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Mode selection of a camphor boat in a dual-circle canal

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Abstract

The mode selection of a camphor boat was investigated. When a camphor boat, confined in a container with a shape of number 8, was floated on the surface of water, one of the three modes of motion (rotation within one cell, outer rotation without passing through the intersection of the two cells, and 8-shaped rotation) was maintained for several tens of cycles. This mode selection depended on the conditions of camphor scrapings attached to the boat. When two camphor boats were floated on the water, a synchronized motion between them was observed. The present system suggests a chemo-mechanical transducer, where the vectorial process is sensitive to the shape of the cell and the surface concentration of the camphor molecule under isothermal conditions. © 2000 Elsevier Science B.V. All rights reserved.

1. Introduction

Autonomous motors, driven by the dissipation of chemical energy under isothermal and heterogeneous conditions, have been studied experimentally and theoretically to understand biological and molecular motors and to create an artificial chemo-mechanical transducer [1,2]. The spontaneous motion of a liquid droplet on a solid surface or a solid grain on a liquid surface has been studied extensively [3–9]. Such a spontaneous motion is generated as a result of the Marangoni flow, which is induced by the effect of a chemical or thermal gradient on the droplet or the solid [3–12]. The direction of this motion and its velocity depend on the concentration gradient of the surface active substance on the solid surface in contact with the droplet or at the air/water interface around the solid.

The spontaneous motion of camphor at an air/water interface is driven by the concentration gradient of camphor as it diffuses [13–20]. We have previously reported that this system can produce various types of motion, such as clockwise rotation, counterclockwise rotation, uni-directional translation, and alternate mode-switching between revolution and translation, depending on the shape of the camphor scraping [15,16]. In addition, the motions of camphor and its derivative scrapings change characteristically depending on the outer environment; for instance, a camphoric acid scraping sometimes exhibits a motion with a uniform velocity, or an intermittent motion, or no motion depending on the pH of the aqueous phase [17,18]. We believe that these spontaneous phenomena, which exhibit mode-switching, play an important role in creation of a chemo-mecha-

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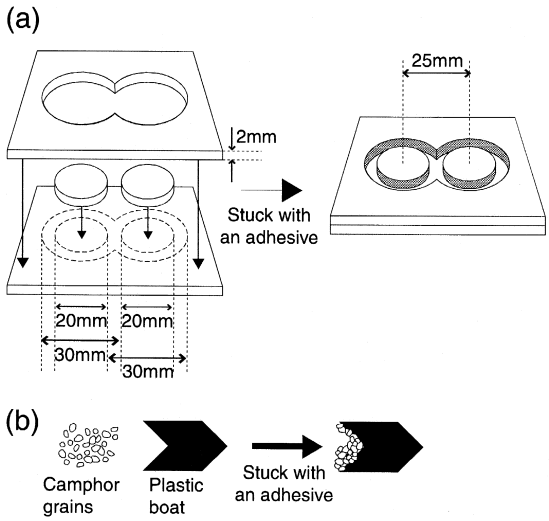

Fig. 1. The present experimental system. Designs of (a) a figure-eight-shaped water route, including one plate, two disks, and one frame are stuck together, and (b) a camphor boat; the shape of the boat was drawn using a computer software and printed on a polyester sheet with a laser printer.

nical transducer with mode-switching, which mimics a bacterial motion, such as that of a flagellum motor [21,22].

The present Letter reports that a camphor boat exhibits one of three modes of self-motion in a water route. Such mode selection is discussed in relation to the sticking state of camphor grains to the boat and the shape of the water route; an especially notable phenomenon is the synchronized self-motion observed between two camphor boats floated on the water route.

2. Experimental section

(+)-Camphor was obtained from Wako Chemicals (Kyoto, Japan). Teflon plates including one plate, two disks, and one frame, were stuck to one another to make a container with a shape of number 8 (Fig. 1a). A plastic boat was made by cutting a polyester film (thickness: 0.1 mm) into an appropriate shape, and small camphor grains (a typical mass: 2 mg) were stuck on the back of the boat with an adhesive, as seen in Fig. 1b. The container was filled with about 2 ml of water (pH: 6.3), which had been distilled and purified with a Millipore Mill-Q filtering system. When the camphor boat was floated on the water, it exhibited self-motion. The movement of the boat was monitored with a digital video camera (SONY DCR-VX700) and recorded on a videotape. The two-dimensional positions of the boats were measured using a digitizer with a minimum time resolution of 1/30 s.

3. Results and discussion

Fig. 2 shows three modes of motion at the boat observed in the present system. Each mode was maintained for at least several tens of cycles. The velocities of modes (A) and (C) stayed nearly constant. In mode (B), the velocity in the vicinity of the intersection was higher than those in the right and left cells. The mean velocity of (A) was the slowest among the three modes.

