



The beam-mode stability of periodic functionally-graded-material shells conveying fluid



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ABSTRACT

The characteristics of beam-mode stability of fluid-conveying shell systems are investigated in this paper for shells with clamped-free (cantilevered) boundary conditions. An FEM algorithm is developed to conduct the investigation. A periodic shell structure of functionally graded material (FGM), termed as PFGM shell here, is designed so as to enhance the stability for the shell system, and to eliminate the stress concentration problems that exist in periodic structures. Results show that by the introduction of periodic design the critical velocities can be raised over several desired ranges of the dimensionless fluid density β , and the stress concentration is effectively reduced in the PFGM shell. Finally, the effects of the geometric shape, material parameters and spring supports on the dynamical stability are probed.

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1. Introduction

The dynamic behavior of cylindrical shells conveying fluid has important practical applications, for instance in heat exchangers, hydraulic systems, power plants, air conditioning and nuclear reactor systems. It is not surprising, therefore, that the dynamic problems of fluid-conveying shells have been extensively investigated both theoretically [1–5] and experimentally [6–10].

In general, two aspects of the dynamics of the fluid conveying shells have been studied extensively: (i) dynamic responses, including both the transient [11–16] and the frequency responses [17–21], and (ii) dynamic stability [22–26]. The focus of the present work is on the second aspect, as the previous work has shown that the dynamic stability of the system is quite fascinating [23]. Païdoussis [24,25] and Chen [26] have presented excellent reviews related to the dynamic stability of shells and pipes interacting with the flowing fluid. This aspect has continued to be studied at an accelerating pace, as more and more applications emerge, as may be appreciated from [27]. Amabili et al. have performed a systematical study of the nonlinear dynamics and stability of simply supported, circular cylindrical shells [4–6]. In particular, the cantilevered shell system, as a non-conservative system, displays some at-first-sight surprising behavior [24,28], thus its stability characteristics have received a great deal of attention [24,26]. More recent studies have been on the effect on stability of non-uniform flow profile [29–31] and on cantilever pipes with added masses and flexible supports [32]. Also, there are a few

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recent studies on the periodic design, attempting to enhance the dynamical stability for fluid-conveying pipes and shells [33,34].

The initial attraction of using periodic structures may be due to its unusual dynamical characteristics [35–39], e.g., the existence of wave bands within which the propagation of elastic waves is forbidden over some selected frequency ranges. Here, we focus on the stability of periodic shells. Aldraihem presented a study on a periodic pipes consisting of identical substructures or cells, such as a uniform pipe segment and a collar, and the stability maps obtained demonstrate that the collar-stiffened periodic pipe exhibits unique stability characteristics [33]. Ruzzene placed circumferential stiffeners periodically along the axial direction as a means to enhance the stability of the considered class of shells, and the stability maps obtained indicate that the stiffening rings significantly extend the range of stable operating conditions by reducing the regions of dynamic instability [34]. Although such periodic shells could improve the dynamical stability for fluid-conveying shells or pipes, a serious shortcoming is found in the periodic systems, namely, the stress concentration produced by the material/geometric discontinuities, which can lead to damage in the form of matrix cracking, adhesive bond separation, and so on.

Functionally graded materials (FGMs) are a class of composites that have a smooth and continuous variation of material properties from one surface to another and thus can alleviate the aforementioned stress concentration problem. Extensive research has been carried out on this new class of composites and its applications [40–42]. Abrate [40] considered the problems of free vibrations, buckling, and static deflections of functionally graded plates in which material properties vary through the thickness. Tornabene et al. investigated the dynamic behavior of moderately thick FGM conical and cylindrical shells and annular plates [42]. The continuous change in FGM composition leads to a smooth change in the mechanical properties; with the application of FGM in shells, the stress concentrations found in the laminated composites can be alleviated.

The introduction of FGM for periodic shells conveying fluid could help to overcome the shortcomings of stress concentration, yet retaining the superior stability characteristics of periodic shells. Nevertheless, not much research has been done on the application of FGM, such that material properties vary continuously in the axial direction, in the area of stability enhancement for fluid-conveying shell systems. The present work is motivated by the aforementioned useful properties of FGM and periodic structures. The skeptical reader might question the usefulness of this study, as there are simpler ways for enhancing stability of the fluid-conveying shell system than resorting to the use of geometric/material periodic shell structures. However, it can be known that much of the total body of work on the dynamics of pipe and shell systems conveying fluid has been curiosity-driven, yet applications emerged a few or many years later [23,27], or proved useful in other areas of applied mechanics [43]; it is very likely that it is only a matter of time before this happens in this case also.

Several studies [44–48] have been presented earlier on the stability analysis of cylindrical shells and the most popular numerical tool in carrying out these analyses is the finite element method (FEM). Here, the FEM algorithm is also utilized to investigate the dynamic stability of the cantilevered periodic FGM shell (PFGM shell) conveying fluid.

The paper is organized into four sections and one appendix. In Section 1, a brief introduction is given. Section 2 develops the FEM algorithm for the PFGM shell. In Section 3, the stability characteristics for the PFGM shell are investigated, for clamped-free boundary conditions; the effects of geometric and material parameters on the stability are considered; also, the stability of the cantilevered PFGM shell with various spring supports is studied. Finally, a brief summary of the conclusions and suggestions for future work are given in Section 4.

2. Governing equations and FEM method

The fluid-conveying periodic shell system to be investigated is sketched in Fig. 1; the flow velocity is U . The dynamic problem of the fluid-filled cylindrical shell is formulated in a cylindrical polar coordinate system (x, θ, r) , where the coordinate axis x is coincident with the cylindrical shell centre-line, whereas the coordinate axes r and θ are taken along the radial and circumferential directions, respectively. The longitudinal, circumferential and radial displacements, i.e., u , v and w , are assumed to be constant across the thickness according to the Flügge shell theory [49]. The basic equations of this shell theory are given in Appendix A.

When the circumferential wavenumber n is equal to 1, the equations are reduced to the case of beam-mode motion of the shell. Probably, the most “natural” type of motion of a long shell is its deformation in the “beam-type” mode [19,20]. A considerable number of studies have been carried out on the dynamic analysis of the beam-mode dynamics for fluid-conveying shells [49–52]. The basic design methodology and analysis method for this mode may be applicable to other modes, or even other structures, such as beams and plates, as the stability characteristics generated by the periodic design could be similar. The beam-mode stability is what the current paper will focus on, particularly, because considerable simplification is thereby introduced in the computations needed to obtain the characteristics of wave propagation for this mode. Specifically, it is reasonable to assume, that no distortion of the cross-sectional shape occurs in this case and displacements are linked with each other as [19]

$$v = -w, \quad u = -\partial w / \partial \xi, \quad (1a)$$

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