flow channel and result in a non-uniform steady state area. The assumption of wake independence has led to the acceptance of the assumption that the flow attachment and separation points are time-independent. This may not be realistic because when the tube moves, the flow field around it is bound to change which, in turn, is expected to alter the locations of the attachment and the separation points. This interpretation is supported by an experimental observation by Hara (1987). The motion of the attachment and the separation points varies over the area in which the flow is able to interact with the tube, thus altering the forces acting on the tube. The motion of the attachment and the separation points was not accounted for in the original Lever and Weaver (1982) model or the advancement by Yetisir and Weaver (1993a,b). Even the more recent adaptations of the model by Hassan and Hayder (2008) and Hassan and Mohany (2013) have not investigated the effect of the temporal variation of the attachment and separation points on the fluidelastic instability.

The main objective of this paper is, therefore, to formulate a time-domain model based on the original flow cell model developed by Lever and Weaver (1982) that accounts for the temporal variations in the boundary layer development over the moving tube. The effect of the reduced flow velocity and response amplitude on the boundary layer motion and the tube response is also investigated.

2. Model description

2.1. Flow channel subdomain

The complex flow through a tube array is approximated as one-dimensional inviscid flow through a number of flow channels. Referring to Fig. 1, the flow cell is comprised of a number of rigid tubes (2–6), a single flexible tube (1) and two flow channels. The rigid tubes act only to define the flow channels through the flow cell. The position along the length of a flow channel is described using the curvilinear coordinate s, which originates at the centre of the single flexible tube and decreases in the direction of the flow cell inlet. The flow channel interacts with the single flexible tube over the attached region ($s_a \leq s \leq s_s$), where s_a and s_s are the flow attachment and the separation points, respectively.

In the original formulation the system is assumed to oscillate harmonically at its natural frequency to simplify the calculations. This is realistic only at the onset of the instability where the response frequency approaches the natural frequency of a linear system. The subsequent work of Yetisir and Weaver (1993a,b) relaxed the assumption of the frequency being at the natural frequency of the tube. However, it still assumes that the vibration response is periodic at a certain frequency, which is true for linear cases at the onset of stability. However, tubes are usually loosely supported without a well-defined natural frequency which complicates the response prediction. In addition, in the subcritical range the