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Nonlinear three-dimensional dynamics of flexible pipes conveying fluids

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A B S T R A C T

This paper presents a model which describes the non-planar vibrations of an elastic pipe induced by the pulsations of a flowing fluid. The motion of the pipe has been described by a set of four non-linear partial differential equations with periodically varying coefficients. The analysis has been conducted with the use of Galerkin method by applying functions describing the free vibrations of the beam as the shape functions. Floquet theory has been used to determine the unstable areas. The influence of the flow velocity and the pulsation frequency on the character and modes of vibrations and on the ranges of the increased vibration intensity has been examined. The possibility of the excitation of sub-harmonic and quasi-periodic vibrations in ranges of simple and combination parametric resonances has been proved. The results of experiments which confirm the occurrence of the parametric resonance phenomenon have also been presented.

1. Introduction

Pipe vibrations induced by a fluid flow are an important and interesting scientific problem which refers to many practical applications in oil and chemical industries, power industry, or in power hydraulics systems. For a sufficiently high velocity of the pulsating flow, a very interesting but also dangerous for the system phenomenon of parametric vibrations may occur in specific conditions. For elastic pipes with small axial and transverse stiffness, parametric resonances are connected with many vibration modes. Apart from simple resonances of subsequent vibration modes, combination resonances of two or more modes of free vibrations may occur. Thus, a precise explanation of the occurring physical phenomena requires taking into account a relatively high number of modes in the analysis.

Vibrations of flexible pipes supported at both ends take place generally in space. However, due to a high complexity of 3D models, 2D models are usually considered. These models describe the phenomenon of parametric resonance very well. They allow the determination of the parameter ranges in which vibrations are generated in the system. They also allow the determination of the vibration amplitudes and a rough estimation of vibration modes. However, due to the non-planar character of vibration modes, especially in combination resonances, such a simplified plane model seems to be insufficient.

Since static deformations caused by gravitational forces in elastic pipes may be quite high, it is necessary to build a model which describes the system vibrations about the equilibrium position. The geometrically non-linear Euler beam model is most frequently

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used in research. In this model, non-linear term results from the influence of the axial force on the transverse vibrations is taken into account. In the geometrically non-linear model, there are links between vibrations in-plane and vibrations out-of-plane, which sometimes result in non-planar vibrations, especially in combination resonances.

Scientific research of pipes conveying fluid has a long history. As it has been counted (Païdoussis, 2008; Ibrahim, 2010), more than 500 significant papers, several monographs and approximately 2000 publications in related science disciplines referring to this problem, have been issued so far. In those publications researchers examined pipes of various shapes and support types, pipes for a flow with and without pulsation, taking into account additional concentrated mass and rigid supports or elastic fastenings, highly-stiff or elastic hoses, and also pipes immersed in a fluid. The influence of flow parameters, first of all velocity, on the system's behaviour, including also the supercritical range, is analysed. For a pulsating flow, the influence of, for instance, frequency and pulsating amplitude on the stability ranges and on vibration character in parametric resonances is tested. The review of the modelling and analysis methods is presented by Païdoussis, (1998, 2003) in a two-part monograph.

There are relatively few papers that refer to pipe vibrations in space and that apply to 3D models. The biggest group consists of papers which analyse spatial vibrations of cantilevered pipes. Non-linear models of pipes with a free end are considered (Bajaj and Sethna, 1984), with an additional mass (Copeland and Moon, 1992) or with intermediate spring support (Steindl and Troger, 1988, 1995). In a three-part paper (Wadham-Gagnon et al., 2007; Païdoussis et al., 2007; Modarres-Sadeghi et al., 2007), equations describing the pipe motion in space for a flow without pulsation are formed and analysed. This model is also verified experimentally (Ghayesh et al., 2011).

In models which describe vibrations of cantilevered pipes, there is most often an assumption that the centreline is inextensible. It is not true for the model of a pipe with the ends fixed in a non-sliding way.

