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Dynamic analysis and stability of variable length vertical pipe containing fluid using Timoshenko's beam theory

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Abstract
In this article, the dynamics of pipes containing fluid is investigated according to Timoshenko's beam theory. The problem's equations were extracted with the help of Hamilton's principle, and then their responses were obtained using Galerkin's numerical approach. The modeling of the vertical pipe containing fluid was done using Timoshenko's beam theory. It is prominent to mention that the considered vertical pipe containing fluid has variable length. The results of this analysis will be compared with previous researches, which were according to Euler–Bernoulli theory. Also, the gravity effect on the pipe stability will be analyzed. Finally, by examining the impact of rotational inertia and shear deformation separately, it was determined that the effect of shear deformation on the pipes' dynamic behavior containing fluid will be more than the effect of rotational inertia.

Keywords
dynamics behavior, stability, Timoshenko beam theory, pipe containing fluid, variable length, Argand diagram

1. Introduction

The dynamics of fluid-contained pipes presents a very deep-rooted past. Cylindrical structures that flow inside or outside of them are used in many engineering devices, especially in chemical and petrochemical energy production industries. Due to the increasing growth and development of various industries, it is very important to equip all the necessary parts and necessities in the water, oil, gas, and petrochemical industries. Transmission pipes transfer a major part of oil and gas reserves extracted from the seabed. The materials of these pipes cannot withstand the alternating pressure of deep ocean flows, and researchers are looking to overcome it because without curbing this pressure, it will be impossible to dig from the sea bed.

Vertical pipes containing fluid are also extensively utilized in industrial systems, and sometimes, the length of the pipe expands and contracts with changes in fluid speed, causing problems in practice. The casting process is a clear example where the expansion and contraction of the pipe can be clearly seen during the filling of the tanks. During tank filling, it's crucial to maintain the pipe's tip in proximity to the liquid surface at all times because the expansion and contraction of the pipe at different speeds will cause the fluid to splash around and cause problems in operation.

During the last decades, researchers have faced the problems of vibrations and stability in pipes carrying fluid flow. The first serious studies on the dynamics of tubes containing fluid were carried out in Païdoussis and Li (1993). Acceptable results were obtained from these studies, but most of them were destroyed in the First World War. After that, research was conducted in the field of tubes containing fluid with different boundary conditions (Païdoussis and Li, 1993). The report of tube bending due to flow instability, which is similar to column failure under static axial load, has also been

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investigated (Gregory and Païdoussis, 1966). In addition, the lateral vibrations inside and outside the plate have been investigated in a small range of a flexible suspended fluid transfer tube that rotates horizontally (Panussis and Dimarogonas, 2000). These research studies discussed the critical frequency and the critical flow rate of the suspended system of the fluid carrier pipe in internal and external plate vibrations. In the first published research on stability of vertical tubes of non-rotating fluid flows, the calculations were performed without considering the critical conditions of fluid (Gregory and Païdoussis, 1966). More complete theories and more detailed experiments were done later. For example, tests of out-of-plane vibrations were performed considering critical conditions (Gregory and Païdoussis, 1966). In a research study, the effect of angular acceleration and liquid flow acceleration on the dynamic behavior of a suspended rotating fluid transmission tube was studied (Yoon and Son, 2007). In this study, the investigation focused on linking the natural frequencies of a suspended fluid transfer tube with the tube's angular acceleration and mass in axial and transverse directions. Additionally, by expanding Hamilton's law to open systems, the equation of motion for the flexible pipe system used in fluid transmission was derived (Kheiri et al., 2014). Another article explored the dynamics and stability of a fluid transmission pipe using an extended version of Hamilton's law designed for open systems (Kheiri and Païdoussis, 2014).

The stability of tubes containing fluid according to Timoshenko's beam theory at different angles has been investigated considering the finite element approach with the help of Ansys software with boundary conditions of two free ends (Wang et al., 2009).

The Hamilton principle is used in an investigation for the nonlinear vibration and stability analysis of rotating functionally graded (FG) piezoelectric nanobeams based on the nonlocal strain gradient theory in Li et al. (2023) to derive nonlinear equations of motion and their related boundary conditions, which are then discretized to form a set of algebraic equations. A study (Shaaban et al., 2023) was carried out experimentally to analyze how imperfections in the clamping of cantilevered pipes, either releasing or drawing in fluid, influenced their behavior. It was observed that the heightened static deformation in the imperfectly suspended discharging pipes seemed linked to additional linear motion, whereas in the imperfectly supported aspirating pipes, the increased static deformation primarily resulted from rotational movement at the support. The vibration characteristics of axially traveling moderately thick plates resting on an elastic foundation are presented in Sui et al. (2023). It is confirmed that the gradient index is closely related to material properties, while the axial velocity affects vibration natural frequencies through centrifugal force and Coriolis force.

For cantilever pipes that convey fluid, a feedforward vibration suppression technique is suggested in Li et al. (2019). The cantilever pipeline system's fluid–structure interaction dynamic equation is developed using the Euler–Bernoulli beam model as a basis. Theoretical derivation and experimental findings in industrial machinery demonstrate that the suggested approach (i.e., optimization of pressure function parameters) is a useful technique for reducing structural vibration in fluid-conveying cantilever pipes.

The natural frequencies are numerically determined via the Galerkin method in the paper (Li et al., 2017) which investigated the transverse vibrations and steady-state responses of axially moving viscoelastic piezoelectric two-dimensional nanostructures. It is shown that the dynamic responses of the axially moving viscoelastic piezoelectric nanoplate under the coupling of thermo–electro–mechanical multi-fields are expected to play significant roles in designing biomedical nano-robots. The research (Ye et al., 2023) examines the nonlinear forced vibration of a slightly curved pipe conveying supercritical fluid around the curved equilibrium and by applying the generalized Hamilton principle; the governing equations for the forced vibration of a slightly curved pipe conveying supercritical fluids are obtained. The Galerkin method is used to solve the governing differential equation of the single-link robot using the polynomial approximation method (Rao et al., 2022).

In the present research, the dynamic analysis of the suspended pipe for fluid transmission, which is expanding and contracting vertically, based on Timoshenko's beam theory, which is investigated and based on (Yao et al., 2020) is going to be studied. Quantitative analysis by eigenvalues and numerical analysis with constant and free boundary conditions which is performed until the effect of the speed of expansion and contraction are also discussed. In the present study, the mass ratio and stability of the fluid transmission pipe during expansion and contraction should be investigated in such a way that at first only rotational inertia is considered and then shear deformation is also added and its effect on the results will be obtained. Timoshenko modeling and this type of fluid modeling with the Euler–Bernoulli beam have already been done, but using this type of fluid modeling with Timoshenko model for a vertical pipe containing expansion and contraction is completely new. Our study aims at exploring the vibration behavior and stability of vertical pipes containing fluid based on Timoshenko beam theory.

It is generally considered that a Timoshenko beam is superior to an Euler–Bernoulli beam for determining the dynamic response at high frequencies but that they are equivalent at low frequencies. The inclusion of shear deformation and rotational inertia in the Timoshenko beam formulation leads to differences in their frequency