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Experimental determination of time lag due to phase shift on a flexible pipe conveying fluid

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ABSTRACT

A finite element model of a flexible tube conveying fluid is developed in MATLAB© based on the principle of virtual work, using a three-node isoparametric beam element. Finite element equations are formulated by applying Galerkin technique on the coupled equations of pipe conveying fluid. The present element developed is capable to model three-dimensional flexible tubes by including curved geometry, effects of damping, velocity and gyroscopic effects. The external excitation applied at the middle of the tube in the lateral direction produced a time lag between the lateral responses, which were measured at two equidistant points from the excitation point. This is due to the Coriolis effect, and the same is simulated using the developed code. An experiment, supported with a robust error analysis, is also conducted on a straight polyurethane tube conveying water, subjected to a sinusoidal excitation at the center between the clamped supports. The measured time responses are compared with the numerical values predicted by the code. The time lags for both cases are obtained from the temporal shift along the time axis, between the zero crossing points of the time–response curves. The results obtained agreed well. The code can be used to predict the time lag, which is correlated to the mass flow rate. The proposed method will help to design Coriolis mass flow meters for existing pipelines, without altering the system.

1. Introduction

The study of dynamics of pipe flow is of great importance in the field of Fluid–Structure Interactions (FSI). A good amount of numerical and experimental data is available from earlier researchers. The present study attempts to develop a mathematical model of a flexible pipe conveying fluid, using finite element method and MATLAB, to predict the time lag, which can be correlated to the mass flow rate. A carefully designed experiment and robust error analysis, will be performed to validate the numerical results predicted by the code developed.

1.1. Literature review

Over the years, a large number of researchers had worked in the field of dynamics of pipe conveying fluid and reported their findings. Paidoussis and Issid [1] studied the dynamics and stability of flexible pipes with flowing fluid. They found that, for a gyroscopic system like a pipe fixed at both ends, besides buckling, couple-mode flutter occurs at higher flow velocities, and that it is associated with Coriolis/gyroscopic forces. In their study, Paidoussis and Luu [2] presented the dynamics and stability of short

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tubes conveying fluids based on a three dimensional fluid-mechanical model instead of a conventional plug flow model. The dynamics and stability were analyzed for different configurations of curved pipe conveying fluids by Paidoussis and Misra [3], based on the inextensible theory (i.e., the center line of pipe is inextensible). Dupis and Rousselet [4] suggested a mathematical modelling of the curved pipe problem and arrived at a non-linear differential equation. Their study was based on the Newtonian approach and assumed the geometry as a one-dimensional line, arbitrarily curved and twisted in space. The review compiled by Paidoussis and Li [5] focuses on the dynamics of pipes conveying fluids along with details of dynamics of straight and curved pipes, which are grouped as simply supported and cantilevered. A finite element approach for solving non-linear problems in pipes conveying fluids was made by Lin and Tsai [6] based on Timoshenko beam element formulation. Based on both the Lagrangian principle and the Ritz method and considering the coupling between the pipe and the fluid, Zhang et al. [7] developed a dynamic equilibrium matrix equation for pipe flow, which included the concept of fictitious loads for kinematic correction. According to this, they modelled a long simply supported fluid conveying pipe subjected to axial tension, and its numerical and experimental results were presented. The study, on the effects of fluid–structure interaction in fluid filled flexible piping, performed by Wiggert and Tijsseling [8] summarises the numerical as well as experimental studies for a span of fifteen years.

Kochupillai et al. [9,10] developed a semi-analytical finite element method for the analysis of pipes conveying fluids with elastic and composite shell elements. The fluid–structure interaction was modelled using velocity potential formulation leading to a symmetric eigenvalue problem but assumed compressibility in an acoustic sense. Kochupillai et al. [11] also proposed an efficient model reduction technique for the analysis of parametric instability in flexible pipes conveying pulsating fluids with a mean pressure. Sreejith et al. [12] presented a finite element formulation for the fully coupled dynamic equations based on velocity potential formulation of pipeline systems used in nuclear reactors. The response of the same to transient excitation caused by valve closure was also studied by him. Experimental enumeration on the effects of steady and pulsating Newtonian fluid flow through a stretched rubber tube subjected to external vibration were reported by Zhang et al. [13]. Examinations on the effects of fluid flow velocity and initial stretch were performed and the effects of these parameters in damping ratio, and in dynamic response were presented. Reddy and Wang [14] formulated the equations of motion for the deformation of fluid conveying beams based on Euler–Bernoulli and Timoshenko beam theories. The geometric non-linearity and the effects of flow velocity to kinetic energy and body forces were also presented. Kochupillai et al. [15] proposed a numerical method for investigating the stability of linear time-varying systems modelled using finite element (FE) methods. The parametric instabilities in a pipe conveying pulsating flow was studied using model reduction technique and analyzed with the help of multivariable Floquet–Lyapunov theory. Kochupillai [16] also suggested a simulation model for fluid–structure interaction that occurs in a pipeline due to transient events. The water hammer phenomenon was modelled using velocity formulation was coupled with beam formulation for structure, and included Poisson and junction couplings. Wang numerically modelled the non-linear dynamics of simply supported pipe independent of motion constraints [17]. Dan Meng et al. [18] investigated the three dimensional non-linear dynamics of a fluid conveying pipe subjected to overall motions and equations of motion were suggested by considering the effect of external fluid and large overall motions. A threefold study on the dynamics of simply supported pipe conveying fluid with geometrical imperfections was done by Wang et al. [19]. The study included the presentation of equations of motion for a pipe with immobile supports and accounting for the geometrical imperfections. The linear dynamics of the system with the effect of flow velocity and different geometric imperfections were reported along with their effect in post-buckling. Yi-Min et al. [20] suggested a technique based on Ferrari's method for the analysis of natural frequency on a pipeline supported at both ends. The modelling of a pipeline was done by making use of Hamilton's variation principle based on Euler–Bernoulli beam theory. Natural frequency equations with fixed boundary conditions were also considered in this work. To describe the fluid–structure interaction behavior of pipes conveying fluid, a transfer matrix method was proposed by Li et al. [21] and its application was elaborated by distinct pipeline schemes. Studies on the impact of supports, different structural properties and fluid parameters on dynamics response and natural frequencies were also discussed.

Review of literature revealed that a limited number of studies are done with respect to the numerical, as well as the experimental determination of time lag in a straight-flexible pipe conveying fluid, subjected to external excitation. The time lag can be correlated to the mass flow rate through the pipe. The work is highly significant due to the industrial application of the code in predicting the mass flow rate through a flexible tube based on the computed time lag. The present formulation uses the principle of virtual work, and the combined fluid–structure equations derived by Paidoussis [1]. An isoparametric three-node beam element with quadratic shape functions is used to discretize the structure. The weak form of the governing differential equation, representing the fluid–structure coupled system, is converted to finite element equations by applying Galerkin technique. A MATLAB program is developed to simulate the dynamics of fluid conveying tubes in three dimensions subjected to external excitation. The developed element can simulate curved geometry, damping, velocity and gyroscopic effects for three dimensional flexible tubes. The numerical model is validated experimentally by using a straight flexible tube conveying fluid, which is clamped at both ends. The fluid-filled pipe is excited at its first fundamental frequency using an electro-dynamic shaker. The experiment is performed for different flow velocities.