Journal of Sound and Vibration 429 (2018) 34–44

Contents lists available at ScienceDirect

Journal of Sound and Vibration

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

Acoustic active two body clusters

Majid Rajabi [a, *], Alireza Mojahed [b]

[a] *Sustainable Manufacturing Systems Research Laboratory, School of Mechanical Engineering, Iran University of Science and Technology, Narmak, Tehran, Iran*
[b] *Linear and Nonlinear Dynamics and Vibrations Laboratory, Department of Mechanical Science and Engineering, University of Illinois at Urbana-Champaign, Urbana, IL 61801-2307, USA*

ARTICLE INFO

Article history:
Received 26 October 2017
Received in revised form 18 April 2018
Accepted 7 May 2018

Handling Editor: Y. Auregan

Keywords:
Active stable cluster
Multi-body carriers
Acoustic radiation force
Drug or material delivery systems

ABSTRACT

Inspired from the stable bubble clustering phenomenon known as bubble grapes, and following the capabilities of recent novel concept of active carriers subjected to stimulating wave fields, we aim to propose the theory of noncontact clusters composed of harmonically activated spherical objects as the carriers. As the first step, the simplest case of two body cluster is considered which the sustaining field is due to self monopole (breathing mode) radiation of spherical components. The acoustic radiation forces on the bodies are analytically derived and it is shown that these interaction forces may have the nature of repulsive or attractive for each specific configuration (size), depending on the radiation characteristics (e.g., frequency and phase difference) and fluidic environment properties. In the rest states which the zero radiation force is exerted upon both bodies, the stability or instability of the cluster is examined. For the stable configurations, the frequency of oscillation of cluster is estimated $O(10^{-3})$ of the frequency of operation. The instability situations may lead to two cases of dispersion (expansion) or bunching (contraction) of cluster's components. Due to existence of stable spatial configurations between each two successive unstable rest states, it is predicted that any deviation from the stable or unstable rest points, may guide the cluster to sustaining its stable rest state or migration toward another (probably closest) stable configuration. The proposed research will develop the advanced therapeutic agents, drug and material delivery systems and introduces a new configuration in active multi-body carrier design or remotely stable multi-body mechanism.

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1. Introduction

The acoustic radiation force as one of the features of nonlinear acoustics due to interaction between suspended objects and sound fields in both forms of progressive or standing waves, in host medium, has attracted many attentions because of its remarkable amplitude in comparison with its electromagnetic counterpart and steady effect which may be utilized as: the driver of mili-, micro- and molecular-sized objects in material or drug delivery systems [1–6], low gravity acoustic levitation [7,8], bubble dynamics in low gravity [9], acoustic coagulation of aerosols [10,11], cell and particle handling and trapping systems [12–16], calibration systems [17], acoustic cavitations and sonoluminescence phenomena [18–20].

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* Corresponding author.
E-mail addresses: majid_rajabi@iust.ac.ir (M. Rajabi), mojahed2@illinois.edu (A. Mojahed).

