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Numerical investigation of the cross flow fluidelastic forces of two-phase flow in tube bundle

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ABSTRACT

This paper presents a numerical model to predict the unsteady fluid forces in a parallel triangular array subjected to two-phase flow. The numerical model utilizes the RANS formulation with aid of Spalart–Allmaras turbulence model, while the physics of the two-phase flow are modeled by the mixture model, drift-flux model, and the interfacial area concentration concept. This numerical model was utilized to simulate an air–water flow in tube array with various air void fractions. The predicted fluid force coefficients were compared with the available experimental data. The comparison showed a good agreement in terms of the force magnitude and phase at various reduced flow velocities. The obtained force coefficients were employed in a Hybrid analytical-CFD model representing a kernel of 7 tubes. The stability was investigated by studying the eigen values of the system as a function of the flow velocity. In addition, the stability thresholds were examined by simulating the same 7 flexible tubes kernel in cross flow using the direct flow/structure coupling. The predicted stability threshold obtained via these two models agrees very well with the experimental counterparts. They represent a lower bound for the stability data. These results are very promising and represent an important step towards an analytical frame work to accurately predict the stability of tube arrays.

1. Introduction

Fluidelastic instability (FEI) is the most important excitation mechanism the can cause severe flow-induced vibration in tube bundles. This mechanism is characterized by a threshold (critical flow velocity) beyond which very large oscillations take place. This form of instability can lead to excessive fatigue stresses, tubes collision, and fretting wear at the supports. Heat exchangers and steam generators are typical industrial devices that are prone to the occurrence of the fluidelastic instability. Such occurrences often lead to tube failure in a very short period of time. Due to the devastating nature of the FEI large number of efforts was directed towards understanding the FEI mechanism. These efforts have resulted in a number of guidelines and theoretical models. These empirical and theoretical models were developed to obtain a reliable estimation for the onset of the instability. The theoretical models can be categorized into four main streams: the quasi-static models of Connor and Blevins (Blevins, 1977; Connors, 1970), the coefficients-based unsteady models (Chen, 1983; Tanaka and Takahara, 1981), the quasi-steady models (Price and Paidoussis, 1984, 1983), and the semi-analytical models of Weaver et al. (Lever and Weaver, 1982; Yetisir and Weaver, 1993). Out of these efforts, the Connor's equation which is based on the quasi-static approach is widely used in the industry because of its simplicity. Industrial guidelines are based

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Nomenclature

a	Volume fraction [–].
c	Force coefficient [–].
C	Damping coefficient per unit length [N s/m^2].
D	Tube diameter [m].
f_n	Natural frequency [Hz].
F	Force per unit length [N/m].
k	Stiffness per unit length [N/m^2].
K	Stiffness matric per unit length [N/m^2].
m	Mass per unit length [kg/m].
M	Mass matrix per unit length [kg/m].
P	Pitch [m].
$\overrightarrow{u}$	Flow velocity vector [m/s].
U	Gap velocity [m/s].
U_r	Reduced velocity [–].
U_∞	Free stream flow velocity [m/s].
x, y	Spatial coordinates in lift and drag directions [m].
$\alpha_{ij}, \beta_{ij}, \sigma_{ij}, \tau_{ij}$	Flow added mass coefficients [kg/m^3].
$\alpha'_{ij}, \beta'_{ij}, \sigma'_{ij}, \tau'_{ij}$	Flow added damping coefficients [–].
$\alpha''_{ij}, \beta''_{ij}, \sigma''_{ij}, \tau''_{ij}$	Flow added stiffness coefficients [–].
δ	Damping logarithmic decrement parameter [–].
ϕ	Phase angle [deg].
ρ	Density [kg/m^3].
μ	Dynamic viscosity [N s/m^2].
ν	Kinematic viscosity [m^2/s].
ω	Angular frequency of the oscillating tube [rad/s].
χ	Interfacial area concentration [1/m].

Subscripts:

c	Cell.
f	Flow.
k	Phase.
m	Mixture.
p	Dispersed secondary phase.
q	Continuous primary phase.
s	Structure.
t	Turbulent.

on fitting the Connor's equation constants to the experimental data. The semi-analytical model by Lever and Weaver (1982) was derived from the first principal of structural and fluid mechanics and does not require many experimentally measured coefficients. Subsequent developments of the model include provisions to handle nonlinearities due to the loose supports (Hassan and Hayder, 2008) and simulating U-bend tube bundle vibrations (Hassan and Mohany, 2012). The unsteady models relate the destabilizing fluid forces to the tube bundle response through a number of fluid force coefficients. This requires the knowledge of these coefficients over a wide range of reduced flow velocities. This approach could be very effective if these experimental data are generated. Direct experimental measurements of the flow forces acting on an oscillating tube were used to obtain these coefficients. The applicability of this approach is limited to only those tube arrays with existing measured force data. This is considered to be the major drawback of this approach.

Due to the complexity of the two-phase flow-induced vibrations, the majority of the investigations were directed towards experimental studies. Experimental investigations utilized steam–water (Axisa et al., 1985; Mitra et al., 2009; Nakamura et al., 1995), refrigerants (Feenstra et al., 2000), or air–water mixture (Pettigrew, 1989). While the experiments using the steam–water mixtures closely resemble the actual steam generators such experiments are very expensive and difficult to perform. Experiments using refrigerants such as Freon-11 are easier to perform. It is argued that the density ratio of the two phases will affect the difference in flow velocity between the phases. Additional factors such as the liquid surface tension, plays an important role in controlling the bubble size. As such, the use of refrigerants represents a practical alternative where the density ratio and surface tension are closer to those of the steam–water mixture than air–water (Mohany et al., 2012). However, the majority of the two-phase flow experiments were performed via air–water mixture at isothermal and atmospheric conditions. This is because air–water mixture experiments are much easier to perform and the data obtained