

Acoustic radiation force of a solid elastic sphere immersed in a cylindrical cavity filled with ideal fluid



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HIGHLIGHTS

- Acoustic radiation force on solid elastic sphere in cylindrical cavity is derived.
- The effect of a cavity on radiation force is studied for different relative radii.
- The acoustic radiation force for a sphere with different materials is analyzed.
- The relationship between negative forces and backscattering is discussed.

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ABSTRACT

An expression for the acoustic radiation force function on a solid elastic spherical particle placed in an infinite rigid cylindrical cavity filled with an ideal fluid is deduced when the incident wave is a plane progressive wave propagated along the cylindrical axis. The acoustic radiation force of the spherical particle with different materials was computed to validate the theory. The simulation results demonstrate that the acoustic radiation force changes demonstrably because of the influence of the reflective acoustic wave from the cylindrical cavity. The sharp resonance peaks, which result from the resonance of the fluid-filled cylindrical cavity, appear at the same positions in the acoustic radiation force curve for the spherical particle with different radii and materials. Relative radius, which is the ratio of the sphere radius and the cylindrical cavity radius, has more influence on acoustic radiation force. Moreover, the negative radiation forces, which are opposite to the progressive directions of the plane wave, are observed at certain frequencies.

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1. Introduction

Acoustic radiation forces (ARFs) are acoustically induced by hydrodynamic forces that can cause particles to become suspended in a host fluid or cluster in certain regions. This phenomenon is part and parcel of many recent scientific, technological, and medical applications such as acoustic radiation force imaging, colloidal assembly, and various bio-separation assays. There have been numerous studies ARFs for plane waves acting on spheres or cylinders in an unbounded space [1–14]. King first proposed the theory of acoustic radiation pressure on a sphere in a compressible fluid [15]. Fox used a simple approximation to obtain the expression of the ARF function for a rigid sphere [16]. Faran studied the scattering and the directivity of solid cylinders and spheres [17]. Doinikov extended the theory by considering a sphere in a viscous

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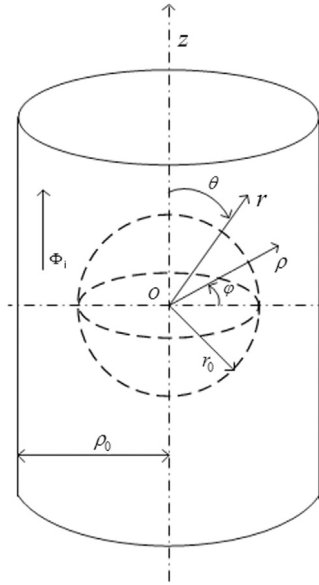


Fig. 1. The schematic illustration of a sphere in a cylindrical cavity.

medium [18,19]. Hasegawa and Yosioka et al. deduced the exact expression of the acoustic radiation pressure on solid elastic particles in an unbounded liquid, and they also reported the experimental results of elastic spherical particles [20–25]. Wu first put forward the conception of acoustic tweezers, which can trap particles using ARF [26]. Mitri studied ARF on spherical and cylindrical particles in different sound fields [27–30]. Marston et al. reported on numerous studies on ARF of beam wave on a sphere [31–33]. K. H. Lam et al. conducted a series of experiments on acoustic particle manipulation [34–36].

In recent years, G. C. Gaunard, A. K. Miri, and Jingtao Wang et al. provided a potentially practical understanding of the radiation force acting on a cylinder near a boundary [37–39]. Kubenko et al. considered the sound scattering and the ARF for a rigid or liquid spherical object immersed in a cylindrical cavity filled with an ideal compressive fluid [40–44]. However, the derived expression of the ARF is different if the material of the sphere is altered. In this study, an exact equation of the ARF function for a solid elastic sphere immersed in an infinite rigid cavity filled with an ideal fluid is deduced. Simulation results for different spherical particles are provided to validate the theory.

2. Scattering on a solid elastic sphere with a plane wave

Consider a sphere suspended in an infinite cylindrical cavity filled with an ideal compressive fluid. The density γ_1 of the sphere differs from the density γ_0 of the surrounding fluid. The wall of the cylindrical cavity is configured to be rigid, and the radii of the sphere and cylindrical cavity are r_0 and ρ_0 , respectively. The center of the sphere lies at the center of the cylindrical cavity. A spherical coordinate system (r, θ, φ) is established in such a way that its origin O coincides with the center of the cylindrical cavity. Moreover, a cylindrical coordinate system (ρ, φ, z) that has the same origin as the spherical coordinate system is introduced to the model. A plane progressive wave travels along the positive axis of z . The velocity of sound in the surrounding fluid is c_0 . A schematic illustration of the coordinate systems is shown in Fig. 1.

The wave equation can be expressed in terms of a scalar velocity potential Φ_0 as

$$\nabla^2 \Phi_0 = \frac{1}{c_0^2} \frac{\partial^2 \Phi_0}{\partial t^2}, \quad (1)$$

where Φ_0 is the total velocity potential, which is the linear superposition of the incident wave velocity potential Φ_i , the scattered wave velocity potential Φ_s from the sphere and the reflected wave velocity potential Φ_c from the inner wall of the cylinder.

In the spherical coordinate system, the incident wave velocity potential and the outgoing scattered velocity potential are represented as

$$\Phi_i(r, \theta) = \phi_0 e^{-i\omega t} e^{ikz} = \phi_0 e^{-i\omega t} \sum_{n=0}^{\infty} (2n+1) i^n j_n(kr) P_n(\cos \theta), \text{ and} \quad (2)$$

$$\Phi_s(r, \theta) = \phi_0 e^{-i\omega t} \sum_{n=0}^{\infty} A_n h_n^{(1)}(kr) P_n(\cos \theta), \quad (3)$$

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