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Synchronized motion of the water surfaces around two fixed camphor disks

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ABSTRACT

The synchronized motion of the water surfaces in contact with two fixed camphor disks was investigated. When the distance between the two camphor disks was greater than 8 mm, the shapes of the water surfaces at the bottoms of the disks oscillated independently. In contrast, synchronized oscillation was observed when the distance was shorter than 7 mm. Depending on the distance, the nature of the Marangoni convection and the difference in the shape of the meniscus changed. The convection was numerically simulated based on the Navier–Stokes equation. The mechanism of synchronization is discussed in relation to the rolling structure of the Marangoni convection.

1. Introduction

Synchronization, which is observed in coupled nonlinear oscillators, is one of the most interesting phenomena in nonlinear systems [1,2]. Synchronization is widely observed in living organisms, such as in the beating heart, circadian rhythm, and flashing of fireflies [3,4]. Many experimental and theoretical studies have been performed on the synchronization of physicochemical coupled oscillators. For example, as a coupled chemical oscillator, a synchronized chemical reaction on small beads [5] or in stirred containers [6] has been reported using the Belousov–Zhabotinsky reaction. The synchronization of electrochemical oscillations on electrode arrays has also been investigated [7–9]. In other systems, the coupling of salt-water oscillators [10,11] and candle oscillators [12] has been reported.

As a system that exhibits autonomous motion, the self-motion of a camphor fragment or a camphor boat driven by a difference in surface tension has been extensively studied [13–20]. The nature of this motion is affected by internal (shape and chemical structure of the fragment) [14,15] and external (shape and size of the chamber, and chemical species of the aqueous phase) factors [16–21] under nonequilibrium and anisotropic conditions. The essential features of this self-motion can be reproduced by a computer simulation based on an equation of motion that includes reaction–diffusion equations and surface tension. We have also shown that two camphor boats on a water chamber exhibit synchronized sailing, which is coupled with the surface tension of the camphor molecular layer [20,21].

We recently reported periodic oscillation of the shape of the water surface in contact with a fixed camphor disk and that of the force to fix the disk [22,23]. As an application of this system, in this report we describe the coupled oscillators composed of two camphor disks fixed on water. The oscillations of the shapes of the water surface were synchronized when the distance between the two camphor disks was short. The features of the Marangoni convection and the difference in the heights of the water levels on the two camphor disks were measured to clarify the mechanism of synchronization. A numerical simulation of convection was performed based on the Navier–Stokes equation. The mechanism of synchronization is discussed in relation to the rolling structure of the Marangoni convection [17,24,25].

2. Experimental

All chemicals were of analytical grade and used without further purification. Water was first distilled and then purified with a Millipore Milli-Q filtering system (pH of the obtained water: 6.3, resistance: >20 MΩ). A solid disk (diameter: 3 mm, thickness: 1 mm,

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mass: 7 mg) of camphor (Wako Pure Chemical Industries, Japan) was prepared using a pellet die set for FTIR. 240 ml of water was poured into a plastic dish (135 × 135 × 30 mm), and the depth of the aqueous phase was 13 mm.

Fig. 1a shows a schematic representation of the experimental setup. In this experiment, one end of a platinum wire (diameter: 0.5 mm, length: 30 mm) was attached to the center of the camphor disk. The bottoms of two disks were then placed in contact with water, and the disks was vertically lifted to $L_{cw} = 1.7 \pm 0.1$ mm, where L_{cw} is the difference in height between the bottom of the disk and the water surface before contact. The disks were adjusted to have almost the same heights. To observe convection in the water phase, visualization particles (DIAION, HP20S, relative density: 1.01, Mitsubishi Chemical Co. Ltd, Japan) were dispersed in the water phase. The experiments were performed at room temperature. Motion of the water surface was monitored with a digital video camera (DCR-DVD508, Sony, Japan, minimum time-resolution: 1/30 s) or a high-speed camera (SV642M, EPIX Inc., USA, minimum time-resolution: 5 ms), and then analyzed by an image-processing system (ImageJ, NIH, USA).

