Reliability analysis of pipe conveying fluid with stochastic structural and fluid parameters

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A B S T R A C T

In this article, Monte Carlo simulation method is used in conjunction with finite elements for probabilistic self-excited vibration and stability analyses of pipes conveying fluid. For fluid–structure interaction, Euler–Bernoulli beam model is used for analyzing pipe structure and plug flow model is used for representing internal fluid flow in the pipe. By considering structural and fluid parameters of the system as random fields, the governing deterministic partial differential equation (PDE) of continuous system is transformed into a stochastic PDE. The continuous random fields are discretized by mid-point and local average discretization methods. For self-excited vibration analysis, the complex-valued eigenvalue problem is solved for investigating the eigenvalues and critical eigenfrequencies. Consequently, using complex eigenfrequencies and divergence velocities for every realization, the statistical responses of stochastic problem are obtained as expected values, standard deviations, probability density functions, and the probability of divergence occurrence. Moreover, the randomness effects of fluid parameters on the system are compared to those of structural parameters.

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1. Introduction

The main purpose for imposing the problem of fluid–structure interaction (FSI) is to analyze the effects of fluid flow on vibrational behavior of structure and to calculate critical velocities. The divergence and flutter instabilities occur at the critical velocities. FSI occurs whenever the in-contact fluid applies pressure or thermal load to the solid wall. Bourrieres [1] conducted the first systematic study for dynamic behavior of pipes conveying fluid. He acquired governing equations of motion correctly for the first time and achieved precise responses for stability of a cantilever pipe conveying fluid. Afterwards, Housner [2], Benjamin [3], and Paidoussis and Issid [4] analyzed this problem more precisely. According to Paidoussis and Issid [4] studies, two types of divergence and flutter instabilities could occur in FSI phenomenon. Guo et al. [5] attained a coefficient to amend centrifugal force term in pipe equations of motion, considering unsteady flow velocity for laminar and turbulent flow profiles. Lin and Qiao [6] studied vibration and instability of an axially moving beam immersed in fluid with simply-supported ends as well as torsional springs. Liu et al. [7] analyzed FSI problem for an elastic cylinder by numerical simulations and

acquired the vibrational behavior of cylinder for both laminar and turbulent flows. Mirramezani et al. [8] investigated the instabilities of carbon nano-tubular shells subjected to combined external and internal flows by considering slip condition. They observed that as the nonlocal parameter and Knudsen number increase, the critical flow velocities for the first-mode divergence instability decrease. Huang et al. [9] used Galerkin's method to obtain eigenfrequencies of pipes conveying fluid having different boundary conditions. Further, they calculated effect of Coriolis forces on the variation of system eigenfrequencies and expressed a correlation between a pipe conveying fluid and Euler–Bernoulli beam eigenfrequencies. Lee and Oh [10] developed a spectral element model for the pipe conveying fluid to study the flow-induced vibrations of the system. They obtained the spectral element model by the exact dynamic stiffness matrix.

Randomness is the lack of pattern or regularity [11]. Uncertainty could be observed widely in engineering systems and nature. Sometimes, these uncertainties act like external forces for a dynamical system and make the excitations random, while sometimes they act like inherent properties of a dynamical system and make system parameters stochastic. On the other hand, the considerable effect of uncertainties on system behavior has made the engineers to use a probabilistic approach for engineering problems. The analysis of FSI problems is usually done by considering the system parameters as deterministic, while actually these parameters

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are not deterministic. Accordingly, it is preferable to use a probabilistic approach for understanding actual behavior of these types of systems. T.-P. Chang and H.-C. Chang [12] used the perturbation stochastic finite element method to obtain the statistical responses of a non-uniform beam with stochastic Young's modulus. They compared some of the statistical responses with Monte Carlo simulation method (MCSM). Also they performed the reliability analysis based on certain failure criteria of the structure. Kareem and Sun [13] discussed about the structures with uncertain damping. They used a second-order perturbation technique to obtain the damping variability on the transient response of structural systems. Ramu and Ganesan [14] investigated a beam with random Young's modulus to which undetermined forces were applied. In this study, the finite element method and local averages of the random parameter was used to obtain the statistical parameters of buckling loads, such as mean, variance, and uncertain buckling modes. In another work, Ramu and Ganesan [15] used the Galerkin weighted residual method for analysis of a beam with more than one random parameter. In their paper, they considered the parameters of mass per unit length and Young's modulus as random parameters. Finally, they obtained the mean and variance of system eigenfrequencies using local average discretization and covariance matrix methods. They did not investigate the probability of instability occurrence and their probability density functions. Cheng and Xiao [16] investigated free vibrations of a beam with random parameters under axial load by an algorithm based on stochastic finite element method. They calculated frequency response of the beam using a combination of response surface methods, FEM, and MCSM. Zhai et al. [17] obtained dynamic response of a pipe conveying fluid with Timoshenko beam model under random excitation and used the pseudo excitation method in conjunction with complex mode superposition method to solve the governing equation. They assumed that the parameters of load were random. They did not investigate a system having random parameters. The random parameters of an FSI system could be modeled as random fields, the subject that they did not investigate. Esmailzadeh and Lakis [18] presented a method to predict average response of an open curved thin shell structure. To this structure, a random pressure field arising from a turbulent boundary layer was applied. Further, the spectral density function of pressure fluctuations in turbulent pressure field was described using the Corcos formulation.

