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A pseudo-coupled analytic fluid-structure interaction method for underwater implosion of cylindrical shells

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ABSTRACT

Underwater implosion, the rapid collapse of a structure caused by hydrostatic pressure, is a fully coupled, highly dynamic and nonlinear fluid-structure interaction (FSI) problem. The primary motivation behind studying implosion is the short-duration, high-pressure pulse generated in the surrounding water. This paper presents a simplified analytic method to estimate the energy in the pressure pulse, based on potential flow theory. The method accounts for the varying fluid pressure and accompanying FSI. The focus is on long, thin, unstiffened metallic cylindrical shells that collapse in mode 2. The implosion pulse energy is shown to be equal to the maximum system kinetic energy developed during collapse. The kinetic energy is calculated using an energy balance approach and analytic solutions for plastic energy dissipation and energy required to compress the internal air. The time-varying fluid pressure, and subsequently the work done by the fluid on the cylinder, is found using a novel explicit time-stepping methodology. The result is a pseudo-coupled analytic solution for the fluid pressure time history and implosion pulse energy. Solutions for pulse energy agree with RANS numerical simulations within 5%.

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1. Introduction

Underwater implosion is the rapid, catastrophic collapse of a structure caused by external pressure. Any structure with an internal gas-filled volume carries the risk of implosion, including autonomous underwater vehicles (AUVs), subsea pipelines, air flasks, and light bulbs. Implosion generates a very short, high-pressure pulse in the surrounding water, similar to the bubble pulse following an underwater explosion (UNDEX) event. This pulse has the potential to damage adjacent structures or people, and is the primary reason for studying the implosion phenomenon. Implosion has been extensively studied in recent years, both experimentally and numerically, with the main goal of predicting the pressure pulse for a given structure geometry and hydrostatic pressure (e.g., [1,2]). Gish and Wierzbicki presented an alternative approach: an analytic solution to estimate the energy in the implosion pulse, assuming steady and uniform fluid pressure [3]. This paper expands on that work by focusing on the coupled fluid-structure interaction (FSI) aspect of the problem.

A general FSI problem consists of an elastic or elastic–plastic solid body surrounded by a fluid. The solid body may be rigid or deformable. The problem is solved by imposing continuity conditions at the fluid-solid interface. Specifically, kinematic continuity of displacement and velocity and kinetic continuity of normal stress must be imposed at the interface [4].

An FSI problem is complicated if the solid body undergoes large deformations, as in the case of underwater implosion. During implosion, the hydrostatic pressure loading on the solid body causes rapid movement of the solid surface (i.e., deformation or crushing of the body). This rapid movement of the solid surface causes corresponding motion of the adjacent fluid (because of kinematic continuity requirements), which in turn causes a local hydrodynamic pressure change (decrease) in the fluid. The hydrodynamic pressure during the cylinder collapse is illustrated in Fig. 1. The negative phase corresponds to collapse of the walls and in-rush of water. The large positive spike is caused by contact between opposite cylinder walls, leading to rapid deceleration and compression of the water. The varying fluid pressure acting on the surface changes the acceleration of the surface, which consequently changes the fluid velocity and pressure. A typical underwater implosion occurs in a few milliseconds. Thus, implosion is a fully-coupled, highly dynamic and nonlinear FSI problem.

Fully-coupled FSI problems are usually too complex to be solved analytically, so they are evaluated numerically. The general solution approach is to solve the equations governing fluid flow and solid displacement at each time step, while simultaneously imposing the continuity requirements. Extensive work has been done on

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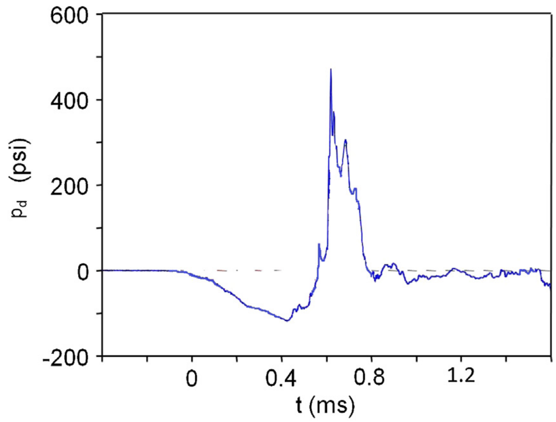

Fig. 1. Typical dynamic pressure history for an underwater implosion event.

optimizing numerical methods for solving FSI problems (e.g., [5,6]). However, these methods are time-consuming and computationally expensive. This paper presents a simplified pseudo-coupled solution method based on potential flow theory to approximate the changing fluid pressure during collapse, and thereby obtain an accurate estimate of the energy in the implosion pulse.

