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Transverse free vibration and stability analysis of spinning pipes conveying fluid

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ABSTRACT

In this paper, the transverse free vibration and stability are analyzed for spinning pipes conveying fluid as a typical example of doubly gyroscopic systems. The partial differential equations of motion are derived by the extended Hamilton principle, and are then truncated by the 4-term Galerkin technique. The natural frequencies, complex modal motions and responses to initial conditions are comprehensively investigated to display the essential dynamical properties of such spinning structures conveying fluid. It is indicated that the qualitative stability of the present system mainly depends on the effects of fluid-structure interaction (FSI) and mass ratio, while the spinning speed plays a significant role in determining the quantitative values of the frequency. The critical flow velocities are independent of the spinning speed and mass ratio. Forward and backward whirling motions are found to take place alternatively for the first four modes, and a 'traveling wave' with spatial configuration is observed during vibrations. The gyroscopic couplings caused by spin and FSI will yield great impacts on the energy transfers between different general coordinates.

1. Introduction

The pipes have been extensively applied in various engineering fields used as common devices containing and conveying fluid [1–3]. By absorbing the kinetic energy of the flowing fluid, the pipe often vibrates intensely due to the fluid-structure interaction (FSI), namely self-excited vibration, which is hazardous or potentially risky for mechanical structures. Conventional FSI dynamics focuses on the buckling and vibration of initially static pipes, which mainly depends on the fluid excitation. However for some fluid-conveying pipes accompanying spinning motion, such as drill string pipes conveying drilling mud in oil and gas exploitations, the additional Coriolis force and centrifugal force induced by spin will be coupled with the fluid effect. This may lead to a great limitation of traditional FSI theories for such complicated problems.

The spinning pipes conveying fluid can be defined as a doubly gyroscopic system just because of the involvements of gyroscopic effects caused by FSI and spinning motion. The rotor dynamics in conjunction with FSI theories is consequently an available path to perform analysis for such system, even though it is of considerable difficulty to be executed in practice. In the early 1990s, Jansen [4] proposed the rotor dynamics for analysis of the dynamic behavior of whirling drill collars, with account taken of the nonlinear influences caused by drilling fluid. Zhang and Miska [5] and Ritto et al. [6] confirmed the significant influence of fluid-pipe interaction on the vibrations of drill strings. Gulyayev et al. [7] and Pei et al. [8] treated the spinning effect of the drill strings as centrifugal forces or periodic excitations. In the recent research reports, Guzek et al. [9] found that the non-Newtonian behavior of the drilling fluids may reduce the vertical vibrations in drilling. Ghasemloonia et al. [10] generalized the fluid damping as Rayleigh damping and a hydrodynamic drag force. Eftekhari and Hosseini [11] extended the study to the spinning functionally graded cantilevered pipes conveying fluid.

The bending, torsional and axial vibrations always occur simultaneously when a drill string works, whereas the transverse mode is said to be responsible for 75% of drill string failures [12–14]. For a spinning pipe conveying fluid, the transverse vibration doesn't take place in a single plane, which results in whirling motions with spatial configuration, similar to a working gyroscope. Meanwhile, the additional centrifugal force due to spin varies the transverse vibration amplitude. It is clear that such spatial motions are much more complex than the vibrations of a common pipe conveying fluid. In the previous researches, Baumgart [15] derived nonlinear differential equations of the drill string in three planes. Christoforou and Yigit [16] developed a three-dimensional model to design a controller for stick-slip mitigation. Khulief and Al-Naser [17] proposed an FEM model for finite shaft elements with 12 degrees of freedom for analysis of three-dimensional vibrations of the drill string. Khulief et al. [18] developed a coupled lateral-torsional elastodynamic model at the impact point of the drill string, which was verified

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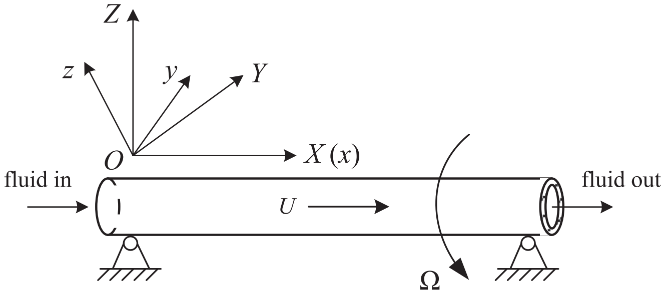
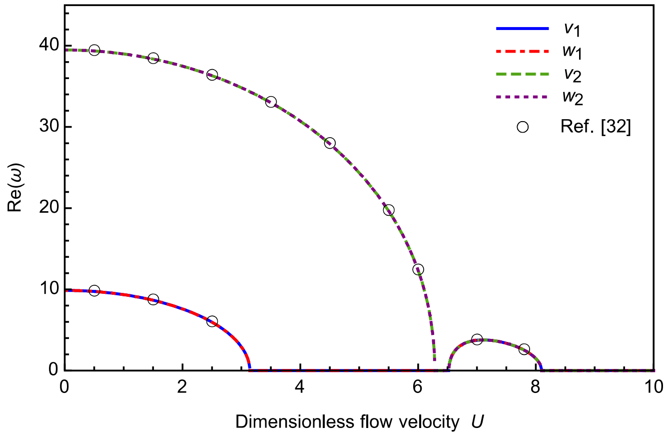
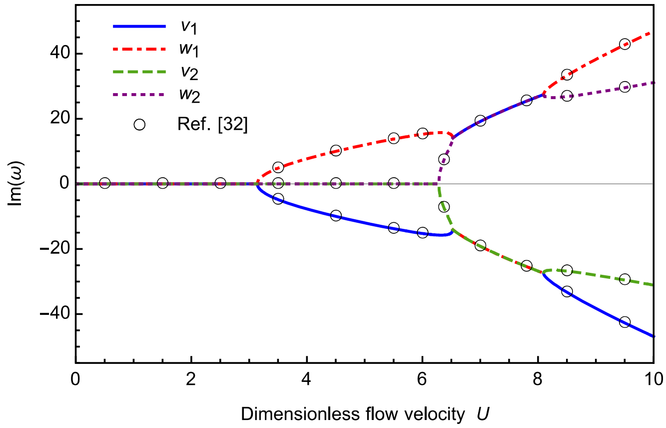