Holmes (1977), as one of the first scientists, introduced a non-linear model which described in-plane vibrations of a pipe fixed at both ends. To the linear equation obtained by Païdoussis and Issid (1976), Holmes added a non-linear component connected with a force resulting from an axial extension. After accepting a viscoelastic model of the Voigt-Kelvin type material, the pipe motion was described by one partial differential equation. A more precise non-linear description of vibrations in the plane of a pipe clamped at both ends was given by Modarres-Sadeghi and Païdoussis (2009) for a vertically mounted pipe, and by Łuczko and Czerwiński (2015) for a pipe placed horizontally. Nikolić and Rajković (2006) compared the results of a bifurcation analysis for various models of pipes supported on both ends mounted vertically. They also examined the influence of gravity forces. Jin and Song (2005) analysed a non-linear model of a pipe fixed on both ends and simply supported, described by the equation proposed by Holmes (1977). Using numerical methods they investigated the effect of pulsation amplitude, average flow velocity, internal damping and mass on the parametric resonance ranges, and in some ranges they also analysed the character of vibrations.

The majority of papers about pipes clamped on both ends refer to the vibrations of straight pipes in the plane. There are significantly less papers for curved pipes. Chen (1972, 1973) proposes a linear model of a curved pipe which describes its motion in the plane of bending and out of it. For the model of a pipe with a non-deformable axis, Chen shows that the loss of stability occurs after exceeding the critical velocity, as it is in the case of a straight pipe. Hill and Davis (1974) take the opposite assumption (a deformable axis) and prove that even at very high flow velocities the pipe does not buckle. Misra et al. (1988a, 1988b) compare various models of curved pipes, regarding the model that takes into account the deformation of the pipe's axis as the most proper one. Dupuis and Rousselet (1992, 1993) additionally take into consideration the influence of geometrical non-linearities. Jung and Chung (2008), using the Galerkin method, determine free frequencies in-plane and out-of-plane for the nonlinear model of a semi-circular pipe conveying fluid. Also Ni et al. (2014), examining the non-linear model of a curved pipe, determine parametric vibrations ranges. They also present comparisons of selected results with the experiment. Nakamura et al. (2009) and Yamashita et al. (2010) theoretically and experimentally examine a curved pipe with a pulsating flow with reference to the interaction between vibrations in-plane and out-of-plane; they notice the excitation of the parametric resonance outside the curve plane.

A separate group contains studies about modelling of flexible marine pipes transporting fluid (Chucheepsakul et al., 2003; Kaewunruen et al., 2005; Chai and Varyani, 2006; Chatjigeorgiou, 2010; Athisakul et al., 2011). Due to large deflections caused, among others, by gravitational forces, a specific approach to modelling is applied. It is based on the examination of motion in space with reference to an equilibrium position. Natural coordinate systems are additionally introduced. They are connected with a pipe element in the following states: undeformed configuration, equilibrium configuration, and in the displaced configuration (Athisakul et al., 2011). The differential equations of the motion are most frequently solved with the use of the finite element method (Kaewunruen et al., 2005) or the finite differences method (Chatjigeorgiou, 2010). In the case of large static deformations, numerical methods are proposed to solve the boundary problem (Chucheepsakul et al., 2003).

For the description of non-planar vibrations, the approach applied in the papers by Simo (1985) and Simo and Vu-Quoc (1986) is useful. The authors of these papers present a geometrically exact model of a beam. According to the approach used by Simo and Vu-Quoc, the description of the movement of each element of the pipe can be reduced to the motion of a body frame, which is a moving frame attached to a typical pipe cross-section. The position and orientation of the body frame is determined respectively by the displacement vector and the rotation matrix. The rotation matrix with the properties thoroughly described by Argyris (1982) is very comfortable in applications. The important characteristic of this matrix from the numerical point of view is a fact that this matrix, and also its approximations, have a symmetrical form due to the parameters (angles) taken into the description of rotation. Many important characteristics of the rotation matrix were also given by Hassenpflug (1993), who proposed to name the introduced parameters the Argyris angles.

This paper presents a proposition of a non-linear system model which describes transverse vibrations in two mutually perpendicular directions, and axial and torsional vibrations. After the introduction of certain simplifications, the Galerkin method is applied into the analysis. The method takes into consideration eight modes of vibrations in an approximated solution. The presented