Fig. 3 shows a schematic diagram to examine the mechanism of this mode selection. The self-motion of the boat may be induced by the following mechanisms (1)–(4) [15]: (1) The camphor scraping dissolves into the air–water interface on the water route as a camphor molecular layer. (2) A gradient in the surface tension is induced, due to the spatial hetero-

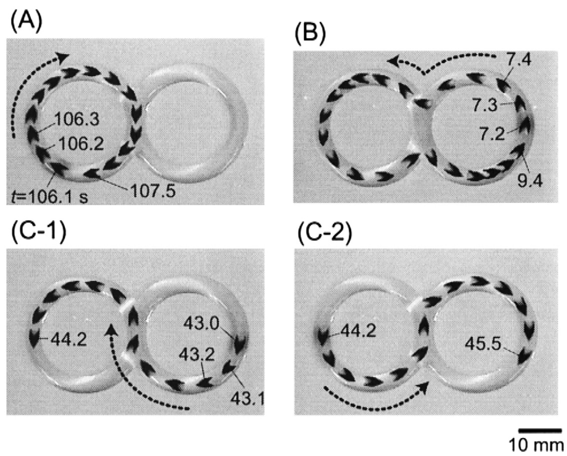

Fig. 2. A time trace (in units of s) of the self-motion of a camphor boat with a time interval of 0.1 s (top view). Three modes of self-motion were observed: (A) rotation within one circle, (B) outer rotation without passing through the intersection of the two circles, and (C) figure-eight rotation between the two cells. The arrow in each figure represents the direction of the self-motion.

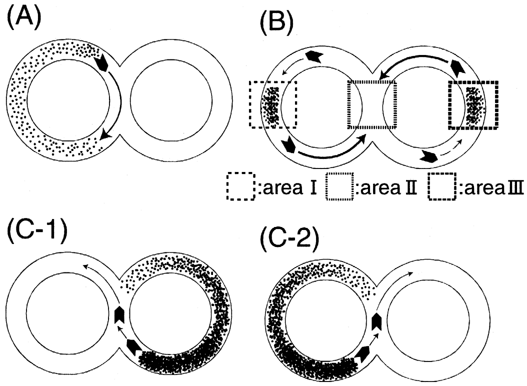

Fig. 3. A schematic diagram to discuss the mechanism of mode selection of the camphor boat (top view). Symbols (A)–(C) correspond to those in Fig. 2.

geneity in the surface concentration of the camphor layer, between the front (without) and back (with the camphor scraping) of the boat. (3) The boat is accelerated by the spatial gradient of the surface tension around the boat. (4) Since the camphor molecular layer can easily be sublimed to the bulk air phase, the spatial gradient of the camphor layer around the boat (the driving force) is maintained, i.e., the self-motion is maintained for about 5 min and the velocity is nearly constant.

In mode (A), the camphor boat continues to rotate within a cell without moving to another cell. The vector of the motion of the boat is somewhat oriented toward the inside of the circle (Fig. 2A), because more camphor grains are attached to the outside of the back of the boat than to its inside. However, the boat moves without touching the edge of the inner circle. The constant velocity of this self-motion indicates that the spatial gradient of the concentration of layer around the camphor scraping remains almost constant at the air–water interface in one circle; i.e., a constant driving force is maintained.

In mode (B), the boat rotates around the perimeter of the two cells without passing through their intersection, because the vector of the self-motion of the boat is oriented somewhat to the outside of each circle (Fig. 2B). More camphor grains are attached to the inside of the back of the boat than to the outside. The velocity around the intersection (area II) was higher than those in the right and left sides of the cells (areas I and III). Such a variable velocity suggests that the surface concentration of the camphor layer in area II is lower than those in areas I and III, since the surface concentration of the camphor layer may not decrease rapidly due to the smaller surface area, such as in areas I and III. On the other hand, the surface concentration of the camphor layer in area II may decrease more rapidly than those in areas I and III because the boat does not pass through the intersection of the greater surface area II. Thus, the velocity of the boat is sensitive to the concentration of the camphor layer remaining on the water surface.

In mode (C), the camphor scrapings are attached to the boat almost symmetrically, and therefore the boat moves nearly straight through the water route. When the boat reaches the intersection via the right cell, the simple probability of its subsequent route, right or left, is simply $1/2$. However, the surface concentration of the camphor layer in the right cell is higher than that in the left cell, because the boat has just passed through the right cell. Therefore, mode (C) is maintained, and the boat preserves its mode. Though it was possible to reproduce mode (C) by making a precisely symmetric camphor boat, modes (A) and (B) were more stable than mode (C), because it was much easier to make an asymmetric camphor boat.

The three modes were sometimes interchanged to one another, and the new mode was retained for several tens of cycles. Such mode-switching may be due to a change in the conditions of camphor grains on the boat.

From the dynamical point of view, the vector of the motion of the boat depends on the direction of tangent on the inner or outer cylinder because the vector is determined by the shape of the cylinder. In modes (A) and (B), the boat moves along the edge of the inner and outer circles, respectively. In mode (C), the symmetric boat dashes out of one inner circle along the tangent direction and may switch to move along the edge of another circle at the intersection if the velocity is relatively fast. However, this dynamical system cannot necessarily account for these experimental results, because the average velocity of the boat in mode (A) was generally the lowest of three modes and the velocity in the intersection was faster than those in other areas due to the concentration of the remaining camphor molecules on the water surface. In mode (C), the boat passed the center of the intersection.

