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Dynamics and optimal control of an electromagnetically actuated cantilever pipe conveying fluid

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ABSTRACT

This paper deals with the problem of applying electromagnetic devices of the motional type to improve the dynamic stability of a pipe conveying air. When the flow velocity reaches a critical value, the steady equilibrium position becomes unstable, and self-excited lateral vibrations arise. In contrast, electromagnetic devices of the transformer type have been demonstrated to be highly effective in the passive stabilization of such a system, as well as the active stabilization of similar non-conservative systems with a follower force. In the present paper, we apply a pair of motional devices made of a conducting plate which is attached to the pipe and moves together with it within the perpendicular magnetic field generated by the controlled electromagnets. This motion generates eddy currents in the plates and a drag force of a viscous character. In this setting, we first investigate the possibility of designing a stabilizing control within the region of the magnetic field where every passive solution results in an unstable or conservative state. For that purpose, we determine a practical condition justifying the existence of a stabilizing control for a given set of system parameters. Later we pose and solve an optimal control problem aiming at stabilizing the system with the optimal rate of decrease of the system's energy. The solution is examined by means of numerical simulations performed within the three regions of the flow velocity: low subcritical, where the Coriolis acceleration of the conveyed fluid generates the predominate damping force; high subcritical, where the inertia of the fluid begins to dominate the dynamics of the system; and low supercritical, where unstable flutter vibrations start to arise. The effectiveness of the designed optimal controller is validated by comparisons with the corresponding passive solutions.

1. Introduction

Since the first half of the twentieth century, pipes conveying fluid have attracted much the subject of much research [1]. The reasons for this include not only the practical importance of the problem itself, but also gathering knowledge useful in other areas of fluid–structure interactions [2]. Moreover, cantilever pipes with flow are one of the few examples in engineering applications of a non-conservative elastic system subjected to a follower force, i.e., a force that always remains tangential to the deflected axis of the slender structure [3]. When the flow velocity becomes sufficiently high, self-excited flutter vibrations arise, unlike the case of pipes supported at both ends, which are prone to a buckling type of instability [4]. This can be easily observed when a strong stream of water starts flowing inside a garden hose: its free end begins a snake-like motion on the grass. Such systems are extremely susceptible to changes in the physical parameters and to the introduction of new effects. Even the simple

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effect of a viscous-type damping or an additional lumped mass can decrease the critical flow velocity or stabilize the system, depending on the values of its parameters [5,6].

The aforementioned article of Imbrahim [1] lists over 30 research papers related to the control of fluid-conveying pipes. Almost all of them describe the concept of generating transverse forces or bending moments acting on the system in an active way, depending on the system's state, within a closed feedback loop. For this various actuators have been used. Examples include servomotors connected to a pipe via tendons or springs [7–9], gyroscopic mechanisms [10], and piezoelectric elements mounted on a pipe [11,12] or embedded in its material [13]. In some of these papers, the type of actuator is not defined, aiming at more general results, for example the simultaneous optimization of the pipe's shape and the actuators' position [14] or exploring the possibility of applying a reduced model for active nodal vibration control [15].

A drawback of active methods is the possibility of destabilizing the system if a failure happens, because the action of external forces or moments can introduce additional energy into the system (here, the system refers to the pipe and the fluid volume enclosed within it). In the present paper, we propose the use of a semi-active method based on an electromechanical eddy-current damper of the motional (Lorentz) type. In various structural control applications, the employment of the semi-active devices verified a favorable balance between the performance and robustness [16–20] while reducing the amount of consumed energy compared to the active actuators. Electromechanical dampers of the motional type are reported to be usually more effective than the dampers of the other widely used category, namely, the transformer devices [21,22], which exhibited mediocre performance when used for passive stabilization of a fluid-conveying pipe [23]. In its simplest form, the motional damper consists of a conducting plate which moves within a perpendicular and constant magnetic field, as for example in an analogue electricity meter. This motion generates eddy currents in the plate and a drag force, which is a consequence of the Lenz law. Due to the constant value of the magnetic flux, the damping force depends linearly on the plate's velocity, and thus these dampers act as viscous ones, with a damping coefficient depending on the geometry of the plate and the magnetic flux [24].

Motional dampers were considered for use in vehicle suspension systems [25] as well as for reducing the lateral vibrations of a rotating shaft [26]. Such actuators are contact-free, so they do not disturb the pipe, apart from introducing an additional mass. Moreover, they allow an easy implementation of a control strategy by appropriate changes of the magnetic field.

Another key feature of our approach is an open-loop scheme. In the majority of the literature referred to above, closed-loop control schemes are employed. An observation of the system's state is necessary if it undergoes a complicated motion, such as, the chaotic vibrations which may occur if a pipe is subjected to non-linear constraints [27]. It is also known that pipes with flow and added mass or even plain pipes may lose the stability with a rich variety of bifurcations, including a 3-d chaotic motion or jump phenomena [28–32], depending on the system's parameters. However, in our case, we deal with periodic, thus predictable, both free and self-excited vibrations, which is guaranteed by the relevant selection of the parameters (see Section 2.2).

In the control design, we shall focus on stabilizing the vibrations of the pipe while respecting the constraints imposed by the physical properties of the electromechanical damper employed. First, we will examine the existence of stabilizing controls operating within the input range where any passive solution results in conservative or unstable dynamics. Then, we will propose a controller relying on the solution to a constrained bilinear optimal control problem. The numerical algorithm for solving the optimization problem will be given and examined for convergence. The performance of the designed control will be validated by means of numerical simulations. We will investigate several scenarios for a range of flow velocity and different placements of the actuator.

The remainder of this paper is structured as follows. Section 2 introduces the mathematical model of the fluid-conveying pipe actuated by the electromechanical damper. In Section 3, we derive a discrete representation of the investigated system. The fundamental dynamical properties of the examined structure are studied in Section 4. In Section 5, the optimal stabilization problem is formulated and the method of solution is presented. In Section 6, the performance of the designed control method is validated by means of numerical simulations. Some conclusions and avenues for future research are provided in Section 7.

2. The examined system

2.1. The equations of motion

We are going to study the dynamics of a standing cantilevered pipe conveying a fluid, with motional-type electromagnetic devices attached to it, see Fig. 1. The pipe is slender, and small transverse vibrations in the plane of symmetry $\xi - w$ are considered, so the linear Bernoulli–Euler theory can be applied. The horizontal deflection of the pipe is denoted by $w = w(\xi, t)$. A viscous-type internal damping is present. Gravity is taken into account and acts vertically downwards. The mass of the conducting plates that are part of the actuators is incorporated in a lumped form, but their rotatory inertia is neglected. We employ the plug flow model, i.e., we assume that the flow velocity is constant across every cross-section perpendicular to the pipe's longitudinal axis.

Under the above assumptions, the governing equation of the pipe's motion takes the form

$$\begin{aligned} &EI\frac{\partial^4 w}{\partial \xi^4} + E^*I\frac{\partial^5 w}{\partial \xi^4\,\partial t} + \left[m_f v^2 + \left(m+m_f\right)(L-\xi)\,g + \mathbf{1}_{[0,\xi_a]}M_a g\right]\frac{\partial^2 w}{\partial \xi^2} + 2m_f v\frac{\partial^2 w}{\partial \xi\,\partial t} \\ &-\left(m+m_f+M_a\delta_a\right)g\frac{\partial w}{\partial \xi} + C\left(B_1^2+B_2^2\right)\delta_a\frac{\partial w}{\partial t} + \left(m+m_f+M_a\delta_a\right)\frac{\partial^2 w}{\partial t^2} = 0, \end{aligned} \tag{1}$$