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Shock initiated instabilities in underwater cylindrical structures

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ABSTRACT

An experimental investigation to understand the mechanisms of dynamic buckling instability in cylindrical structures due to underwater explosive loadings is conducted. In particular, the effects of initial hydrostatic pressure coupled with a dynamic pressure pulse on the stability of metallic cylindrical shells are evaluated. The experiments are conducted at varying initial hydrostatic pressures, below the critical buckling pressure, to estimate the threshold after which dynamic buckling will initiate. The transient underwater full-field deformations of the structures during shock wave loading are captured using high-speed stereo photography coupled with modified 3-D Digital Image Correlation (DIC) technique. Experimental results show that increasing initial hydrostatic pressure decreases the natural vibration frequency of the structure indicating loss in structural stiffness. DIC measurements reveal that the initial structural excitations primarily consist of axisymmetric vibrations due to symmetrical shock wave loading in the experiments. Following their decay after a few longitudinal reverberations, the primary mode of vibration evolves which continues throughout later in time. At the initial hydrostatic pressures below the threshold value, these vibrations are stable in nature. The analytical solutions for the vibration frequency and the transient response of cylindrical shell are discussed in the article by accounting for both (1) the added mass effect of the surrounding water and (2) the effect of initial stress on the shell imposed by the hydrostatic pressure. The analytical solutions match reasonably well with the experimental vibration frequencies. Later, the transient response of a cylindrical shell subjected to a general underwater pressure wave loading is derived which leads to the analytical prediction of dynamic stability.

1. Introduction

Cylindrical metallic shell structures are extensively used in the design of many underwater structures, such as deep-ocean submersibles, autonomous underwater vehicles (AUVs), underwater pipelines etc. (Mesloh et al., 1973; Palmer and Martin, 1975; Turner and Ambrico, 2012). Often, these structures contain internal gas, at a pressure lower than the environment's, to ensure proper functionality of electronics and other major components. The external pressure of water at

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Nomenclature

x, θ, z initial coordinate system for the cylindrical shell. $x \to$ longitudinal direction, $\theta \to$ circumferential direction, and $z \to$ radial direction.
E, G, ν and ρ elastic modulus, shear modulus, Poisson's ratio and density of cylindrical shell material
h wall thickness of the cylindrical shell
R radius of middle surface of cylindrical shell
L unsupported length of the cylindrical shell
b inner radius of the pressure vessel
ρ_w density of water
n no. of circumferential waves
m no. of axial half waves
P_c experimental static buckling pressure
P_{in} initial hydrostatic pressure/initiation pressure prior to shock wave loading
E_p $Eh/(1-\nu^2)$=shell extensional modulus
D $Eh^3/[12(1-\nu^2)]$=shell flexural modulus
u, v, w displacement components of the middle surface of the cylindrical shell in x,θ,z direction respectively.
N initial circumferential stress on the cylindrical shell
T initial axial stress on the cylindrical shell
ΔF_x, ΔF_θ, Δq axial, circumferential and radial components, respectively, of the change of the initial shell surface tractions, due to deformation, taken per unit un-deformed middle surface area
m_x, m_θ shell moment due to axial and circumferential traction, respectively
Δm_x, Δm_θ changes in m_x,m_θ, respectively, due to deformation
t time
$\tau = \frac{t}{R}\sqrt{\frac{E_p}{\rho h}}$ normalized time
P_0 applied axisymmetric pressure wave loading
$P_n = -M\frac{\partial^2 w}{\partial t^2} = M'\rho h\left(\frac{n^2+1}{n^2}\right)\left(\frac{1}{1+2\beta^2}\right)\frac{\partial^2 w}{\partial t^2}$ self-induced pressure loading due to added mass of water
$\bar{P} = \frac{PR}{E_p}$ normalized pressure loading
ω_1 vibration frequency
ω_0 vibration frequency at zero initial pressure without effect of added mass
$\omega_s = \frac{\pi}{h}\sqrt{\frac{G}{h}}$ vibration frequency of the first simple thickness-shear mode of an infinite plate with thickness h.
$\Omega_{0,1} = \frac{\omega_{0,1}}{\omega_s}$ normalized vibration frequency
$\beta = \frac{m\pi R}{Ln}$ ratio of circumferential to axial wavelength
$s = \frac{h}{2R}$ thickness to diameter ratio of cylindrical shell
$\bar{N} = \frac{N}{E_p}$, $\bar{T} = \frac{T}{E_p}$ normalized circumferential and axial stress, respectively
$M' = \frac{n^2}{1+n^2}\frac{M}{\rho h}(1+2\beta^2)$ added mass coefficient where $M = \frac{\rho_w(R+h/2)}{n}\left[\frac{(b/R)^{2n}+1}{(b/R)^{2n}-1}\right]$
P_{c_exact} analytical exact solution of the static buckling pressure for a simply supported cylindrical shell
P_{c_plane} analytical solution of static buckling pressure for infinitely long cylindrical shell (plane strain case)
$\bar{W} = \frac{w}{R}$ normalized total radial deformation
$\bar{W}_0$ normalized axisymmetric radial deformation
$\bar{W}_2$ normalized radial deformation for mode-2 (m=1, n=2)
$\bar{W}_i$ normalized initial imperfection in cylindrical shell
δ_2 normalized imperfection for n=2
$P_{sim}(t)$ Approximate triangular shaped shock wave loading
Δt time-period of $P_{sim}(t)$

extreme sea depths may cause the enclosed shell to become structurally unstable and collapse onto itself (implode). The resulting collapse is violent and causes a rapid release of energy in the form of shock waves, high velocity fluid motion, and sound (LeBlanc et al., 2014). In recent years, many catastrophic implosion events such as the super Kamiokande laboratory accident, where over 7000 photomultipliers tubes collapsed (Cartlidge, 2001), and the implosion of the Nereus AUV (Robotic Deep-sea Vehicle Lost on Dive to 6-Mile Depth, 2014), have shown the importance of better understanding the implosion phenomenon to create safer underwater structures. There have been several investigations reported by researchers on the mechanics and fluid-structure interaction (FSI) during a "free-field natural implosion" process (Isaacs and Maxwell, 1952; Urick, 1963; Vanzant et al., 1967; Vath and Colletti, 1969; Orr and Schoenberg, 1976; Turner, 2007; Turner and Ambrico, 2012; Farhat et al., 2013; Gupta et al., 2014b; Pinto et al., 2015a, 2015b; Chamberlin et al., 2014). Turner (2007) measured the near-field pressure history during the implosion of glass spheres in a free-field environment and concluded that the failure time history of the structure has a significant influence on an implosion pressure pulse. Later, both Turner and Ambrico (2012) and Farhat et al. (2013) studied the implosion of aluminum cylindrical tubes experimentally and numerically. Turner and Ambrico (2012) identified the key features of a typical mode-2 implosion process by correlating the important signatures of the pressure pulse with the structural deformation. Farhat et al. (2013) extended this work by comparing both mode-4 and mode-2 implosion, and showed that the higher mode of collapse generates a higher pressure peak but of smaller duration when compared to a lower mode collapse. Recently, the authors have reported real-time high-speed DIC deformation measurements to correlate the structural deformations and the pressure history (Gupta et al., 2014b). The study showed that the time period and impulse of the positive pressure wave directly correlates to the time taken for the collapse to propagate along the length of the specimen. Moreover, this study demonstrated the usefulness of both structural