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Influence of the mass ratio on the fluidelastic instability of a flexible cylinder in a bundle of rigid tubes

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ABSTRACT

Several linear lumped-parameter models were proposed in the past to identify the main mechanisms underlying the cross-flow instability of a single flexible cylinder in tube bundles. Basing on such models, we analyze the influence of the mass ratio when the cylinder vibrates in the transverse direction, without structural damping (corresponding to a zero Scruton number). For two selected mass ratios, we focus on this linear interaction plotting the poles of the fluid–structure system as a function of the reduced velocity (root locus). This asymptotic approach allows a better understanding of the combined influence of the transient fluidelastic coupling and the mass ratio.

1. Introduction

The fluidelastic interaction in cylinder arrays is complex, since it combines three types of instability (Khalifa et al., 2012; Païdoussis et al., 2010; Blevins, 1994):

- Instability by antisymmetric stiffness similar to classical flutter, with at least two degrees of freedom involved in the motion. It is the main mechanism when reduced velocity is much higher than unity.
- Dynamic instability for a Single-Degree-Of-Freedom cylinder. It is the main mechanism when reduced velocity is of the order of unity.
- Static instability (divergence) for a Single-Degree-Of-Freedom cylinder. It was highlighted by Paidoussis et al. (1989) for peculiar geometrical patterns.

The difficulty to differentiate these instabilities can be evoked as one of the reason for the high experimental scattering on the values of critical velocity U_c or the reduced critical velocity

$$U_{rc} = \frac{U_c}{f_S D},$$

where f_S is the structural natural frequency and D the cylinder diameter. In addition to the geometric pattern influence, U_c is affected by other phenomena:

- Vortex-Induced-Vibration domain and Movement-Induced-Vibration domain overlap when Scruton number is low (Weaver, 2008). According to Granger and Paidoussis (1996), this can explain some modeling difficulties for fluidelastic instability prediction.

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Table 1
Nominal parameters for the experiment and simulations.

Parameter	Notation	Value
Fluid density (kg m^{-3})	ρ_F	1.2
Dynamic viscosity (m^2 s^{-1})	ν	15×10^{-6}
Cylinder length (m)	L	0.6
Cylinder diameter (m)	D	0.08
Pitch (m)	P	0.12
Pitch ratio	P/D	1.5
Aspect ratio	$a=(P/D)/(P/D-1)$	3
Total mass (kg)	M_S	0.5
Mass per length (kg/m)	$m=M_S/L$	0.83
Structural damping coefficient (N/(ms^{-1}))	C_S	0
Structural stiffness coefficient (N m^{-1})	K_S	3000
Structural reduced damping	ξ_S	0
Structural natural frequency (Hz)	f_S	12.3
Structural natural frequency (rd/s)	ω_S	77.46
Pitch Reynolds number	$\text{Re}=U_pD/\nu$	51 500
Mass ratio	$m^\star=m/(\rho_F D^2)$	108
Scruton number	$\text{Sc}=2\pi\xi_S m^\star$	0
Reduced velocity	$U_r=U/(f_S D)$	3.26

- The Reynolds number strongly influences the physics of the flow, but it is very seldom taken into account. Gillen and Meskell (2008) show an important influence on the static efforts and notable consequences on the critical velocity by the quasi-unsteady model of Granger and Paidoussis (1996).

This critical velocity value is a crucial criterion for design of heat exchangers. It is usually plotted as a function of the mass ratio ($m^\star$) and reduced structural damping (ξ_S), defined in Table 1. The three constants K, p, q in relation (1)

$$U_{rc}=K(m^\star)^p\xi_S^q \tag{1}$$

are then fitted from experimental data. The Scruton number ($\text{Sc}=2\pi\xi_S m^\star$) appears if $p=q$ is considered. This dimensionless group quantifies the ratio between the energy dissipated by the structure and the energy taken from the fluid (Axisa, 2001). Since experimental evidence of a specific dependence to the structural damping and the mass ratio are numerous (Tanaka and Takahara, 1981; Price, 2001), it is not relevant to assume that $p=q$, as suggested by Connors-type equations (Connors, 1970).

Some efforts are still necessary to unfold the specific influence of the mass ratio and reduced structural damping according to the value range of the Scruton number (Weaver, 2008). In order to contribute to this analysis, we propose to isolate the influence of the mass ratio, considering an undamped structure, which corresponds to the asymptotic case $\text{Sc}\to 0$. The linear models with lumped-parameter approach will be considered, leading to a user-friendly description of the fluidelastic instability in cross-flow cylinder arrays. Nevertheless, they show substantial weakness in accurately predicting critical velocities for specific industrial applications such as steam generators (Price, 2001). This industrial application is characterized by low Scruton numbers and reduced velocities of the order of unity. That implies a strong fluidelastic coupling and the need for taking into account of the transients of the coupling mechanism (Tanaka and Takahara, 1981). For a bibliographical synthesis on these phenomena and the various modeling options to predict these instabilities (generally referred as damping-controlled instability), one can consult (Price, 2001; Païdoussis et al., 2010).

We propose to distinguish two classes of models, according to whether the fluid–structure system is described by:

- a model of the same order as that of the structure model order. The interaction is then characterized by a damping coefficient and a stiffness coefficient added by the flow, which depend on the reduced velocity, since the quasi-static theory is not valid. It is for example the approach of Chen (1987).
- a model of a higher order than that of the structure model order. The interaction is identified by its own dynamics. It is for example the approach of Price and Païdoussis (1986) or Granger and Paidoussis (1996), that we will compare (Section 2.3). The model of Lever and Weaver (1982) also belongs to this category.

In order to analyze the influence of the mass ratio on the loss of stability, it is necessary to precisely describe the dynamics of the interaction and not only its consequences on the dominant mode of the coupled system. Only the second category of models can thus bring elements of physical insight. This is why we will limit the discussion to this class of models. Only linear models are considered here, but the nonlinear tools for simulation are set up for the continuation of the study. We will use the symbolic formalism for its ease of handling, although the temporal formulation by the operator of convolution is more explicit in describing the physics of the memory.

All the cylinders are fixed, except the central one that is flexibly mounted. It can move in the z direction only in an in-line square array, with P the pitch between cylinders (Fig. 1). The ratio between the pitch velocity U_p and the free-stream single