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Flow-induced oscillations of a cantilevered pipe conveying fluid with base excitation

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ABSTRACT

It is known that a plain cantilevered pipe conveying fluid loses its stability by a Hopf bifurcation, leading to either planar or non-planar flutter for flow velocities beyond the critical flow velocity for Hopf bifurcation. If an external mass is attached to the end of the pipe (an end-mass), the resulting dynamics become much richer, showing 2D and 3D quasiperiodic and chaotic oscillations at high flow velocities. In this paper, a cantilevered pipe, with and without an end-mass, subjected to a small-amplitude periodic base excitation is considered. A set of three-dimensional nonlinear equations is used to analyze the pipe's response at various flow velocities and with different amplitudes and frequencies of base excitation. The nonlinear equations are discretized using the Galerkin technique and the resulting set of equations is solved using Houbolt's finite difference method. It is shown that for a plain pipe (with no end-mass), non-planar post-instability oscillations can be reduced to planar periodic oscillations for a range of base excitation frequencies and amplitudes. For a pipe with an end-mass, similarly to a plain pipe, three-dimensional period oscillations can be reduced to planar ones. At flow velocities beyond the critical flow velocity for torus instability, the three-dimensional quasiperiodic oscillations can be reduced to two-dimensional quasiperiodic or periodic oscillations, depending on the frequency of base excitation. In all these cases, a low-amplitude base excitation results in reducing the three-dimensional oscillations of the pipe to purely two-dimensional oscillations, over a range of excitation frequencies. These numerical results are in agreement with the previous experimental work.

1. Introduction

Pipes conveying fluid have been studied extensionally. Païdoussis [1] has dedicated the first volume of his comprehensive two-volume book on axial fluid–structure interactions to discuss various aspects of the problem of a pipe conveying fluid. In this volume, he has given a detailed introduction to the problem and he has discussed several examples of the applications of the problem in various engineering devices. The interested reader is referred to this book for a comprehensive introduction to pipes conveying fluid. Depending on the boundary conditions and the system parameters, a pipe conveying fluid exhibits various structural instabilities and a range of dynamical behavior, including quasiperiodic

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and chaotic motions. If the pipe is fixed at its both ends, a buckling instability occurs at a critical flow speed, after which the pipe buckles to its new equilibrium. At higher flow velocities, the amplitude of buckling is increased, but no other instability is observed [2,3]. For a pipe with clamped–free boundary conditions, a Hopf bifurcation occurs at a critical flow velocity and the pipe undergoes limit cycle oscillations for higher flow velocities. No post-critical instability is observed for a cantilevered pipe with no external attachment – i.e., when no external spring or mass is attached to it. If the pipe is supported at a point along its length by a spring, or if an external mass is attached to it, the resulting dynamics become much more complicated than the case of a plain pipe. Besides the buckling and Hopf bifurcations, the pipe can undergo period-doubling and torus instabilities, resulting in quasiperiodic, period-n and eventually chaotic oscillations [4–6]. The fact that various kinds of response can be observed in the same system with slight adjustments makes it an ideal platform for applying novel ideas.

The initial models used to predict the behavior of a pipe conveying fluid were 2D linear models, which showed that the system would lose its original stability at a critical flow velocity, leading to periodic oscillations. The large amplitude as well as 3D oscillations observed in the experiments [1] initiated studies toward nonlinear and 3D models to predict the pipe's motion. Bajaj and Sethna [7] derived a nonlinear model for a plain pipe (i.e., with no additional mass or spring) conveying fluid. They used the center manifold and normal form techniques and found that a horizontal pipe loses its original stability through a Hopf bifurcation and develops either 2D (planar) or 3D (orbital or rotary) flutter, depending on a mass parameter β (defined later, in Eq. (14)).

An additional mass or spring attached to the pipe can either stabilize or destabilize the system, depending on the system parameters and location of the additional mass or spring [1]. Copeland and Moon [8] studied the three dimensional dynamics of a cantilevered pipe with an end-mass, and observed various planar and non-planar periodic, quasiperiodic and chaotic oscillations. Wadham-Gagnon et al. [4] derived a 3D nonlinear model for a pipe conveying fluid with an additional mass and spring attached to it. They showed that an additional spring would lead to 2D or 3D periodic, quasiperiodic and chaotic oscillations after the initial planar flutter [5]. The type of motion depends on the spring array configuration, point of attachment and spring stiffness. In some configurations, the system loses stability by divergence, followed by oscillations in the plane of divergence or perpendicular to it, where these oscillations can be periodic, quasiperiodic or chaotic. Using this model, the 3D oscillations of a pipe conveying fluid with an end-mass [6], and with both an end-mass and an added spring [9] have been studied. It has been shown that a plain pipe oscillates mainly in a plane, for small mass parameters, β (except for $\beta = 0.2$) and in a 3D circular way for larger values of β ($0.7 < \beta < 0.9$) where for the intermediate β values the oscillations switch between 2D and 3D as the flow velocity increases [10]. If the pipe is supported at its both ends, however, no dynamic response is observed [2]. Recently, twenty years after the experimental work, numerical results have been obtained [11] for the experiments Copeland and Moon [8] conducted on a very long pipe conveying fluid with very large end-masses.

In some recent studies, the response of a flexible pipe has been considered for cases where the base has a prescribed motion. In these cases, the shear force, applied from the base motion to the flexible pipe, makes the pipe oscillate. Manela [12] studied the response of a flexible cantilevered plate placed in axial flow, when it was excited at its base with a periodic or a non-periodic force. He focused on cases for which the unforced plate (a plate placed in external axial flow) was stable. The force at the base, therefore, resulted in the excitation of one of the natural modes of the structure. In the current study, the focus will be on the cases in which the original unforced system (a pipe conveying fluid, rather than a plate) already undergoes self-excited oscillations and the base excitation is not the sole source for the observed oscillations.

Furuya et al. [13] studied the stability of a cantilevered pipe conveying fluid with an end-mass in the case of a horizontal excitation at the upper end, and for a flow velocity slightly over the critical value. By solving nonlinear equations of motion with base excitation numerically, they showed that the non-planar vibrations are reduced to planar vibrations when the excitation frequency is nearly equal to the frequency of the original flow-induced pipe vibrations. This finding was in agreement with their experimental result. They conducted their study for one point in the parametric space only, in which the original response of the pipe was a limit cycle oscillation.

In the present work, a comprehensive study will be conducted on the influence of base excitation on the oscillations of a cantilevered pipe conveying fluid over a wide range of flow velocities and system parameters. Cases will be considered in which the original pipe with no base excitation undergoes either limit cycle oscillations or quasiperiodic oscillations. Also, cases where different structural modes are excited will be considered. The goal is to investigate the possibility of controlling the pipe's non-planar motion and limiting it to a planar motion in a pre-defined direction.

2. The equations of motion and the method of solution

Three-dimensional equations of motion for a cantilevered pipe conveying fluid were derived by Wadham-Gagnon et al. [4] for a pipe with extra mass added at the tip and springs attached somewhere along the length of the pipe. These equations are extended slightly here by introducing an external force acting at the base of the pipe, in a way similar to what Furuya et al. [13] and Nayfeh and Pai [14] have done. Fig. 1 shows the schematic diagram of the system under consideration.

In the derivation, the Lagrangian coordinates (X_0,Y_0,Z_0), which label specific particles at the original equilibrium state of the pipe, are related to the Eulerian coordinates (x,y,z) through the displacement (u,v,w) of any material point as

$$x = X_0 + u, \quad y = Y_0 + v, \quad z = Z_0 + w. \tag{1}$$