International Journal of Mechanical Sciences 115-116 (2016) 689–701

Contents lists available at ScienceDirect

International Journal of Mechanical Sciences

journal homepage: www.elsevier.com/locate/ijmecsci

Dynamic stability analysis of a cylindrical shell subjected to swirling annular flow under thermal loads

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ARTICLE INFO

Article history:
Received 8 March 2016
Received in revised form
24 July 2016
Accepted 31 July 2016
Available online 2 August 2016

Keywords:
Cylindrical shell
Annular flow
Dynamic stability
Fluid rotation
Viscosity
Temperature effects

ABSTRACT

Considering thermal loads, a dynamic stability analysis is presented for a flexible cylindrical shell conveying a viscous, incompressible, swirling fluid in the annulus between the inner shell and the outer shell in this paper. The inviscid fluid-dynamic forces associated with shell motions are treated in the frame of the potential flow theory. And the steady viscous forces are derived by using fully developed turbulent theory. The thermal loads are determined by the thermo-elastic theory. Shell motions are described by Flügge's thin shell equations, which are modified to incorporate the prestresses relating to the steady viscous forces. The theoretical analysis is conducted by the zero-level contour method and the Galerkin's method. This study shows that, for annular flow, the effect of viscosity renders the system more unstable. Fluid rotation strongly degrades the stability of the shell. The influences of a combined action of the viscous annular flow having two velocity components and the thermal loads on the stability of shells are discussed in detail. Also, the critical temperature rise is found.

1. Introduction

Dynamics and stability of cylindrical shells have been investigated quite extensively. Yamaki [1] studied the buckling and post-buckling behaviors of shells in detail. Leissa [2] presented the vibrational characteristics of shell structures. The nonlinear dynamic responses of functionally graded cylindrical shells were studied by Strozzi and Pellicano [3]. Taking into account the geometric nonlinearity, the large-amplitude vibrations of the cylindrical shells were investigated by using Lagrange approach [4]. It was found that the results obtained from different shell theories were extremely close. In recent years, coaxial shells containing flowing fluid in the annulus between the two shells are often found in many engineering applications. Typical examples are canned components between the stator and the rotor, fuel stings in coolant channels, nacelles into pressured vessels, control rods in guide tubes, existing in various types of nuclear reactors. An important reason for interest in such systems is that flow-induced instability and vibration problems can be mostly observed. The nonlinear vibration and stability of dry or fluid-conveying cylindrical shells were studied by Amabili [5]. A more detailed review on stability and dynamics of pipes and shells conveying fluid was presented by Païdoussis [6,7] in the form of a two-volume book. Tijsseling [8] surveyed the development of fluid-structure interaction in liquid-filled pipe systems. Srinivasan [9] firstly studied the aeroelastic stability of a thin cylindrical shell under external helical air flow based on the classical shell theory and linear potential flow theory by travelling-wave approach. Through numerical simulations, it was found that the system loses stability by coupled mode flutter. Subsequently the experimental studies were performed [10], and the experimental data were compared with the theoretical predictions. Based on Sanders shell theory, Chen and Bert [11] considered dynamic stability of isotropic or composite-material cylindrical shell containing a swirling fluid flow by using travelling-wave method. The obtained results showed that the fluid rotation severely decreases the stability of the shell-fluid system. The dynamic behaviors of coaxial cylindrical shells subjected to annular fluid flow with having both the axial and tangential velocity components were given by Bochkarev and Matveenko [12,13]. They found that the combined action of both velocity components affects the stability of the system essentially.

Kozarov and Mladenov [14] studied the dynamic behaviors of infinitely long coaxial cylindrical shells conveying an ideal fluid based on

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http://dx.doi.org/10.1016/j.ijmecsci.2016.07.043
0020-7403/

