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Mathematical modeling of the dynamic stability of fluid conveying pipe based on integral equation formulations

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ABSTRACT

In this paper, a mathematical modeling of flutter and divergence analyses of fluid conveying pipes based on integral equation formulations is presented. Dynamic stability problems related to fluid pressure, velocity, tension, topography slope and viscoelastic supports and foundations are formulated. A methodological approach is presented and the required matrices, associated to the influencing fluid and pipe parameters, are explicitly given. Internal discretizations are used allowing to investigate the deformation, the bending moment, slope and shear force at internal points. Velocity–frequency, pressure-frequency and tension-frequency curves are analyzed for various fluid parameters and internal elastic supports. Critical values of divergence and flutter behaviors with respect to various fluid parameters are investigated. This model is general and allows the study of dynamic stability of tubes crossed by stationary and instationary fluid on various types of supports. Accurate predictions can be obtained and are of particular interest for a better performance and for an optimal safety of piping system installations.

1. Introduction

Structures submitted to non conservative forces and fluid convening pipes constitute basic parts of many complex engineering structures. The main forms of instability of these structures are Buckling, flutter and excessive vibrations. The accurate prediction of static and dynamic critical induced loads and responses of fluid conveying pipes are very significant in practice and it relies on a better design of pipes which can be safely used in the pre-buckling and post buckling ranges. Existing literature indicates that, many researchers studied the stability problems of piping systems [1–9]. Most dynamic analyses of a ‘single-span’ piping system are performed using modal analysis method [1–4,10] or Finite Element Method (FEM) [5,6]. The only problem with this method is that its formulation is quite laborious and needs a large amount of computer storage and at the same time slows the computations. A powerful alternative method based on integral equations is the Boundary Element Method (BEM) [11]. Using the fundamental solution corresponding to the exact solution of a part of the problem, the others terms are moved to the right hand side of the governing equation and considered as a fictitious source density. For buckling and vibrations of pipes under elastic foundations, domain integrals are necessary in the formulation.

In addition, the conventional FEM can become very laborious when the numbers of spans is very large. For the case when the compressive force is absent, the problem of determining the stability has been treated by Bolotin [12] and by George and Paidoussis [13]. It was concluded that the pipe loses stability through flutter. Hamadiche and Gad-El-Hak [14] have studied the stability of the Hagen-Poiseuille flow of a Newtonian fluid in an incompressible (viscoelastic tubes contained within a rigid) hollow cylinder using the linear stability analysis. Various generalizations of the basic model were analyzed by Paidoussis and Issid [2] and Guran and Plaut [15]. In all these work, the Euler-Bernoulli model is used for slender pipe. The classical problem of the pipe conveying fluid has been generalized by Dupui and Rousseled [16] in two directions. First, initially curved pipes are analyzed and this results in the spatial motion of the pipe when the fluid flows through it and the second generalization deals with the Timoshenko beam model for the pipe material. The influence of the shear stresses at the pipe-fluid interface on the motion of the pipe is taken into account. George and Paidoussis [13] have shown that within the approximation used, the dynamical problem is independent of the pipe-

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fluid friction. In the case of initially spatially deformed pipes, it is shown in Ref. [16] that the dynamics of pipe is "not always axial-friction independent". Other models of fluid convening pipe problem are studied by Guran and Atanackovic [4]. They have analyzed the problem in three aspects. They suppose, first, that the axial force is acting on the free end of the pipe. The second aspect consists of using Haringx's type of constitutive equations and taking into account the influence of shear stresses on the pipe deformation. This assumption is more accurate for short pipes (Atanackovic, 1997 [17]). The third aspect is that the rotary inertia of the pipe element is considered in their model. De Langre and Ouvrard [18] have studied the effect of internal flow on the lateral stability of fluid conveying pipes by determining the absolute or convective nature of instability from the analytically derived linear dispersion relation. In this analysis, the effect of damping has not been considered. They also have investigated the relationship between the local and global bending motion of fluid conveying pipe on elastic foundation [19]. The local approach refers to an infinite pipe, while in the global approach the pipe is of finite length with a given set of boundary conditions. The nonlinear dynamics of elastically constrained pipe is studied by Yoshizawa et al. (1995) [20]. Elfelsoufi and Azrar [21] have studied the dynamic stability of the Euler-Bernoulli beams using the integral equation formulation taking into account different parameters such as the elastic foundation, elastic support, subtangential parameters, internal and external damping effects. The structural vibration and fluid-borne noise induced by turbulent flow through a 90° piping elbow have been studied by Zhang et al. [22]. They have studied the effect of guide vanes in different positions installed at the elbow on the flow-induced vibration and flow-induced noise. Large Eddy Simulation (LES) model is adopted for time varying pressure and velocity fields. The structural vibration is investigated based on a fluid−structure interaction (FSI) code using harmonic response analysis. Sukaih [23] presents a systematic and structured approach to piping vibration assessment and control. Piping vibration assessment is a complex subject, since there are no general analytical methods to deal with the resulting vibration problems. It was noted that most existing vibrating piping systems had poor or degraded support arrangements. This approach therefore focuses mainly on vibration control through assessing and improving the supporting systems. A simplified procedure is presented to determine when a simple assessment may be carried out and when specialist/consultant services are required. Mathan and Prasad [24] have studied the dynamic response of piping system with gasketed flanged joints at various temperatures. Finite element simulation with thermo-mechanical analysis is performed, followed by modal and harmonic analyses. Important parameters affecting the vibration are discussed. Temperature of internal fluid induces thermal stresses which influence the natural frequencies significantly. A comparison has been made between metal gasket and spiral wound gaske. Onizawa et al. [25] have developed a probabilistic fracture mechanics (PFM) analysis codes for reactor pressure vessels (RPVs) and piping, called PASCAL (PFM Analysis of Structural Components in Aging LWRs).