Fig. 4 shows the synchronization of two camphor boats. Under these conditions, boats α and β exhibited clockwise and counterclockwise motions within their respective cells. Fig. 4a and b show the initial stages of their self-motions. Anti-phase synchronization of the two boats was observed 20 s after Fig. 4a, as shown in Fig. 4c–f and Fig. 5a, even though the shape and initial velocity of boat α were different from those of boat β. Indeed, anti-phase locking was confirmed by analyzing the phase difference between the two boats at $t = 20$–70 s, i.e., the phase difference of $(1.0 \pm 0.1)\pi$ rad was maintained. Fig. 5b shows the time-development of the velocities of these boats. The amplitudes of the velocities at mode-locking were greater than those at the initial stage (before mode-locking). The velocity of one boat decreased before another boat passed through the intersection, and it increased afterwards. These findings suggest that two camphor boats are sensitive to the camphor molecules remaining on the water surface. Thus, the synchronization of two camphor boats is developed with the spontaneous modulation of their relative velocities.

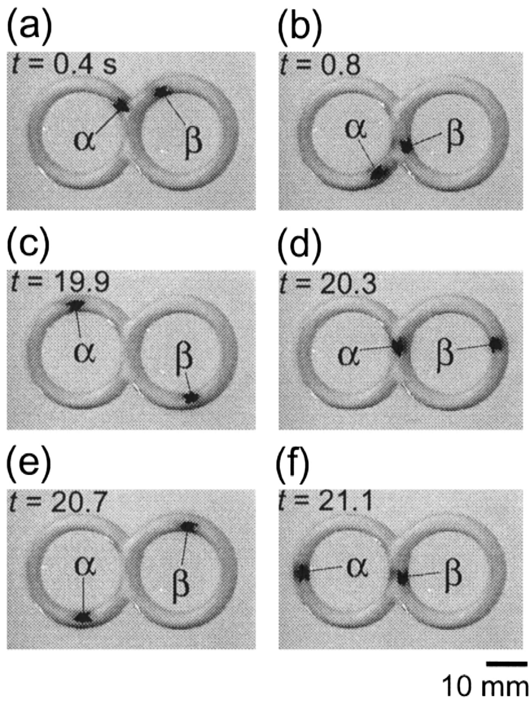

Fig. 4. Time traces (in units of s) of the anti-phase self-synchronization of two camphor boats α and β (top view). Symbols (a) and (b) are the initial stages of the self-motion of the boats. Anti-phase synchronizations between the two boats, (c)–(f), were observed 20 s after (a).

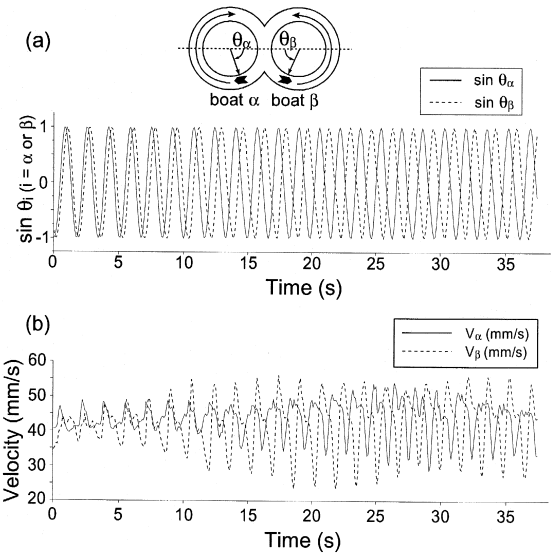

Fig. 5. Time traces of the trajectories of camphor boats α and β as sin θ_α and sin θ_β, where phases θ_α and θ_β are defined in (a). (b) A time trace of the velocities of the camphor boats. The velocities were obtained from $[(dx/dt)^2 + (dy/dt)^2]^{1/2}$, where x and y are the coordinates of the x- and y-axes of the water route (top view).

4. Concluding remarks

Mode selection in the self-motion of a camphor boat and the synchronization of two camphor boats have been observed. The present study has brought forth a number of problems to be solved in future studies: connection of two asymmetric circles, designing of different types of cells, and variation in the shapes and sizes of the boats or circles. The present study has observed oscillations of the boat at the intersection between the two circles when the shape of the boat is changed and translational motion with a small amplitude vibration in mode (C) at the intersection due to a rugged shape of the intersection. Thus it may also be meaningful to measure the direction of the boat changing its inertia at the intersection, the effect of the contact angle on the dynamical modes, and the distribution of concentrations of the camphor layer.

According to the Curie–Prigogine theorem, vector processes cannot couple with scalar variables, such as an ideal chemical reaction, in an isotropic system under a steady state [21–23]. This implies that a vectorial flow can be induced when the reaction field is ‘anisotropic’ [23–26], such as the present experimental system, and also as seen in the artificial and biological membranes with heterogeneity [27]. The results that we obtained so far have prompted us to consider the possibility of selecting a specific mode among various modes and regulating a spatial gradient in chemical potentials by suitably designing boundary conditions and designing fields for chemical reactions, in striking contrast to the conventional use of circular beakers or dishes.

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