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Self-motile swimmers: Ultrasound driven spherical model

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ABSTRACT

The concept of ultrasound acoustic driven self–motile swimmers which is the source of autonomous propulsion is the acoustic field generated by the swimmer due to the partial oscillation of its surface is investigated. Limiting the subject to a body with simple spherical geometry, it is analytically shown that the generated acoustic radiation force due to induction by asymmetric acoustic field in host medium is non-zero, which propels the device. Assuming low Reynolds number condition, the frequency-dependent swimming velocity is calculated as a function of design parameters and optimum operating condition is obtained. The proposed methodology will open a new path towards the micro- or molecular-sized self propulsive machines or mechanism with great applications in engineering, medicine and biology.

1. Introduction

In the future maker race toward biomimetic technology, with advanced applications in engineering, medicine, microfluidics and biotechnology, micro- and molecular-sized robots and mechanism with the ability to swim at low Reynolds number condition (i.e., the small ratio of the inertial forces to the viscous forces in the Hydro-dynamical governing equations of the fluid flow) have attracted the attention of researchers who work with living matters, micro-biological systems and micro-swimmers and robotic design.

Considering the low Reynolds number hydrodynamics (i.e., assuming typical scales of $v \sim O(10^0) - O(10^1)\,\mu\text{m/s}$ for swimming velocity, $\rho \sim O(10^3)\,\text{kg/m}^3$ for fluid mass density, $\eta \sim O(10^{-4})\,\text{Pa s}$ for fluid viscosity and $l \sim O(10^0) - O(10^2)\,\mu\text{m}$ for length scales, leads to $Re = \rho v l/\eta \sim O(10^{-5}) - O(10^{-2})$ for Reynolds number) of living and operating conditions in micron-size scales corresponding to microorganism, living matters and swimming micro- robotics and mechanisms, in which the host medium viscosity effects are dominant, it was believed that any harmonic (reversible) motion may not yield to net motion and swimming, due to this simple fact that any local motion generated in desired direction would be cancelled out at the end of the oscillation period, primarily because the inertia effects are negligible [1]. Therefore, swimmers with non-reciprocal periodic motion have been suggested to tackle the time reversal symmetry such as Purcell swimmer [2,3], three linked spheres swimmer proposed by Golestanian [4] and magnetic colloidal particles attached by DNA-linker which is controllable by an external oscillatory magnetic field [5], etc. The last idea has been promoted to a more versatile and fully controllable mechanism of DNA-linked anisotropic colloidal rotor composed of paramagnetic colloidal particles with different or similar size [6]. Broadening the subject, the self-motile particles have been considered as the active driver of solids [7].

In addition to the mentioned methodologies, stirred from the colloidal particles, many models for molecular machines or artificial swimmers have been examined utilizing the surface phoretic effects (i.e., special surface activities which provides the required driving force by induction of asymmetric body interactive fields due to gradients of for example: concentration of a dissolved species, electric potential, temperature, etc) with different scenarios such as electrophoresis, electro-osmosis, diffusiophoresis which may lead to active and passive self-propulsive steering mechanisms [8–15]. Moreover, some natural phenomenon such as natural convection is devised to propel the immersed objects [16].

Inspired from the bio-locomotion of micro-organisms, the so-called squirmer model has been developed and investigated as a self-motile mechanism driven due to the wavelike deformation of the outer surface of the body [17–20]. Moreover, the exerted force and resulting net speed of propulsion of spherical passive elastic objects due to presence of steady streaming has been thoroughly studied in [20].

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As another strategy, the chemically fueled systems have been considered as self-propulsive mechanisms based on the asymmetric distribution of reaction products which play the role of driving system [9–11,13,21–25].

In the present work, we aim to propose a simple and versatile configuration for a self-motile swimmer which its propulsion is due to a self-generated asymmetric monochromatic acoustic field. The configuration is confined to a simple, but practical and desired spherical geometry. The source of the field is assumed to be the partial breathing mode oscillations of the body's surface and no external wave field exists other than the field generated by the sphere itself to exert radiation force on the body. The acoustic radiation force exerted on the body due to self-generated field is analytically calculated and its frequency dependent non-zero value is confirmed. Verifying the low Reynolds number condition, the swimming velocity of the object as a function of the surface oscillation velocity amplitude, dimensionless frequency (or wavelength) and the portion of internally activated surface of the body is calculated. The consumption power is derived and the discussions on the feasibility of the proposed mechanism and simplification are given.

