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Fluid–structure interaction for nonlinear response of shells conveying pulsatile flow

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ABSTRACT

Circular cylindrical shells with flexible boundary conditions conveying pulsatile flow and subjected to pulsatile pressure are investigated. The equations of motion are obtained based on the nonlinear Novozhilov shell theory via Lagrangian approach. The flow is set in motion by a pulsatile pressure gradient. The fluid is modeled as a Newtonian pulsatile flow and it is formulated using a hybrid model that contains the unsteady effects obtained from the linear potential flow theory and the pulsatile viscous effects obtained from the unsteady time-averaged Navier–Stokes equations. A numerical bifurcation analysis employs a refined reduced order model to investigate the dynamic behavior. The case of shells containing quiescent fluid subjected to the action of a pulsatile transmural pressure is also addressed. Geometrically nonlinear vibration response to pulsatile flow and transmural pressure are here presented via frequency-response curves and time histories. The vibrations involving both a driven mode and a companion mode, which appear due to the axial symmetry, are also investigated. This theoretical framework represents a pioneering study that could be of great interest for biomedical applications. In particular, in the future, a more refined model of the one here presented will possibly be applied to reproduce the dynamic behavior of vascular prostheses used for repairing and replacing damaged and diseased thoracic aorta in cases of aneurysm, dissection or coarctation. For this purpose, a pulsatile time-dependent blood flow model is here considered by applying physiological waveforms of velocity and pressure during the heart beating period. This study provides, for the first time in literature, a fully coupled fluid–structure interaction model with deep insights in the nonlinear vibrations of circular cylindrical shells subjected to pulsatile pressure and pulsatile flow.

1. Introduction

Shell-like structural components used for aerospace and biomechanical applications are particularly challenging as they undergo significant deformations and stresses, involve fluid–structure interactions and are made of materials whose properties are not fully known.

Systematic research on the nonlinear dynamics of shells conveying fluid has been conducted by Païdoussis and it is synthesized in his monograph [1]. The effects of internal flow on the stability of circular cylindrical shells have been studied by Païdoussis and Denise [2], Weaver and Unny [3] and Païdoussis et al. [4,5].

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Theory for the dynamic stability of circular cylindrical shells subjected to incompressible subsonic liquid and air flow have been reported by Amabili et al. [6–9] and experiments by Karagiozis et al. [10,11]. In the theoretical part of these studies, the shell was assumed to be in contact with inviscid fluid, and the fluid–structure interaction was described by the potential flow theory. Experiments on nonlinear dynamics of clamped shells subjected to axial flow were described in Ref. [10] and its visual experimental evidence was provided in Ref. [11]. A subcritical nonlinear softening behavior was reported for shells subjected to internal and external flow for the first time by Amabili [6]. It was found that, the interaction between the shell and the fully developed flow gives rise to instabilities in the form of static or dynamic divergence at sufficiently high flow velocities. The effect of imperfections on the nonlinear stability of shells containing fluid flow has been investigated by Amabili et al. [12] by using the most refined model at present; fluid viscosity has also been considered. Good agreement was shown with the available experimental results for divergence of aluminum shells conveying water.

Additional work can be found in the literature. The combined effect of geometric imperfections and fluid flow on the nonlinear vibrations and stability of shells has been investigated by del Prado et al. [13]. The behavior of the thin-walled shell was modeled by Donnell's nonlinear shallow-shell theory and the shell was assumed to be subjected to a static uniform compressive axial pre-load plus a harmonic axial load. A low-dimensional model was obtained by using the Galerkin method and the numerical solutions were found by using a Runge-Kutta scheme. It was shown that the parametric instability regions, bifurcations and basins of attraction are affected by the initial geometric imperfection and the flow velocity. The effect of fluid viscosity was also retained by Karagiozis et al. [14] in studying the nonlinear vibrations of harmonically excited circular cylindrical shells conveying water flow. Periodic, quasi-periodic, sub-harmonic and chaotic responses were detected, depending on the flow velocity, and amplitude of the harmonic excitation. It was found that, the softening behavior is enhanced by increasing the flow velocity.

