Multidimensional Self-Propelled Motion Based on Nonlinear Science

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Self-propelled objects, which exhibit characteristic features of motion, are proposed based on nonlinear science. At first, a self-propelled object with length like undulatory swimming is designed, i.e., the phase of oscillation at several points on the object is propagated in the opposite direction of motion. Second, the vertical oscillation of a camphor disk is created at an amphiphilic molecular layer developed on water. The proposed systems suggest that nonlinearity can enhance the autonomy of self-propelled objects as multidimensional motion.

Keywords: nonlinear, oscillation, self-propelled object, camphor, nonequilibrium, autonomy

INTRODUCTION

Several types of inanimate self-propelled objects such as nano wires and Janus particles have been developed for environmental, industrial, and medical applications [1–4]. In general, self-propelled objects exhibit random motion or unidirectional motion which is determined by their shape or the external force [1–7]. On the other hand, animate self-propelled objects such as bacteria exhibit characteristic features of motion depending on the information of the environment. These facts suggest that the autonomy of animate self-propelled objects is significantly higher than that of the inanimate ones [5–7].

We introduced nonlinear science into systems to enhance their autonomy, and as a result, characteristic nonlinear phenomena such as oscillation, bifurcation, synchronization, hysteresis, and pattern formation could be reproduced experimentally [5–7]. Several types of self-propelled objects, which exhibit characteristic features of motion from the viewpoint of nonlinear science, have been reported [5–18]. Among them, the objects composed of camphor or camphor derivatives, of which the driving force is the difference in surface tension, have been investigated as a simple experimental system [5, 6, 23, 27]. The period of oscillatory motion and bifurcation between continuous and oscillatory motion was observed coupled with chemical reactions [5–8, 36, 37]. When two or more camphor disks or boats were placed in the same circular water channel, synchronized swimming or collective motion was observed [5–7]. Motion with memory, i.e., future motion expected by previous motion, could be realized by using a camphor disk and plastic plate [22, 28, 35]. Recently, the catch and release type of chemotaxis was realized using 6-methylcoumarin as a self-propelled object and sodium phosphate as a chemical stimulus [38]. These characteristic features of motion could be qualitatively reproduced by numerical calculations based on reaction–diffusion equations and the equation of motion [5–7, 28, 31–35, 39].
In this article, we propose novel self-propelled objects which exhibit multidimensional motion at the air–water interface under nonequilibrium: one is a self-propelled object with length like undulatory swimming and the other exhibits vertical oscillation of a camphor disk on an amphiphilic molecular layer developed on water. The proposed systems suggest that nonlinearity can further enhance the autonomy of self-propelled objects.

**SELF-PROPELLED FILAMENT LIKE UNDULATORY SWIMMING**

In this section, we introduce a self-propelled filament placed on water. The filament is produced from a commercial adhesive (consisting mainly of nitrocellulose and acetone), and the energy source is acetone and the driving force of motion is the difference in the surface tension around the filament since acetone reduces the surface tension. As the shape of the filament is deformed and oscillated periodically, information of wave propagation along the filament is added as characteristic features of motion in addition to information of mass movement [40]. When one of the end points of the single filament is fixed on the edge of the chamber, periodic pendulum motion is produced and the phase of the filament near the fixed edge progresses faster in comparison with the phase of the free edge for the pendulum motion. When two filaments are coupled together, in-phase and out-of-phase synchronizations are produced depending on the distance between them and the initial floating state.

We propose a self-propelled filament of which one of the end points is adhered to the free plastic film with V-shape to introduce heterogeneity. Figure 1 shows (a) snapshots of the filament and (b) outline of points a, b, c, and d on the filament. The filament moves in the direction of the plastic film while oscillating except for point a, i.e., the head of the filament. The phase of oscillation was propagated from b to d, i.e., in the opposite direction of the motion. The propagation of the phase oscillation in the animate undulatory swimming is the same as the direction of motion. Thus, the direction of the phase propagation of our inanimate meandering filament is opposite to the animate undulatory swimming like “moon walk” by MJ. The opposite direction of phase propagation suggests that our inanimate filament is passive on the motion since the Marangoni flow occurs in the opposite direction of motion. The shape and size of the head of the filament should be improved to make the direction of the phase propagation the same as animate undulatory swimming.

**VERTICAL OSCILLATORY MOTION OF A CAMPHOR DISK PLACED ON AN AMPHIPHILIC MOLECULAR LAYER DEVELOPED AT THE AIR–WATER INTERFACE**

In this chapter, we introduce vertical oscillatory motion of a camphor disk placed on an amphiphilic molecular layer developed at the air–water interface. Here, nervonic acid is used as an amphiphilic substance [24]. The surface pressure \(\Pi\) vs. area isotherm exhibits a transition point corresponding to a phase transition between the fluid and fluid/condensed phases of nervonic acid. The characteristic features of motion, i.e., no motion, oscillatory motion, and continuous motion, are determined by not only the value of the surface pressure but also the nature of the phase in the nervonic acid molecular layer. These results suggest that the characteristic features of motion can be designed based on the chemical structure of an amphiphilic molecule.

We propose vertical oscillation of a camphor disk (diameter: 3 mm, thickness: 1 mm) placed at the air–water interface. Here, nervonic acid which is developed on water is in the fluid/condensed phase. Figure 2 shows (a1) snapshots of one cycle of vertical oscillation and (a2) time-variation of the lateral location of a camphor disk. The camphor disk exhibited not only lateral oscillation but also vertical oscillation even at the air–water interface. The vertical oscillation may be generated by the following mechanism. As the surface pressure of the nervonic acid molecular layer (\(\Pi_{na} \sim 8 \text{ mN m}^{-1}\) at 293 K and 40 Å molecule\(^{-1}\)) is similar to that of the camphor (\(\Pi_c\), the saturated value of \(\Pi_c \sim 17 \text{ mN m}^{-1}\)), repetition between the resting and motion states is possible since no motion at \(\Pi_{na} \geq \Pi_c\) and motion at \(\Pi_{na} \leq \Pi_c\) occur. The periodicity and...
nonlinearity of the oscillation were observed as the fundamental frequency (~0.3 Hz) and the higher harmonics in the linear spectrum of the fast Fourier transformation (FFT) for Figure 2A2, respectively (see Figure 2A3). Vertical oscillation may occur due to the repetition of fluid and fluid/condensed phases since the development and sublimation of the camphor molecules at the air–water interface induces the phase transition from the fluid/condensed to the fluid phase and vice versa, respectively. No oscillation was observed at 298 K and 40 Å molecule⁻¹, i.e., the fluid phase, as shown in Figure 2B. The change in the surface pressure around the disk induces the change in the meniscus at the camphor solid/water interface including nervonic acid, and as a result, the vertical oscillation occurs.

CONCLUSION AND OUTLOOK

In this article, we proposed novel types of self-propelled objects which exhibit multidimensional motion from the viewpoint of nonlinear science. Further multidimensional motion, such as translation including rotation like drill and pattern formation coupled with motion like collective motion, will be created in the near future by enhancing autonomy.

DATA AVAILABILITY STATEMENT

The data that support the findings of this study are available from the corresponding author, SN, upon reasonable request.

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SUPPLEMENTARY MATERIAL

The Supplementary Material for this article can be found online at: https://www.frontiersin.org/articles/10.3389/fphy.2022.854892/full#supplementary-material
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