Journal of Fluids and Structures 70 (2017) 346–359

Contents lists available at ScienceDirect

Journal of Fluids and Structures

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

Development of a time delay formulation for fluidelastic instability model

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ARTICLE INFO

Keywords:
Fluidelastic instability
Time delay
Theodorsen function
Lift coefficient
Reynolds number

ABSTRACT

Tube arrays in industrial components such as heat exchangers and steam generators are susceptible to damage due to fluidelastic instability (FEI). In the present work a new time delay formulation for the quasi-steady FEI model is derived in the frequency domain in the form of an equivalent Theodorsen function. Unsteady and quasi-static fluid forces were measured to determine the time delay formulation. The effect of Reynolds number on the static force coefficients was also investigated. The time delay function was found to be also dependent on the Reynolds number. Comparison to other time delay functions proposed in the quasi-steady and quasi-unsteady models is made. Using the new function, a stability analysis was carried out to predict the critical velocity for a range of mass-damping parameters and compared with other theoretical models. The results show a significant improvement over the constant time delay quasi-steady model and the quasi-unsteady model.

1. Introduction

Tube arrays in industrial components such as heat exchangers and steam generators are susceptible to damage due to flow-induced vibration (FIV). As the name suggests, FIV is the interaction between fluids and structures that can potentially cause excessive tube vibration. The phenomenon has been studied at least since the 1970s. Significant research effort has been dedicated to FIV so that the main mechanisms are now reasonably well understood. It is generally agreed that four different vibration excitation mechanisms are normally important in heat exchanger tube arrays. These mechanisms include periodic vortex shedding or more generally, flow periodicities, random excitation caused by turbulent flow, fluidelastic instability and acoustic resonance. Fluidelastic instability (FEI), among these mechanisms, is considered to have the greatest potential for short term damage to heat exchangers.

Fluidelastic instability is a self-excitation mechanism due to the motion-dependent fluid forces. The amplitude of vibration grows once the flow velocity exceeds a critical threshold. It is well known that even a single flexible tube in an otherwise rigid tube array subjected to cross-flow may experience large amplitude vibration due to FEI. Because of its extremely destructive nature, a considerable research effort has been undertaken over the past fifty years in an attempt to reveal the underlying mechanisms leading to fluidelastic instability. Some excellent reviews on the subject are provided by Paioussis (1983), Price (1995), Weaver and Fitzpatrick (1988), Pettigrew and Taylor (1991, 2003a, 2003b) and Chen (1984).

Fluidelastic instability may be caused by two distinct mechanisms: the damping controlled and the stiffness controlled instability mechanisms. Damping controlled instability is governed by the velocity dependent fluid forces and takes place when the total damping switches from positive to negative. The mechanism only needs one degree-of-freedom. Stiffness controlled instability is

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http://dx.doi.org/10.1016/j.jfluidstructs.2017.01.020
Received 10 June 2016; Received in revised form 12 December 2016; Accepted 12 January 2017
Available online 24 February 2017
0889-9746/

Nomenclature

M_s,C_s,K_s	The mass, damping and stiffness matrices of the structure, respectively
M_f,C_f,K_f	The added mass, damping and stiffness matrices of the fluid, respectively
$\ddot{x}$, $\dot{x}$, x	Tube acceleration, velocity, displacement vector, respectively
F_f	General form of the fluid force
ρ	Fluid density
U, U_P	Flow free stream velocity, flow pitch velocity, respectively
D	Tube diameter
λ	Complex eigenvalue
μ	The parameter of the constant time delay quasi-steady model
τ	Dimensionless time
$\Phi(\tau)$	Memory function
α_i, δ_i	Memory function parameters
$H(\tau)$	Heaviside step function
C_D,C_L, $\frac{\partial C_L}{\partial \bar{y}}$	Steady drag and lift coefficients, derivative of the lift coefficient with respect to the dimensionless displacement in the lift direction, respectively
ϖ	Reduced frequency
$C(\varpi)$	Equivalent Theodorsen function
$F(\varpi)$, $G(\varpi)$	The real part and imaginary part of $C(\varpi)$, respectively
$A(\varpi)$, $\phi(\varpi)$	The magnitude and phase of $C(\varpi)$
C_f, ϕ_f	The magnitude and phase of the unsteady fluid force coefficient
C_{da}, C_s	Damping and stiffness coefficient, respectively
H_{Fy}	Transfer function between the unsteady fluid force and tube motion

caused by the antisymmetric stiffness term. It is also called coupled mode flutter (in aeroelasticity) since at least two modes are required such that the relative motion between tubes can produce the force needed to overcome the structural damping.