Fig. 1. Mechanical model of a spinning pipe conveying fluid.



(a) The real part of ω

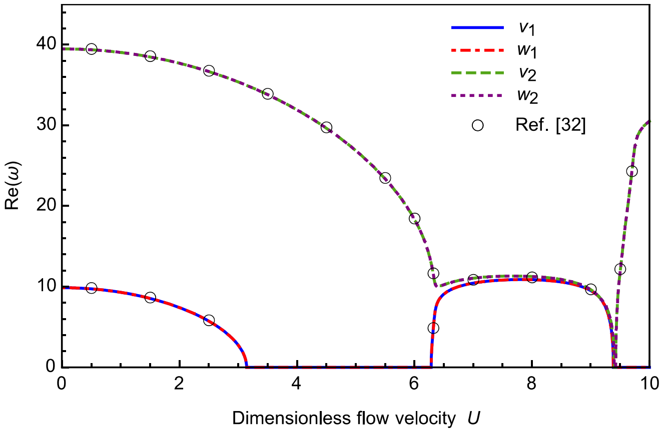


(b) The imaginary part of ω

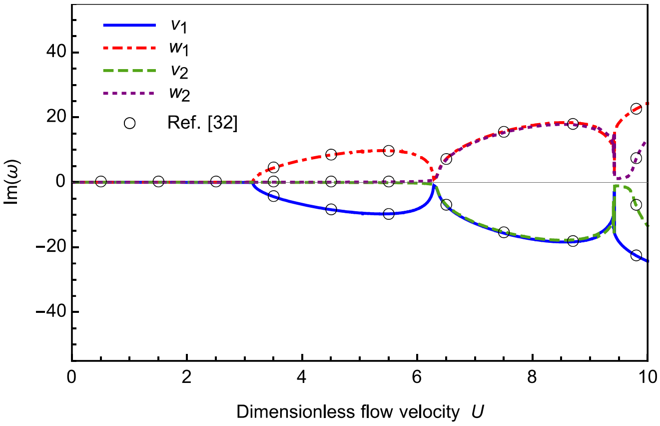
Fig. 2. The complex frequency ω as functions of flow velocity for two transverse directions with $\Omega = 0$, $M_r = 0.2$.

later by a laboratory test rig [19]. The research works of Refs. [6] and [10] are based on three-dimensional models as well.

In dynamical essence, the spinning pipe conveying fluid is analogous to a spinning shaft or beam with both axial and spinning movements. The vibration theories of spinning shafts and beams could therefore be used for reference. Kong et al. [20] developed a mathematical approach to reduce the DOFs of flexible drilling shaft systems. Sino et al. [21], Ren et al. [22] and Ma and Ren [23] paid particular attention to dynamical analysis of rotating composite shaft. Carrera and Filippi [24] evaluated the vibration characteristics of thin/thick rotating cylindrical shells involving the effects of geometrical stiffness due to rotation. Boukhalfa [25] conducted dynamical analysis of a spinning functionally graded material shaft by the FEM. Shahgholi [26] investigated the free vibration of a nonlinear slender rotating shaft with simply support conditions.



(a) The real part of ω



(b) The imaginary part of ω

Fig. 3. The complex frequency ω as functions of flow velocity for two transverse directions with $\Omega = 0$, $M_r = 0.8$.

Lv et al. [27] explored the vibration induced by moving force for a rotating beam. Wang et al. [28] examined the coupled flexural-torsional vibration of spinning smart beams. Nayfeh et al. [29] and Lajimi et al. [30,31] probed the dynamical mechanism of micro/nano gyroscopes. All of these studies takes good advantage of the gyroscopic features of spinning structures.

The dynamical analysis of spinning pipes conveying fluid is essentially a more general scientific topic, which involves two types of gyroscopic effects due to both spinning and axial moving motions. Little study has been found on such general model of a fluid-conveying structure with spinning motion. As a result, the coupling mechanism of the double gyroscopic contributions is lack of in-depth interpretation. In this paper, an interdisciplinary research combining the FSI theories and rotor dynamics is carried out to display the transverse vibration characteristics and stability of a common spinning pipe conveying fluid. Several classical methods such as the extended Hamilton principle, Galerkin technique and complex mode approach are implemented for reliable solutions. Comprehensive results including the natural frequencies, mode shapes and responses to initial conditions are obtained to show the coupled effect of the fluid and spin excitations. The impacts of some key parameters on the dynamical behavior evolution of the system are discussed in detail.

2. Differential equation of motion

The mechanical model of a pinned-pinned spinning pipe conveying fluid is shown in Fig. 1. The pipe is assumed to spin about its longitudinal