2. Problem formulation

2.1. Modes and phases of cylinder collapse

Implosion of an unstiffened metallic cylinder under hydrostatic load is a three-dimensional phenomenon that starts at the center cross-section and progresses towards the cylinder ends. Collapse starts at the center because the end caps in this work are assumed rigid and do not deform. The buckling mode is a function of cylinder length, diameter, and thickness. Longer, thinner cylinders tend to collapse in mode 2, and shorter thicker cylinders into mode 3 or 4 [7]. Modes refer to the shape of a two-dimensional cross-section of the cylinder as it collapses, and are named by the number of lobes formed from the originally circular cross-section. Typical collapse mode cross-sections are shown in Fig. 2. This paper focuses on mode 2 collapse, because it represents a broad range of implodable systems like AUVs, sensors, or torpedoes.

Unstiffened cylinders implode in a predictable sequence, regardless of the collapse mode. The three-dimensional implosion event is defined by three phases [8]:

- Phase 1: symmetric collapse into one of the cross-sectional modes shown in Fig. 2, until first contact between opposite cylinder walls at a single point on the center cross-section.
- Phase 2: center cross-section continues to flatten until reaching a maximum, depending on pressure and the diameter-to-thickness ratio.
- Phase 3: flattening continues longitudinally along the cylinder until reaching a final state.

Fig. 3 depicts the three collapse phases for mode 2 (dark lines outline the flattened regions).

2.2. Energy balance

The energy balance of the entire implosion event is given by:

$$W = E_{\text{int}} + E_{air} + E_{kin} \tag{1}$$

where W is the work done on the cylinder by the fluid, E_{int} is the plastic energy dissipated by the cylinder, E_{air} is the energy required to compress the internal air, and E_{kin} is the total kinetic energy of the structure and surrounding fluid. The maximum kinetic energy occurs just after the end of phase 1, as shown in Fig. 4. Following the maximum, E_{kin} decreases as some kinetic energy is converted into further plastic deformation of the cylinder and the remainder is transmitted as the pressure pulse. The peak value of E_{kin} therefore represents the upper bound on pulse energy, and can be approximated very closely by considering only phase 1 [3].

Evaluation of E_{kin} (and thus the energy of the implosion pulse) is most easily done by calculating the other three terms in Eq. (1). Gish

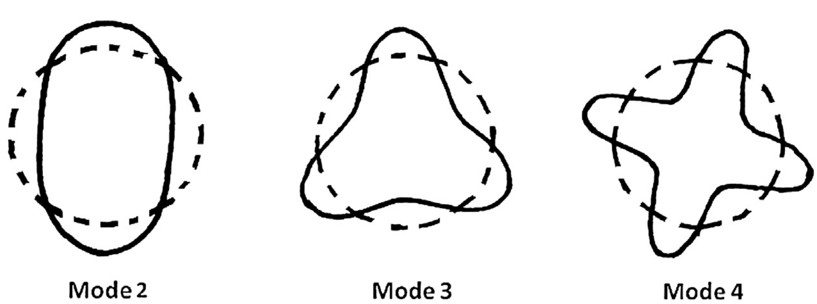

Fig. 2. Cross-sectional collapse modes under purely hydrostatic loading (dashed represents original shape, solid represents deformed shape).

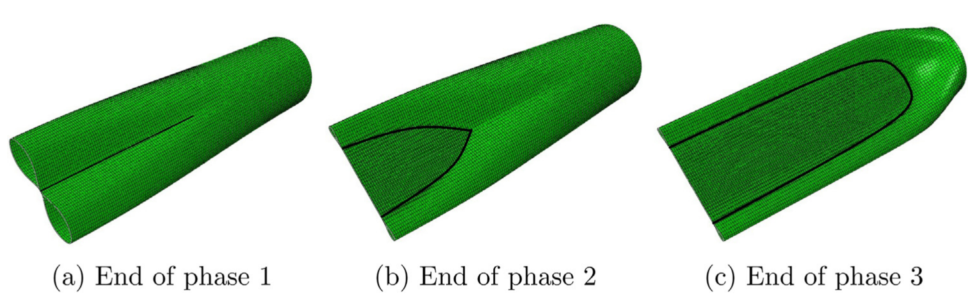

Fig. 3. Phases of mode 2 collapse (half-length shown).