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Dynamic stability of a pipe conveying fluid with an uncertain computational model

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ABSTRACT

This paper deals with the problem of a pipe conveying fluid of interest in several engineering applications, such as micro-systems or drill-string dynamics. The deterministic stability analysis developed by Paidoussis and Issid (1974) is extended to the case for which there are model uncertainties induced by modeling errors in the computational model. The aim of this work is twofold: (1) to propose a probabilistic model for the fluid–structure interaction considering modeling errors and (2) to analyze the stability and reliability of the stochastic system. The Euler–Bernoulli beam model is used to model the pipe and the plug flow model is used to take into account the internal flow in the pipe. The resulting differential equation is discretized by means of the finite element method and a reduced-order model is constructed from some eigenmodes of the beam. A probabilistic approach is used to model uncertainties in the fluid–structure interaction. The proposed strategy takes into account global uncertainties related to the noninertial coupled fluid forces (related to damping and stiffness). The resulting random eigenvalue problem is used to analyze flutter and divergence unstable modes of the system for different values of the dimensionless flow speed. The numerical results show the random response of the system for different levels of uncertainty, and the reliability of the system for different dimensionless speeds and levels of uncertainty.

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1. Introduction

This paper extends the deterministic stability analysis proposed by Paidoussis and Issid (1974) of a pipe conveying fluid. The present work deals with a probabilistic model that takes into account uncertainties induced by modeling errors that arise due to physical simplification introduced in the deterministic model, as it will be explained latter. Slender flexible tubes with internal flow or pipes conveying fluids are present in a number of applications, such as micro-systems, biological devices, drill-strings and heat exchangers. See, for instance, Ritto et al. (2009) for nonlinear dynamics of a drill-string,

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Rinaldi et al. (2010) for microscale resonators, Soltani et al. (2010) for nanotubes with viscous fluid/Kelvin–Voigt model, and Gosselin and Paidoussis (2014) for the dynamic stability of a hose to the sky.

Typically, the standard configuration is a straight tube mounted over supports carrying a steady flow with a constant velocity. If the velocity is kept below a certain threshold, ambient perturbations might entail low amplitude vibrations of the structure around a standard configuration. Above the critical speed, the coupled system, constituted by the structure and the flow, might undergo large vibrations and complex nonlinear dynamical responses. The understanding of such an unstable behavior is required for improving the design of the system and mitigating damage effects. In addition, the large diversity of the dynamical response renders this problem quite attractive for theoretical and numerical studies.

Computer models are nowadays widely used in the design and analysis of standard engineering systems. Many critical decisions are taken based on computational simulations. Despite the consolidation of powerful and reliable methods leading to small numerical errors originated by discretization techniques, the extension of this common practice to more critical systems is hindered by the presence of inevitable uncertainties associated with the modeling. Statistical fluctuations around nominal values of parameters, nonidealized initial and boundary conditions, or production tolerances might entail a large variation on the output of the simulations. So, in order to improve the reliability of predictions, those uncertainties must be taken into account. Here, the consideration of the uncertainties is carried out within a probabilistic framework, hence, design criteria are based on failure probabilities and reliability analysis, such as done by Ghanem and Spanos (1991) and Schueller et al. (2004). The problem of a pipe with internal flow can be modeled using a tridimensional nonlinear elastic model for the structure together with Navier–Stokes equations for the fluid, see Bathe et al. (1999) and Bathe and Zhang (2004). But, usually, simplified physics is introduced. In Piet-Lahanier and Ohayon (1990), for instance, a beam model is used for the pipe, and a compressible and viscous fluid is considered. The use of simplified models, such as the one proposed by Paidoussis and Issid (1974) and reused in this paper, makes feasible the analysis of a significant number of scenarios. However, it is clear that the use of kinematic reductions introduces modeling errors.

The stability of dynamic systems has been extensively studied from a deterministic perspective, see, for instance, Guckenheimer and Holmes (1983) and Nayfeh and Balachandran (1995). There are also some works in the literature dealing with the stochastic stability analysis. For example, in Lin and Cai (1995), the concepts of almost-sure stability, stability in probability and stability in the mth moment are defined and used for analyzing stochastic dynamical systems submitted to time-varying loads.

The stability of pipes with internal flow was deeply investigated by Paidoussis (1998). In Paidoussis and Issid (1974), some historical review of the subject up to the time the article was written is done, and the instabilities due to divergence and flutter phenomena are discussed for steady-state flows and harmonically perturbed flows. This was the first time that the coupled-mode flutter (simply called flutter) was noticed for this kind of coupled system. In Ariaratnam and Namachchivaya (1986b), an analytical method (devoted to the stability of pipes with perturbed internal flow) is proposed by using the method of averaging and the Floquet–Lyapunov theory. In Ibrahim (1986), a more recent review of the mechanics of pipes conveying fluid can be found in which more than 400 references are given.

There are few investigations related to uncertainty for stability of a pipe with internal flow. In Ariaratnam and Namachchivaya (1986a), random velocity fluctuations were considered; the authors used the averaging method and the Floquet theory. In Ganesan and Anantha (1995), system-parameter uncertainties are taken into account. Some statistics of the critical flow velocity are analyzed for a stochastic modeling of the elasticity modulus and of the mass per unit length of the structure. In Yigit (2008), the flutter stability of a cantilever pipe conveying fluid is considered, where active control is used to suppressthe structural vibration. The present paper aims to analyze the dynamic stability of a pipe conveying fluid including uncertainty in the fluid–structure interaction model, as explained in the sequence.

The fluid–structure interaction phenomena are responsible for the existence of unstable modes of the dynamical system and, therefore, play a central role in the present analysis. In order to endow the model with an improved capacity of describing the fluid–structure coupling, a probabilistic approach which has the capability to take into account modeling errors should be used. In this paper, we propose to use the nonparametric probabilistic approach introduced by Soize (2000, 2012), which is a method to take into account model uncertainties induced by modeling errors.

In computational dynamics and in computational fluid–structure interaction such as aeroelasticity and vibroacoustics, the nonparametric probabilistic approach is an alternative method to the output-prediction-error method which allows modeling errors to be taken into account at the operators level of the computational model by introducing random operators and not at the model output level by introducing an additive noise. It should be noted that such an approach allows a prior probability model of uncertainties to be constructed even if no experimental data are available. The nonparametric probabilistic approach is based on the use of a reduced-order model and the random matrix theory. It consists in directly constructing the stochastic modeling of the operators of the mean computational model. The random matrix theory and its developments in the context of dynamics, vibration and acoustics are used to construct the prior probability distribution of the random matrices modeling the uncertain operators of the mean computational model. This prior probability distribution is constructed by using the Maximum Entropy Principle introduced by Shannon (1948) and Jaynes (1957, 2003), in the context of Information Theory, for which the constraints are defined by the available information. Section 4 is devoted to the nonparametric probabilistic model, where the statistically dependent random matrices which are derived from the fluid coupling model are generated thanks to the introduction of an adapted scheme. Consequently, with the aid of the nonparametric probabilistic approach, the uncertainties are globally modeled and modeling errors are taken into account. The nonparametric probabilistic approach of uncertainties has been applied in numerous different areas to

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