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Acoustic manipulation of oscillating spherical bodies: Emergence of axial negative acoustic radiation force

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ABSTRACT

In this paper, emergence of negative axial acoustic radiation force on a rigid oscillating spherical body is investigated for acoustic manipulation purposes. The problem of plane acoustic wave scattering from an oscillating spherical body submerged in an ideal acoustic fluid medium is solved. For the case of oscillating direction collinear with the wave propagation wave number vector (desired path), it has been shown that the acoustic radiation force, as a result of nonlinear acoustic wave interaction with bodies can be expressed as a linear function of incident wave field and the oscillation properties of the oscillator (i.e., amplitude and phase of oscillation). The negative (i.e., pulling effects) and positive (i.e., pushing effects) radiation force situations are divided in oscillation complex plane with a specific frequency-dependant straight line. This characteristic line defines the radiation force cancellation state. In order to investigate the stability of the mentioned manipulation strategy, the case of misaligned oscillation of sphere with the wave propagation direction is studied. The proposed methodology may suggest a novel concept of single-beam acoustic handling techniques based on smart carriers.

1. Introduction

The non-contact techniques for handling, trapping and levitation of mili- or micro-sized particles has many applications in modern effective medicine (e.g., drug delivery systems, contrast agents) and high-tech engineering issues (e.g., micro-gravity or low gravity particle handling), utilizing the remote navigators based on optics [1–6], electro-kinetics [7,8], or acoustics [9–27]. In the techniques based on acoustic waves, the so called acoustic radiation force (RF) which is the result of nonlinear features of wave-object interactions, plays the role of navigator. This force is consisted of two time-averaged parts: resultant momentum of the wave field exerted on the body and the non-uniform surrounding acoustic pressure acting on the outer surface of the body. The handling and levitation process of the object is achievable if only both pushing and pulling forces can be produced. In contrast to the plane acoustic wave interaction with bodies with canonical geometries which only leads to pushing forces, producing a considerable and stable negative radiation forces is complex. The suggested techniques to produce negative radiation force, are assisted by standing waves [19,21,22], focused acoustic beams such as Bessel beams [28–35] and cross-plane beams [25,36,37] instead of acoustic progressive plane wave, which may have many limitation according to the center frequency and bandwidth of transducers and the beam spatial pattern, etc. In other words, in these techniques which may be named the single-beam technique, the handling (i.e., transforming and trapping) process, as

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mentioned, is performed using only one highly focused ultrasonic transducer in which the handling (i.e., pushing and pulling effects) is possible at certain range of frequencies and particular beam spatial distribution with respect to particle geometrical/bulk properties (e.g., the Bessel beams of zero- and high-order (helocoidal) [28,30,31,33–35,38–43], Gaussian beam [28]). However, the generated negative radiation forces by utilizing the mentioned techniques have small values in comparison with the values of positive forces [33,34,44].

The great application of predictable and robust single-beam acoustic manipulation process motivated us to examine the non-intuitive idea of utilizing active oscillating carriers. The mathematical model of interaction between plane progressive acoustic beams and the dipole oscillating spherical body is constructed with the hope of possibility of generating reversed radiation force, considering this not-promising fact that illumination of a rigid spherical body by a simple progressive plane wave field only leads to always pushing effects.

The formulations presented in this paper are derived for the general case of general planar incident wave (i.e., the direction of incident wave propagation is not collinear with the oscillation axis of the spherical body); however, the main body of the numerical results are focused on the special case of interest, axial radiation force, where the incident wave propagation direction is considered to be aligned with the oscillation axis. It has been shown that the axial radiation force on the spherical body may be controlled by amplitude and phase of oscillation in order to push or pull the body, along the wave propagation direction (i.e., desired path).

In the case of possible small deviation between the wave propagation direction and the oscillation axis, it has been shown that a frequency dependent torque is exerted upon the spherical body, perpendicular to the interaction plane (i.e., the plane consists of the wave propagation direction vector and the oscillation axis) which may result in the variation of the oscillation axis of the body. It has been disclosed that the direction of the oscillation may become aligned with the desired direction of incident wave. Therefore, the planar acoustic manipulability is achievable.

2. Formulation

Fig. 1 depicts the configuration of problem including an oscillating spherical body located in the path of an arbitrarily oriented plane progressive ultrasonic beams. The propagation medium is an ideal acoustic fluid medium. The radius of radiator is denoted by a. The coordinate system is set at the center of the sphere so that the incident plane wave propagates in the xz-plane. The angle between the oscillation axis of the sphere (i.e., z-axis) and the incident wave propagation direction is denoted by α.

The formulations treat the acoustic radiation force on the solid sphere with the following assumptions:

- The fluid is ideal and nonviscous.
- The wave propagation is lossless.
- The solid sphere is assumed to be rigid (i.e., its stiffness with respect to the bulk module of the surrounding fluid medium is high).
- The amplitude of oscillation of the spherical body is considered to be too small to prevent possible cavitations so that the continuity conditions between the fluid and the solid body remain valid.
- The induced velocity of the spherical body (i.e., translational motion of the body) due to the exerted radiation force is in accordance with the assumptions of Refs. [45,46] for representing acoustic radiation pressure on the boundary moving at a small velocity (e.g. at the beginning of the accelerating).
- The under control parameters in the handling strategy are assumed to be the displacement characteristics (i.e., amplitude and phase) of spherical body's oscillation and the direction of incident wave field.

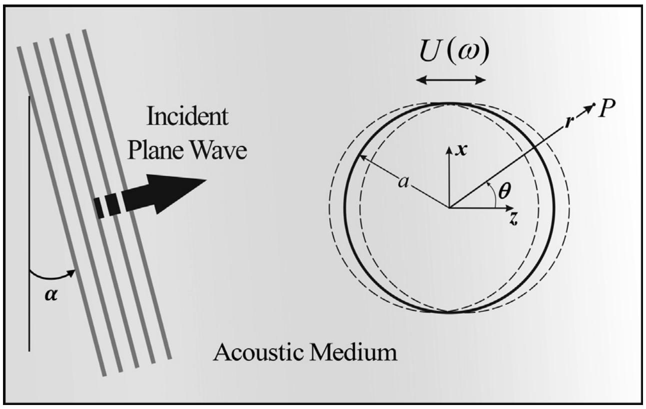

Fig. 1. Configuration of problem.