https://doi.org/10.1016/j.jsv.2018.05.012
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In a small amplitude wave propagation phenomenon, all the physical quantities show a simple harmonic oscillatory behavior and their time-averaged (steady effect) vanishes (i.e., for a time-periodic function f, $<\partial f/\partial t> = 0$). Nevertheless, the acoustic radiation force effects in both primary (i.e., the force exerted on objects due to primarily direct insonification by acoustic wave field) and secondary types (i.e., the force exerted due to the presence of other objects and corresponding scattering fields interactions) emerge, because of the existence of higher order terms in field quantities. (e.g., for an adiabatic acoustic disturbance, the state equation between pressure and density variations, $\delta p = p - p_0, \delta\rho = \rho - \rho_0$, takes the form of $\delta p = \rho_0 c_0^2(\delta\rho/\rho_0) + (1/2!)(\Psi - 1)(\delta\rho/\rho_0)^2 + \mathrm{H.O.T.},$ where p_0, ρ_0 are the ambient pressure and density at rest, $c_0 = (\partial p/\partial\rho)_s^{1/2}$ is the constant entropy wave velocity, Ψ is the ratio of heat constants in an ideal gas host medium or a constant number between 3 and 10 for liquids). This force is responsible for accumulation of gas bubbles, liquid drops and airborne dust at pressure node or anti-node of a standing wave field [21–25], acoustic levitation phenomenon in micro-gravity or normal gravity containerless engineering or medical applications [26], the oscillating deformation of small sized liquid drops (para-zylene) [27], the mutual interaction forces between acoustically excited bubbles known as *Bjerknes* forces [28] and the interaction forces between rigid spheres in fluid flows subjected to acoustic incident wave field, named *Konig* forces, evaluated for the limiting cases of long wavelength to radii and particle-particle spacing ratios, which cause them to attract or repel one another [29], etc. Considering the interesting case of acoustic inter-particle radiation force, some pioneer works may be found in the literature in the past few decades. The mutual interaction force between two spherical object insonified by an acoustic progressive wave field has been studied by Embleton [30]. The acoustic interaction force between air bubbles in externally provided stationary sound field has been studied by Zavtrak [31] and Pelekasis and Tsamopoulos [32]. For biological and medicine applications, Haar and Wyard [33] have illustrated the blood cell banding in ultrasonic standing wave field. They considered the blood cells as non-deformable objects. The acoustic interaction force between blood cells in a quasi-static balanced situation due to the existence of incident wave field has been investigated both theoretically and experimentally by Weiser et al., [34]. In another research done by Zheng and Apfel [35], the acoustic interaction force between two fluid spherical objects positioned in the path of a plane progressive and a standing harmonic acoustic wave field due to the primary and secondary scattering phenomena were derived for the limiting case of small size to wavelength ratio of test fluidic particle. For the limiting case of small size to wavelength ratio of two separate bubbles, it is shown that the results are in agreement with *Bjerknes* force evaluation.

In typical delivery systems, the manipulation or stabilization of carrier at target zones or its passage through fluidic biological environment needs an external driver such as electro-kinetic [36,37], optical [38–41] or acoustical field [1–3,42–51]. The acoustical methods by development of complex tweezers take a distinct place in this area due to their nondestructive nature, in depth penetration and lower side effect.

Just recently, the novel concept of active carriers is introduced as an alternative for complex tweezes which will advance the classical methodologies by upgrading the handling capabilities of single carriers [52–55]. With special focus on the pharmaceutical and biological applications or high-tech industrial material carrying systems in which the small-size passageways such as vessel or micro- or nano-size corridors exist, the risk of blockage should be considered. In the cases that the size of carriers do not be chosen properly or in multi-carrier delivery systems, the occurrence of the coagulation, collision or dispersion is probable.

In the present research, we aim to propose the concept of acoustic driven two body clusters as the first step for developing the multi-body carriers systems. In this proposition, the smaller carriers will perform the task of a larger scale single carrier while hold their stable configuration, keep their union and sustain their cluster migration. This acoustically stable cluster, keep its flexibility of configuration through the relocation of its elements and self-organize structure due to acoustic radiation. It is important to note that in the present work, there is no incident wave field as an external driver and the acoustic field is only due to the monopole (breathing) radiation of objects.

2. Formulation

The model consists of two identical ideal monopole radiators with radii of a, placed at distance d from each other. The problem configuration and the spherical coordinate systems, (r_1, θ_1) and (r_2, θ_2), are depicted in Fig. 1. Surface velocities of radiators are $v_1 = Ve^{i(-\omega t+\gamma_1)}$ and $v_2 = Ve^{i(-\omega t+\gamma_2)}$, respectively, in which V is the amplitude, ω is the frequency of vibrations and $\gamma_j, j = 1, 2$ are their corresponding phases. It should be noted that the azimuthal coordinate is omitted due to axisymmetry.

The formulation is developed based on the below assumptions:

- The fluid host medium is considered to be non-viscous and non-heat conducting [56].
- The wave propagation phenomenon is assumed to be adiabatic [56].
- The acoustic streaming is ignored.
- The bodies are assumed non-deformable except their monopole mode of radiation. This means that the resonant behavior of spheres and their contribution in scattered acoustic field are ignored. Note that the spheres are being excited in their monopole mode.
- The cluster is in neutrally buoyant condition.
- The surface tension effects are ignored due to full submerged state of carriers and the assumption of ideal fluid.

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