Stefanou [19] investigated the response variability of cylindrical shells with material and geometric uncertain parameters. He assumed that the random parameters are two-dimensional univariate homogeneous non-Gaussian stochastic fields. He showed that these random parameters could affect significantly the response statistics. Papadopoulos et al. [20] studied the effect of random geometric imperfections on the buckling analysis of I-section frame structures. They modeled the geometric imperfections as non-homogeneous Gaussian random fields and implemented different types of boundary conditions and histograms of buckling loads. Field and Grigoriu [21] proposed a model for phenomena that had random fluctuations with two states representing spatial and temporal correlations. Also, they assumed that the transition from laminar to turbulent flow over the surface of a structure could have both spatial and temporal random fluctuations concurrently. In another work, Grigoriu and Field [22] obtained a method to approximate the properties of a linear dynamical system with a non-Gaussian noise property. Then, they used this method to solve random vibrations caused by turbulent flow over a flexible plate. Their problem could be categorized as a random load, in contrast to a random field. There seem fewer investigations for stability analysis of pipes conveying fluid with random parameters. Ariaratnam and Namachchivaya [23] investigated the dynamic stability of a pipe conveying fluid with random

velocity fluctuations in time. They used the averaging method and the Floquet–Lyapunov theory. Ganesan and Anantha [24] calculated the statistical responses of critical flow velocity by assuming the structural parameters as random fields; however, they did not consider the random fluctuations in structural and fluid parameters simultaneously as random fields. Ritto et al. [25] used a probabilistic approach for stability and reliability analysis of a pipe conveying fluid. The governing equation was discretized by means of FEM and a reduced-order model was constructed from some eigenmodes of a beam. They did not consider the randomness in structural parameters. Consequently, they could not compare the effect of randomness simultaneously on both structural and fluid parameters, something performed in the present research. Moreover, they used a nonparametric probabilistic approach to model the uncertainty, unlike the present article in which random fields were used to model the stochastic parameters in a FSI problem.

In this article, FSI problem having random parameters for both structure and fluid is investigated. Euler–Bernoulli beam model is used for analyzing pipe structure, while plug flow model is used for representing internal fluid flow in the pipe. Due to the uncertainties in the structural and fluid parameters of the system, such as the mass per unit length of structure and fluid, flexural rigidity, and flow velocity, the self-excited vibrations and dynamic stability of pipes conveying fluid are investigated via probabilistic approach. Each of the stochastic parameters is considered as random field. These random fields are converted into random vectors by means of two different discretization methods, i.e., mid-point and local average discretization methods. Finally, the statistical properties of the system, such as the mean and standard deviation of eigenfrequencies are calculated by using FEM and MCSM. Moreover, probabilistic stability analysis is performed and probability of the instability occurrence and probability density functions are calculated for different flow velocities.

2. Deterministic analysis of pipes conveying fluid

The system in the present analysis is sketched in Fig. 1. To derive pipes conveying fluid governing equations of motion using the Euler–Bernoulli beam model, there are several methods fully explained by Paidoussis [26]. In the sequel, the vibration equation of a beam and modeling of the fluid forces applied to it are used to obtain the governing coupled equation. Since the Euler–Bernoulli beam theory is used for modeling the structure, the governing PDE is derived, as follows, Meirovitch [27]:

$$\frac{\partial^2 M}{\partial x^2} + m \frac{\partial^2 w}{\partial t^2} = f \tag{1}$$

where w is the transversal displacement, M is the bending moment, m is the mass per unit length of beam, f is the external force per unit length, t is the time, x is the longitudinal coordinate of tube elastic axis defined in the interval $[0, L]$, and L is the length of the beam.

The bending moment of an Euler–Bernoulli beam is given by:

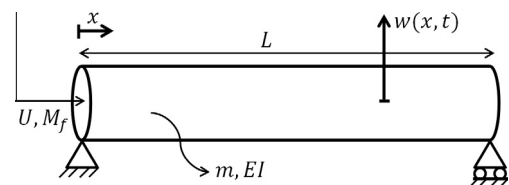$$M = EI \frac{\partial^2 w}{\partial x^2} \tag{2}$$

Fig. 1. Sketch of the system considered in the analysis.