The aim of this paper is to develop a mathematical modeling of fluid conveying pipes on viscoelastic support and concentrated viscoelastic foundations using the integral equation formulation. The effects of internal and viscous damping as well as some fluid parameters are taken into account. The radial basis functions and internal discretization are used and all required matrices are explicitly formulated. The governing dynamic system is presented with many physical problem parameters: slope topography, tension, fluid pressure and velocity (stationary and instationary) and generalized supports. Explicit formulations for the deflection, the slope, the moment and the shear force are presented and the solution can be obtained at interior or boundary points. The buckling, flutter and free vibration of loaded fluid conveying pipe are formulated in a compact matrix form. The effects of fluid parameters on the critical buckling and frequencies have been extensively studied. The frequency-pressure, frequency-velocity and flutter-velocity are analyzed in detail taking into account the material and viscous damping.

2. Mathematical formulation

Let us consider a fluid conveying pipe of length L with constant cross section (Fig. 1). Following Euler-Bernoulli theory of fluids, the total energy of a fluid particle represented by the sum of the pressure energy, the kinetic energy and the gravity energy in the line of current remains constant when friction between fluid and the tube is neglected. If one takes into account the friction effect, the variation of the total energy is equal to the loss of pressure. The modeling of this variation is given by Ref. [26]:

$$\frac{p(z_A)}{\left(\frac{g\rho_f}{S}\right)}+\frac{U^2(z_A)}{2g}+C(z_A)=\frac{p(z_B)}{\left(\frac{g\rho_f}{S}\right)}+\frac{U^2(zB)}{2g}+C(z_B)+H_{AB} \qquad (1\text{-}1)$$

where 'z' is the axial co-ordinate along the undeformed centerline of the pipe. $C(z)$ is the altitude at 'z' and g is the gravity, H_{AB} is the loss of the pressure between points 'A' and 'B'. ρ_f is the mass of the

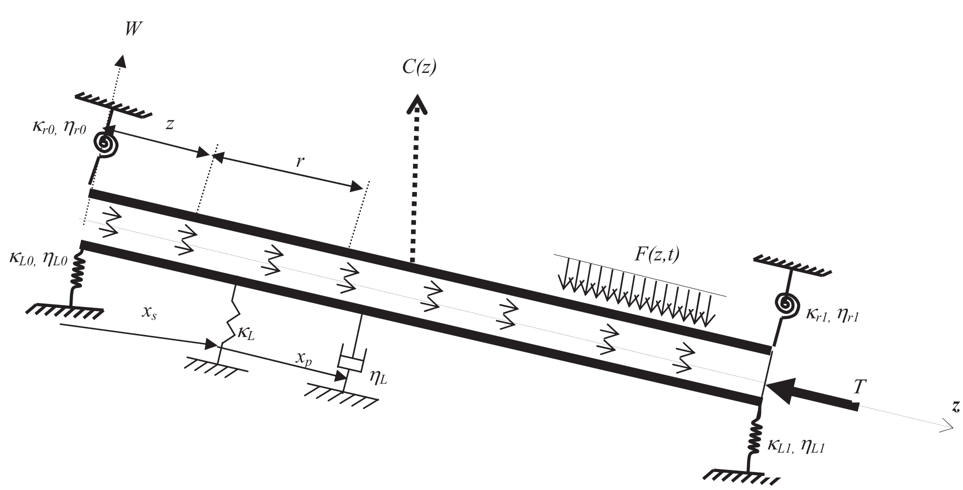

Fig. 1. Fluid convening pipe on viscoelastic foundation submitted to axial tension T and lateral excitation F(z,t).