2. Formulation

Fig. 1a depicts the schematic of the self-motile swimmer with radiating cap. Fig. 1b shows the geometry of problem including an ideal sphere of radius a with a partially radiating cap in the range of $0 \leqslant \theta \leqslant \theta_0$, $0 \leqslant \phi \leqslant 2\pi$ where θ and ϕ correspond to polar and azimuthal coordinate respectively, suspended freely in an ideal fluid medium. The cap radiates radially with the velocity amplitude V. Cartesian coordinates (x,y) and the corresponding spherical coordinates (r,θ) are placed at the center of the sphere. Note that the azimuthal coordinate, ϕ, is omitted due to axisymmetry. It is important to note that all the formulation are developed considering the reasonable assumption that the thermal and viscous boundary layers are negligible regarding the length scales of the swimming object. Note that all the heat transfer effects are neglected in the fluid equations of motion and the wave propagation phenomenon is considered to be adiabatic. Ignoring acoustic streaming, the governing Navier-Stokes equations are reduced to Euler equations for the host medium. In addition, the amplitude of induced pressure field is small enough that the body keeps its rest shape and the boundary conditions holds its simple forms.

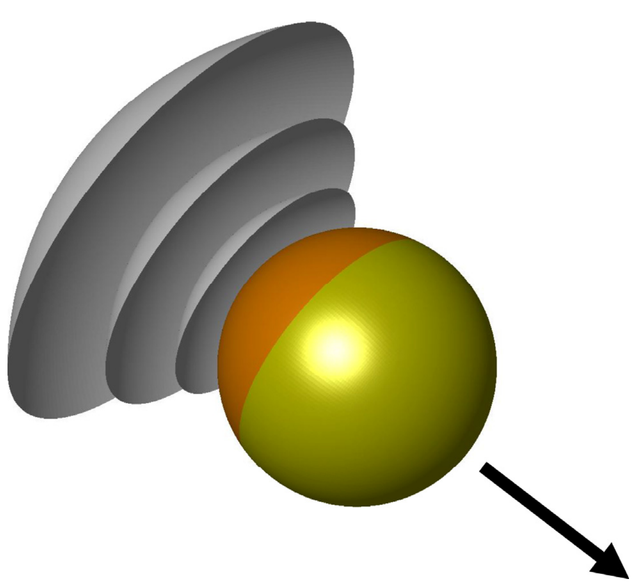

Fig. 1a. Schematic of the problem.

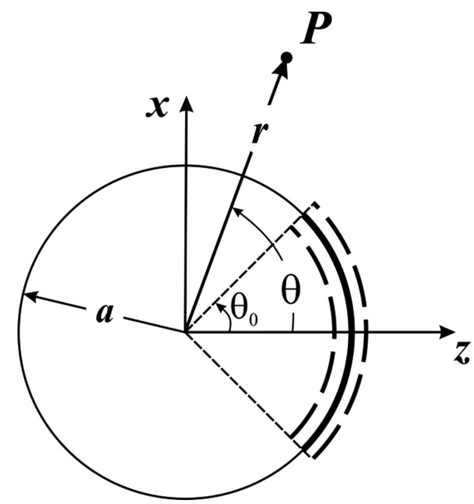

Fig. 1b. Configuration of the problem.

3. Acoustic field equations

Following the standard methods of linear theoretical acoustics, the so-called *Helmholtz* equation can be derived via utilizing Euler and continuity equations with the assumption of irrotational wave propagation. (See [26] for details on derivation of *Helmholtz* equations).

Considering the monochromatic nature of the wave fields, oscillating with the frequency of ω, the so-called Helmholtz equation is represented as

$$(\nabla^2 + k^2)\varphi = 0, \tag{1}$$

where $k = \omega/c$ is the wave number for the dilatational wave and c is the speed of sound in the fluid medium. The solution of the above equation according to the boundary conditions of the system leads to evaluation of the velocity vector field by $\mathbf{v} = -\nabla\varphi(\mathbf{r})$, where $\varphi(\mathbf{r})$ denotes the velocity potential field and the acoustic pressure can be calculated via $p(r,\theta,\omega) = \rho\partial\varphi(\mathbf{r})/\partial t$ in which ρ is the density of the fluid medium. Note that for simplicity, the factor $e^{-i\omega t}$ is omitted throughout the manuscript.

Keeping in mind the Sommerfeld radiation condition, as a solution for Eq. (1), the velocity potential of the radiated acoustic field, $\varphi(\mathbf{r})$, from any axisymmetric object with symmetry axis of z, can be written as [27]

$$\varphi_{rad.} = \sum_{n=0}^{\infty} A_n(\omega) h_n(kr) P_n(\cos\theta), \tag{2}$$

where $A_n(\omega)$ are unknown modal radiation coefficients to be determined by applying appropriate boundary conditions, $h_n(.) = j_n(.) + iy_n(.)$ denotes spherical Hankel function of first kind and order n where $j_n(.)$ and $y_n(.)$ are spherical Bessel functions of first and second kind and order n, respectively, and $P_n(.)$ represents Legendre polynomials of order n.

The corresponding velocity field in the medium due to radiation can be represented as

$$v_{rad.} = -\frac{\partial\varphi_{rad.}}{\partial r} = -k\sum_{n=0}^{\infty} A_n(\omega) h'_n(kr) P_n(\cos\theta), \tag{3}$$

where prime denotes derivative with respect to the argument.