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An isogeometric analysis approach to the stability of curved pipes conveying fluid

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A B S T R A C T

Stability analysis of curved pipes conveying fluid is of significant interest in many engineering aplications such as floating and moored system dynamics. The aim of this paper is to develop a new formulation based on the Isogeometric Analysis (IGA) for vibration and stability analyses of curved pipes conveying fluid. Both divergence and flutter instabilities of curved pipes are investigated. IGA uses B-Splines and Non-Uniform Rational B-Splines (NURBS) as basis functions. The main feature of IGA, as required in dynamic analysis of curved structures, is the ability of the NURBS functions to represent the exact geometry of the problem with fewer control points. This method provides several advantages including high-order continuity of the solution and better accuracy. The governing differential equations of the problem are obtained using the Hamiltonian's principle. The effects of rotary inertias of both pipe and fluid are also included in the mathematical formulation. It is shown that the present formulation can provide accurate results with small number of degrees of freedom. It is concluded that IGA can be used efficiently to predict the instability of curved pipes conveying fluid with the advantage of considering the exact curvature of the pipe.

1. Introduction

Flow-induced vibrations of pipes conveying fluid have been investigated in many practical applications such as oil and chemical industries and power hydraulics systems. Among different types of pipes conveying fluid, a considerable amount of research has been reported on the instability and vibration behavior of straight pipes. A comprehensive review on flow-induced vibrations of straight pipes can be found in [1,2]. The governing differential equations of motion for a pipe conveying fluid can be derived using two approaches: Newtonian and Hamiltonian. In most of the studies, the traditional Newtonian approach has been used to obtain the equations of motion for the straight pipes conveying fluid. It has been shown that the dynamics and stability of straight pipes conveying fluid strongly depend on the supporting conditions. A straight cantilever pipe is a non-conservative system and is subject to flutter at sufficiently high flow velocities. For a straight pipe with both ends supported, the stability is lost by the static divergence and coupled mode flutter (Païdoussis or Hamiltonian types) [1,3].

It is worth noting that although the dynamics and stability of straight pipes conveying fluid have been extensively investigated by many researchers, only a few studies have been devoted to the dynamics of curved pipes conveying fluid. The general reason is that there is a difficulty in deriving the equations of motion for a curved pipe conveying fluid. This difficulty stems from the fact that a

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pipe conveying fluid is an “open system” with both in-flow and out-flow of mass and momentum [4,5]. This requires an extended form of Hamilton's principle to be used for derivation of the equations of motion for a curved pipe conveying fluid. An extended form of Hamilton's principle was developed by McIver [6] for open systems when the constituent particles change with time. This research is motivated by the research interest in dynamics and stability analyses of curved pipes conveying fluid in (i) deriving the governing differential equations based on extended Hamilton's principle and (ii) developing an appropriate numerical solution to cope efficiently with the curvature of the pipe. For the curved pipes conveying fluid, the governing differential equations were derived based on the Newtonian approach in [7,8]; they highlighted the main assumptions and parameter differences in two formulations. The method of solution in these studies was Finite Element Method (FEM). In addition to the FEM, a variety of other numerical methods including fixed grid and smoothed fixed grid finite element methods have been developed in the last decade and implemented in a variety of problems (e.g., unconfined seepage problems, static and dynamic analysis of 2D and 3D elastic solids and inverse heat conduction analysis) [9–11]. This study uses Isogeometric Analysis (IGA). IGA is a new simulation approach with the superiority of capturing exact geometry. It is fudamentally developed based on the Computer-Aided Design (CAD) whereas the geometry of the problem is used in both design processes and numerical calculations. In other words, IGA uses the exact CAD geometry and reduces the geometrical errors introduced by approximation of the physical domain of problem [12–14]. In spite of the extensive achievements in dynamics and stability analyses of pipes conveying fluid, the application of IGA in transverse vibration analysis of curved pipes conveying fluid has not been reported so far. In this paper, the extended Hamilton's principle is used to develop the governing differentil equations of a curved pipe conveying fluid. The mathematical derivation is general and includes the effects of rotary interias of both the curved pipe and the fluid. The differential equations of the problem are then solved by IGA. It will be shown that using Non-Uniform Rational B-Splines (NURBS) in IGA discretization results in improvement of the solution accuracy and provides a promising approach for analysis of curved pipes conveying fluid. Furthermore, a certain mapping is considered between the physical and parametric spaces which was not taken into account in the recent study [1] for a straight fluid-conveying pipe.

The paper is outlined as follows: In Section 2, the governing differential equations of motion for a curved pipe conveying fluid are derived. A short review and the theoretical background of IGA are presented in Section 3. The weak formulation of the problem is derived in Section 4 based on the isogeometric analysis approach and is used in developing the discretized equations in a matrix form. In Section 5, the results obtained by the present formulation are given and discussed. The last section presents the final concluding remarks and the main advantages of using IGA in fluid-instability analysis of curved pipes conveying fluid.

2. Equations of motion for curved pipes conveying fluid

The equations of motion for a uniform end-supported curved pipe of length L, flexural rigidity E_pI_p, mass per unit length m_p, and a conveying fluid of mass per unit length m_f, with mean axial flow velocity magnitude U (uniform across the pipe cross-section) can be derived based on the Euler-Bernoulli beam theory (EBT) (Fig. 1). The fundamental assumption in this theory is that the planes perpendicular to the beam axis remain plane and perpendicular to the deformed axis after deformation [15,16]. Using EBT, the displacement field for the pipe with moderately large rotations can be written as

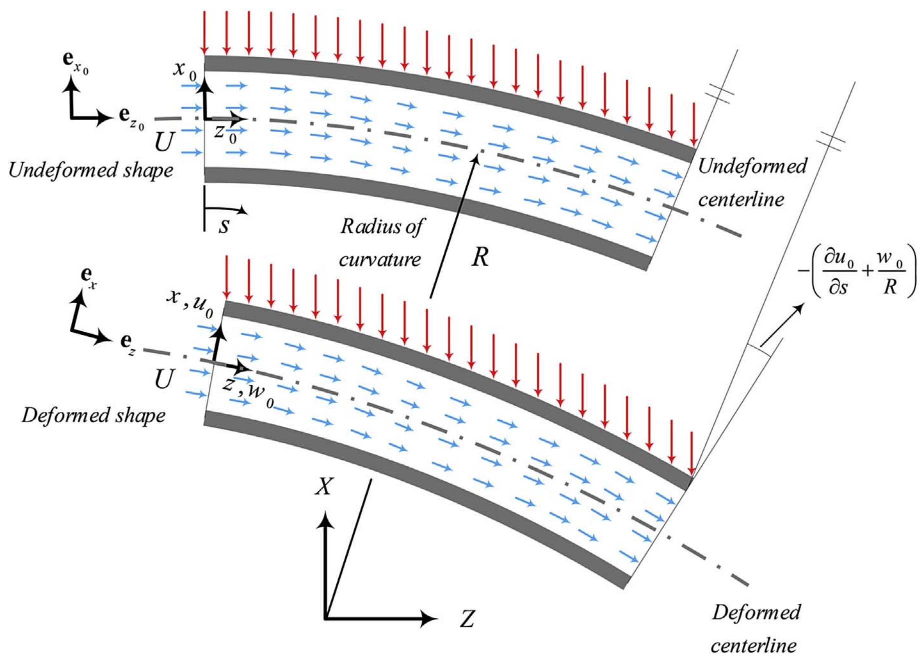

Fig. 1. Schematic of a fluid-conveying curved pipe based on Euler-Bernoulli beam theory.