The general governing equation of motion for the tube array subjected to single-phase cross-flow can be written as

$$[M_s]\{\ddot{x}\} + [C_s]\{\dot{x}\} + [K_s]\{x\} = F_f(\{\ddot{x}\}, \{\dot{x}\}, \{x\}, \ldots) \tag{1}$$

where $[M_s]$, $[C_s]$, $[K_s]$ are the mass, damping and stiffness matrices of the structure, respectively. F_f is the general form of the fluid force, $\{\ddot{x}\}$ the tube acceleration vector, $\{\dot{x}\}$ the tubes velocity vector and $\{x\}$ the tubes displacement vector.

Some theoretical or semi-empirical models have been developed to predict the critical velocity for fluidelastic instability. These include the quasi-static (Blevins, 1974; Connors, 1970), quasi-steady (Price and Paidoussis, 1984), quasi-unsteady models (Granger and Paidoussis, 1996; Meskell, 2009), the analytical channel flow model (Lever and Weaver, 1982) and the unsteady model (Tanaka and Takahara, 1981; Chen, 1987). The differences between these models lie in the definitions of the dynamic fluidelastic forces which are the terms on the right hand side of the governing equation as shown in Eq. (1). For example, the quasi-steady model was developed based on the position dependent steady fluid forces measured on the tubes. In the analytical channel flow model, the fluid forces are estimated directly using the unsteady Bernoulli equation. The unsteady model was developed by measuring directly the unsteady forces acting on the vibrating tubes. One of the most important parameters among these models is the time delay, or phase lag, between the tube motion and the fluid forces generated thereby.

In the quasi-static model, it is assumed that the fluid-dynamic forces acting on the cylinder oscillating in the flow are, at any instant of time, equal to the forces on the stationary cylinders in the identical position. Compared to the experimental results, the model is, however, unable to predict the critical velocity of the single flexible tube in an otherwise rigid tube array. To overcome this difficulty, a constant time delay was introduced in the quasi-steady model by Price and Paidoussis (1986). The modified fluid force then becomes:

$$F_f = -[M_f]\{\ddot{x}\} + [C_f]\{\dot{x}\} + [K_f]e^{-\lambda\mu D/U}\{x\} \tag{2}$$

where $[M_f]$, $[C_f]$, $[K_f]$ are the added mass, damping and stiffness matrices of the fluid. λ is the complex eigenvalue. The function $e^{-\lambda\mu D/U}$, $\mu \sim O(1)$, introduces the time delay which may induce the negative damping. Price and Paidoussis postulated that the time delay is due to the retardation of flow approaching the cylinder.

Later, Granger and Paidoussis (1996) improved the quasi-steady model by replacing the constant time delay with a memory function. The important unsteady effects are then considered. The authors attributed the time delay effect to the diffusion-convection process of the vorticity induced by the motion of the cylinder. Their modified fluid force is expressed as follows:

$$F_f = -[M_f]\{\ddot{x}\} + [C_f]\{\dot{x}\} + [K_f]\{h^*x\} \tag{3}$$

The convolution function which is in terms of the dimensionless time $\tau(\tau = Ut/D)$ in Eq. (3) is defined as follows:

$$h^*x = \int_0^\tau \frac{d\Phi(\tau - \tau_0)}{d\tau_0} x(\tau_0) d\tau_0 \tag{4}$$

This introduces the memory function which is of key interest in the quasi unsteady model. The memory function $\Phi(\tau)$ which accounts for the time delay tends to 1 as $\tau \to +\infty$. The function can be approximated by a linear combination of decaying exponentials and a Heaviside step function $H(\tau)$ as follows

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