Nomenclature

A, B, A_1, B_1	coefficients
$C(x), D(x)$	functions of x
c_1, c_2	constants
d	hydraulic diameter of the cylinder
E	elastic modulus
$E(r)$	function of r
F	constant, $F = P(0, r_o)/\rho_f$
f	friction factor
$G(x)$	weight function
H	coefficient
h_i	thickness of the inner shell
h_o	thickness of the out shell
i	$\sqrt{-1}$
I_n	nth order modified Bessel function of the first kind
K_n	nth order modified Bessel function of the second kind
L	length of the shell
M	axial load
m	number of axial half-wave
n	number of circumferential wave
N_x^T	axial thermal load
$N_x, N_\theta, N_{x\theta}$	axial stress, hoop stress and shear stress
P^t	total perturbed pressure
P_s	stagnation pressure
$\overline{P}$	mean pressure
P	mean pressure of a fully developed turbulent
P_x, P_r, P_θ	axial, radical, hoop loads arising from the mean pressure
p	perturbation pressure
p_e	uniform static pressure of air
$Q_{1,2,3,4}$	forces associated with steady viscous effects
R_e	Reynolds number
r_i	radius of the inner shell
r_o	radius of the out shell
r_m	radius at which the mean velocity U_o is maximum
T	temperature rise
T_r	room temperature
t	time
U_m, V_m, W_m	amplitudes of the displacements in x, θ, and r directions
U_o	axial mean velocity
$\mathbf{u}$	displace matrix
V_o	tangential mean velocity
u, v, w	components of the displacements in x, θ, and r directions
u_x, u_r, u_θ	turbulent fluctuating velocity components in x, θ, and r directions
α	coefficient of thermal expansion
∇	height of surface protrusions
ζ	matrix operator
λ	wavenumber in axial direction
λ_c	ratio $\lambda_c = \frac{r_o}{r_i}$
ν	kinematic viscosity of the fluid
υ	Poission' ratio
ρ_s	density of the shell
ρ_f	density of the fluid
τ	parameter $\tau = r_i\sqrt{\frac{\rho_s(1-\upsilon^2)}{E}}$
Φ	unsteady state potential
Ψ	steady state potential
Ω_o	rotation velocity
i, o	subscripts refer to inner shell, outer shell
$=$	time-mean quantity
$-$	nondimensional quantity

Volson's shell equations. Horáĉek [15,16] developed an approximate theory of annular-flow-induced instability of coaxial cylindrical shells based on the semimembrane theory. Based on Flügge's shell motion equations, dynamics and stability of coaxial cylindrical shells conveying inviscid or viscous fluid were studied by means of Fourier-transform techniques [17–19]. The principal findings of their work were that the instability velocity of annular flow is lower than the value of internal flow and the viscous forces destabilize the system for annular flow. The effects of system parameters on the stability were also discussed. Further work on the same problem was subsequently extended to take into account unsteady viscous forces by Chebair et al. [20]. It was found that the unsteady viscous forces only have a slight influence on dynamics of the system. Considering the viscous effects of fluid, the influences of steady viscous forces on dynamic responses and instability behaviors of fluid-conveying shells were given [21,22]. More thorough work on the dynamic behaviors of coaxial cylindrical shells subjected to axial flow was undertaken by Bochkarev and Matveenko [23–25]. Furthermore, effects of the rotation of shells on the stability of the fluid-shell system were discussed fully [26,27].

Also, dynamics and stability of cylindrical shells are affected by other loads such as mechanical loads, thermal loads, electromagnetic loads, besides hydroelastic forces. Pavikiran and Ganesan [28] considered the effects of water temperature on the dynamic stability of shells by Floquent-Liapunov theory. Sheng and Wang [29] analyzed the vibrations of functionally graded cylindrical shells conveying an ideal fluid under thermo-mechanical loads by using the modal expansion method. Based on the beam-mode, the vibration and instability of fluid-conveying micro-pipe under electromagnetic potential were studied by the Galerkin's method [30]. The results showed that the electromagnetic forces have important effects on the stability of the micro-pipe system. The vibration analysis of fluid-conveying carbon nanotubes subjected to the magnetic field was performed by Ghorbanpour et al. [31]. They found that the magnetic field is basically factor on increasing frequency and critical flow velocity.

Though there are many studies of stability and dynamics of coaxial shells carrying fluid with only an axial velocity component in the literature, little work on the influence of the steady viscous forces on dynamic stability behaviors of a cylindrical shell conveying fluid with both velocity components. Considering thermal loads, the effects of a combined action of the axial and the angular velocities of annular flow on the character of dynamic behaviors of such system are also unexplored up to now. Therefore, dynamic stability behaviors of a thin-walled cylindrical shell subjected to helical annular flow including thermal loads will be investigated based on an analytical model developed by using the travelling-wave approach. Furthermore, the estimation of the influence of the steady force inducted by the rotation of fluid on the dynamic behaviors of such system will be performed. The calculations are conducted by the zero-level contour method and the Galerkin's method. The lowest flow velocities of losing stability (referred to the critical flow velocities) are obtained and relations of them are examined. These studies will provide useful information for the design of certain cylindrical shell-type structures in nuclear reactors, heat exchangers, space shuttles, and others.