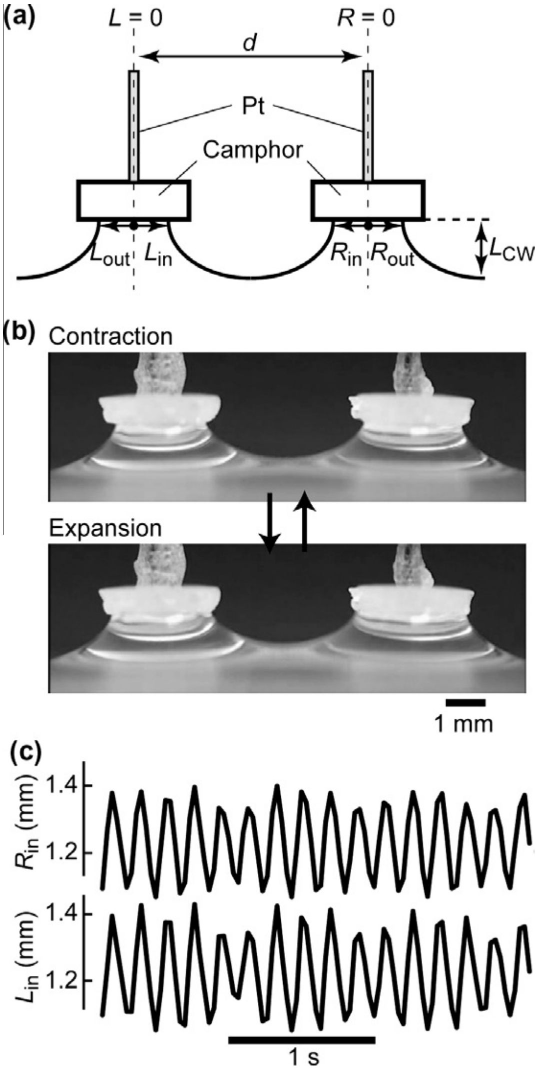

Fig. 1. (a) Experimental setup (side view) and definition of parameters (d, R_{in}, R_{out}, L_{in}, L_{out} and L_{CW}), (b) snapshots of the oscillation of the water surfaces in contact with two fixed camphor disks (side view), and (c) typical data for the time-variation of R_{in} and L_{in} at $d = 6.5$ mm.

3. Results

Fig. 1b shows typical snapshots of the synchronization of the water surfaces in contact with two fixed camphor disks at $d = 6.5$ mm. Oscillation of the shapes of the water surfaces around the two disks (period: 0.18 ± 0.03 s) was observed in synchronization, and this was maintained for 5 min. Fig. 1c shows a typical time series of the contact points L_{in} and R_{in}, which are defined in Fig. 1a. L_{in} and R_{in} oscillated synchronously in phase.

To evaluate the synchronization or non-synchronization of the contact points depending on d, L_{in} *vs.* R_{in} and L_{in} *vs.* L_{out} were plotted individually, as indicated in Fig. 2. When $d = 4.8$ mm (Fig. 2a) and 6.2 mm (Fig. 2b), L_{in}, R_{in}, and L_{out} oscillated synchronously (synchronization), although the correlation of L_{in} and L_{out} at $d = 4.8$ mm was weaker than that at $d = 6.2$ mm. In contrast, when $d = 9.2$ mm, the correlation of L_{in} and R_{in} is weak, and that of L_{in} and L_{out} is strong as indicated in Fig. 2c, which reflects that two oscillators did not interfere each other (non-synchronization). Thus, synchronization and non-synchronization were observed at $d < 7$ mm and $d > 8$ mm, respectively.

To quantify the degree of synchronization, we calculated the correlation coefficient, r_{in-in}, between L_{in} and R_{in}:

$$r_{in-in} = \frac{\int (L_{in}(\tau) - \overline{L_{in}})(R_{in}(\tau) - \overline{R_{in}})d\tau}{\sqrt{\int (L_{in}(\tau) - \overline{L_{in}})^2 d\tau}\sqrt{\int (R_{in}(\tau) - \overline{R_{in}})^2 d\tau}}, \tag{1}$$

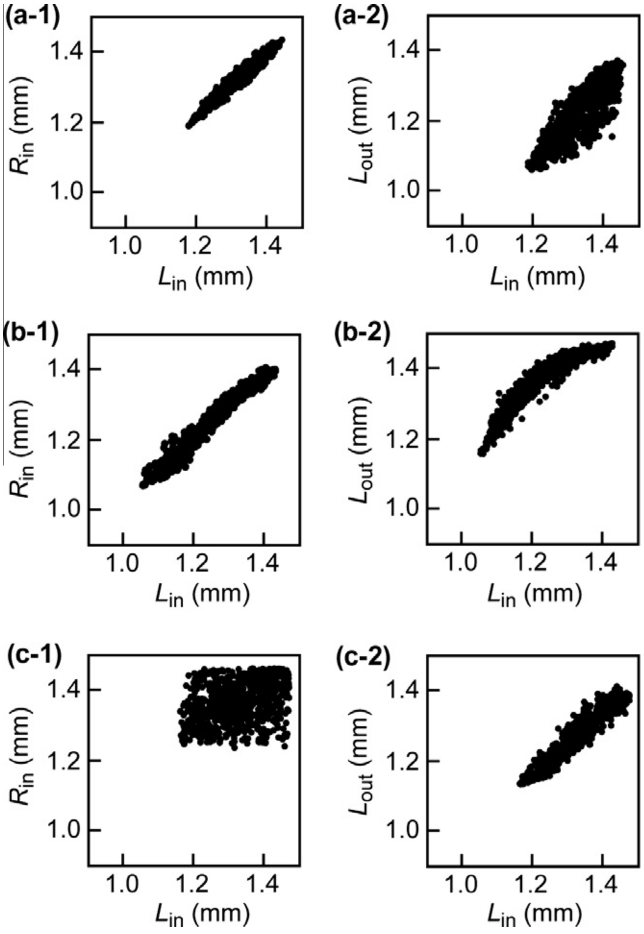

Fig. 2. Phase maps for (1) L_{in} *vs.* R_{in} and (2) L_{in} *vs.* L_{out} for d = (a) 4.8, (b) 6.2, and (c) 9.2 mm.