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An investigation of time lag causing fluidelastic instability in tube arrays

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ABSTRACT

This paper presents an in-depth study of the time lag in a normal triangular tube array subjected to cross-flow. A Computational Fluid Dynamics (CFD) model was developed to simulate the flow inside the tube bundle. A moving tube with a prescribed sinusoidal oscillation was utilized for a range of reduced flow velocities from 1 to 40. An attempt was made to capture the temporal variation of the flow channel dimensions. The results were studied and interpreted in the framework of the flow cell model of Lever and Weaver. The flow channel dimensions were then used to extract the channel area perturbation amplitude and phase lag.

The computed time lag was used in tube stability simulations and a stability threshold was computed for a mass damping parameter range of 10–200. Using the proposed time lag in a time domain implementation of the flow cell model yielded a better prediction of the stability threshold. However, the results show that the original time lag postulation by Lever and Weaver had captured the main essence of the time lag predicted in this study. The difference lies in the time quantification variation along the flow due to the additional influence of the flow separation in the upstream tube.

1. Introduction

Plant equipment design has seen a paradigm shift over the previous decades. The rising cost of energy and the current focus on sustainability has raised efficiency and performance expectations significantly. To satisfy these demands, a widespread use of lighter and more flexible materials was seen. This has caused the plant components to become more susceptible to vibration damage. The integrity of structures is of particular concern in nuclear steam generators, where thousands of tubes are used as an interface to transfer the heat generated from the heavy water to the light water used for the power cycle. In this industry, where shutdowns are costly, the damage due to flow induced vibration is of great concern. As a matter of fact, flow-induced vibration is the second leading cause of tube damage in nuclear steam generators (Green and Hetsroni, 1995). Consequently, a great effort was made to identify the various excitation mechanisms affecting heat exchangers. These mechanisms include vortex shedding, turbulence, and fluidelastic instability.

Turbulence is a random excitation mechanism resulting in low amplitude vibrations. In comparison, vortex shedding is a well characterized periodic excitation whose frequency is linearly related to the flow velocity. The latter becomes a serious issue when the periodicity of the flow coincides with the natural frequency of the structure. Finally, fluidelastic instability

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Nomenclature

$\overline{A}(s)$	steady state channel area
A_0	channel inlet area
$a(s,t)$	channel area perturbation
c	tube structural damping
d	tube diameter
f	tube motion frequency
l_0	relevant fluid length to the time delay
k	tube structural stiffness
m	tube mass
MDP	mass damping parameter
P_0	inlet pressure
$p(s,t)$	pressure perturbation
Re	Reynolds number $\left(\mathrm{Re} = \frac{U_o d}{\nu}\right)$
s	curvilinear position coordinate along the channel
s_0	distance from the centre tube to the inlet
s_a	distance from the centre tube to the flow attachment point
s_s	distance from the centre tube to the flow separation point
s_{us}	distance from the centre tube to the flow separation point of the upstream tube
T	vibration period
$\overline{U}(s)$	steady state flow velocity
U_{cr}	reduced critical flow velocity
U_0	mean inlet flow velocity in the channel flow
U_r	reduced flow velocity $\left(U_r = \frac{U_o}{fd}\right)$
$\psi(s)$	area phase angle in degrees with respect to the tube displacement
$\phi(s)$	velocity phase angle in degrees with respect to the tube displacement
$\tau(s)$	area time lag in seconds with respect to the tube displacement
ω	tube frequency of oscillation

(FEI) is described as the most problematic mechanism as it can cause catastrophic failure. This mechanism is characterized by the existence of feedback between the motion of the tubes in a bundle and the fluid forces.

The interaction between the tube motion and fluid flow within the bundle is rather important as it determines whether the energy of the system is dissipated. When a certain velocity threshold, known as the critical flow velocity (U_c), is reached, the energy added to the structure becomes greater than that dissipated through structural damping. This causes the tubes to vibrate at large amplitudes. Hence, if such a mechanism is ignored there may be disastrous consequences to the structural integrity of the steam generators. Over the past fifty years, this has motivated a lot of research in this field. The focus has been on determining the onset of instability for the purpose of heat exchanger design. The early work of Roberts (1962) and Connors (1970) has led to a widely used representation of the reduced flow velocity (U_r) in terms of the Mass Damping Parameter ($MDP = m\delta/\rho d^2$). This representation is often referred to as Connors' equation ($U_{cr} = K(m\delta/\rho d^2)^a$), and due to its simplicity, it has been widely adopted in industrial applications. The early efforts of Connors (1970) have resulted in values of K and a of 9.9 and 0.5, respectively. In a quest towards obtaining more appropriate values of these coefficients, considerable experimental efforts have been devoted. However, this provides very little physical insight into the underlying mechanisms of the stability of tube bundles. Weaver and Fitzpatrick (1988) provided an extensive review of the factors that influence this stability boundary.

Several techniques and models (Tanaka and Takahara, 1981; Chen and Jendrzjczyk, 1981) have been developed in order to analyze fluidelastic instability problems using a series of empirical force coefficients. These force coefficients are used to represent the effects of fluid flow on the inertia, stiffness, and damping characteristics of the structure, and they need to be determined experimentally. Other models (Lever and Weaver, 1986a,b; Price and Païdoussis, 1984) attempted to utilize semi-analytical techniques in order to understand the underlying physics of the problem. These models allow a qualitative and quantitative description of tube dynamics while reducing the amount of empirical data required.

Price and Païdoussis (1984) utilized the quasi-steady theory to describe the unsteady fluid forces acting on the tube. However, for instability to occur, a time delay, τ, is required between the fluid force and the tube motion. In this case the time lag is attributed to the so-called flow retardation effect. This approach is further expanded in a study by Granger and Païdoussis (1996), which postulates that fluid forces arise from the vorticity, which is generated in the tube boundary layer, diffusing and convecting away in the mean flow. This has led to the development of a time lag function that utilizes a linear combination of decaying exponentials. The new model showed an improvement over the original quasi-steady model (Price and Païdoussis, 1984) when compared to experimental results.

Lever and Weaver (1982, 1986a,b) took a radically different approach, as they directly modelled the fluid flow around the tubes. This has resulted in the development of an analytical expression that sufficiently represented the feedback phenomenon between the tubes and the surrounding flow (Flow Cell), and hence solved for the pressure around the tubes. The flow inside the tube bundle was simplified into channels, and assumed to be one dimensional and incompressible. Using this model the flow channel configuration is dictated by the tube array geometry. Another important assumption is that the wake regions are assumed to have very little influence on fluidelastic instability. As a result, only flow characteristics in the channels on either side of the tube are considered. In addition, it was successfully shown that a single flexible tube surrounded by rigid tubes was sufficient to predict the onset of instability. The model postulated that the tube motion results in a redistribution of the channel area. The change in the channel area is called the area perturbation. For the flow attached to the tube this redistribution is in-phase with the tube motion. However, due to finite fluid inertia, the upstream flow channel area response lags behind the tube motion. This delayed area perturbation caused by the flow