By neglecting the effect of fluid viscosity and considering the potential flow model, nonlinear forced vibrations and stability of shells interacting with fluid flow were investigated in Refs [15–18]. Koval'chuk [15] used Donnell's nonlinear theory together with Galerkin approach and Krylov- Bogolyubov–Mitropol'skii averaging technique to study the nonlinear vibrations of the shell, neglecting the effect of axisymmetric modes. The same theory and solution methodology was used by Koval'chuk and Kruk [16]. However, in their analysis, the numerical model had six degrees of freedom that included four asymmetric modes plus two axisymmetric modes. The axisymmetric modes were described as quartic sine terms. Kubenko et al. [17] extended the previous works of Refs. [15,16] by showing the mathematical procedure for the Krylov–Bogolyubov–Mitropol'skii method in studying multimode nonlinear free, forced and parametrically excited vibrations of shells in contact with flowing fluid. Kubenko et al. [18] have also studied the vibrations of cylindrical shells interacting with a fluid flow and subjected to external periodic pressure with slowly varying frequency. Nonlinear dynamics of cantilevered circular cylindrical shells subjected to flowing fluid has been investigated by Paak et al. [19], but the contribution of axisymmetric modes has been neglected. The nonlinear model of the shell was based on Flügge theory retaining nolinear terms due to mid-surface stretching, and the fluid model was based on the potential flow theory. The unsteady interaction and asymptotic dynamics of a viscous fluid with an elastic shell has also been examined by Chueshov and Ryzhkova [20] using the linearized Navier–Stokes equations and Donnell's nonlinear shallow shell theory.

A specific type of unsteady flows includes oscillatory and pulsatile flows which occur in biological systems, such as human respiratory and vascular systems, as well as in many engineering areas, for example, the flow in hydraulic and pneumatic and pumping systems or applications of heat transfer. Oscillatory and pulsating flows in branching pipes have been extensively studied by investigators concerned especially in biology. Additionally, a number of works have been reported in literature concerning oscillatory or pulsatile flows in straight pipes (see for example, Uchida [21], Gerrard and Hughes [22], Kerczek and Davis [23], Schneck and Ostrach [24], Hino et al. [25], Muto and Nakane [26], Shemer et al. [27], Elad et al. [28]). Pioneering studies related to dynamic instability of pipes conveying fluctuating fluid were from Chen [29] followed by Ginsberg [30], Païdoussis [31] and Païdoussis and Issid [32]. Ginsberg [30] derived the general equations of motion for small transverse displacement of a pipe conveying fluid based on the transverse force exerted by the flowing fluid. For the case of a simply supported pipe Galerkin method was utilized to obtain the solution. The dynamic instability regions were evaluated and it was shown that the region of dynamic instability increases with increased amplitude of fluctuation. Païdoussis [31] presented a theoretical analysis of the dynamical behavior of flexible cylinders in axial flow, the velocity of which was perturbed harmonically in time. He found that parametric instabilities are possible for certain ranges of frequencies and amplitudes of the perturbations. These instabilities occur over specific ranges of flow velocities, and in the case of cantilevered cylinders are associated with only some of the modes of the system. Païdoussis and Issid [32] derived the equation of motion for a flexible pipe conveying fluid; effects of external pressurization and external tension were included, the longitudinal acceleration of the fluid was taken into account, hence this model can be applied to problems when the flow contains harmonic components.

In biomechanics, thin-walled shells can be used to model the mechanics of veins, arteries and pulmonary passages. Kamm [33] investigated the flutter phenomenon of veins and its associated collapse, while Païdoussis [1] investigated the fluid–structure interaction between the blood flow and the veins. The mechanisms leading to static collapse and flutter of biological systems have been explained but there remain questions regarding the causes that may lead to it because of the large deformations the system experiences. Thus, the dynamics of arteries should be easier to explain since arteries are traditionally considered capable of withstanding large deformations without adverse effects. In addition, arterial walls are