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Motion of a liquid bridge between nonparallel surfaces

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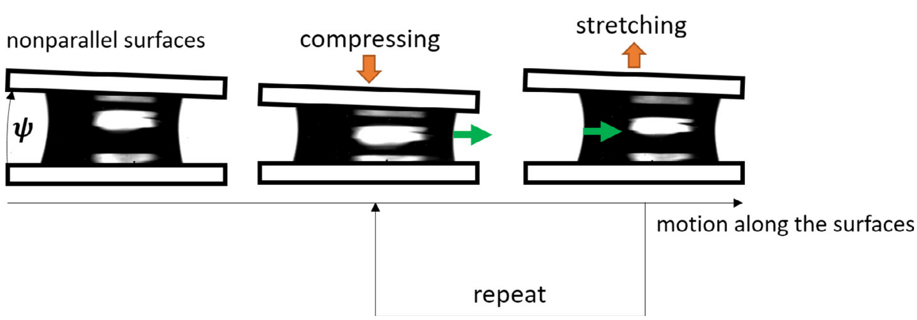
GRAPHICAL ABSTRACT



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ABSTRACT

Bulk motion of a liquid bridge between two nonparallel identical solid surfaces undergoing multiple loading cycles (compressing and stretching) was investigated numerically and experimentally. The effects of the following governing parameters were studied: the dihedral angle between the two surfaces (ψ), the amount of compressing and stretching (Δh), and wettability parameters i.e. the advancing contact angle (θ_a) and Contact Angle Hysteresis (*CAH*). Experiments were done using various combinations of ψ, Δh and on surfaces with different wettabilities to understand the effect of each parameter individually. Additionally, a numerical model using Surface Evolver software was developed to augment the experimental data and extract information about the shape of the bridge. An empirical function was proposed and validated to calculate the minimum amount of Δh needed to initiate the bulk motion (i.e. to overcome the initial lag of the motion in response to the compressing of the bridge), at a given dihedral angle ψ. The effect of governing parameters on magnitude and precision of the motion was investigated. The magnitude of the motion was found to be increased by increasing ψ and Δh, and/or by decreasing θ_a and *CAH*. We demonstrated the possibility of modulating the precision of the motion with θ_a. Additionally, it was shown that the magnitude of the motion (in one loading cycle) increases after each loading cycle, if the contact lines depin only on the narrower side of the bridge during compressing and only on the wider side during stretching (asymmetric depinning). Whereas, depinning on both sides of the bridge (symmetric depinning) reduced the magnitude of bridge motion in each cycle under cyclic loading. A larger ψ was found to convert symmetric depinning into asymmetric depinning. These findings not only enhance the understanding of bridge motion between nonparallel surfaces, but also are beneficial in controlling magnitude, precision, and lag of the motion in practical applications.

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1. Introduction

Rapid rate of development for drop-based systems in technology (e.g. in microfluidics), has meant that more and more methods are being developed to control and employ droplets [1–14]. The dynamic behavior of a liquid bridge between two nonparallel surface has drawn much attention due to its potential applications in transferring small droplets [9–15]. For instance, a drop forming a liquid bridge between two nonparallel hydrophilic surfaces will spontaneously move towards the cusp of the surfaces, if the dihedral angle between the surfaces (ψ) is larger than a critical value (ψ_c) [15]. Such spontaneous movement has been used in practical applications such as plate-based fog collectors [14]. On the other hand, if $\psi < \psi_c$, the liquid bridge remains stable without exhibiting any horizontal movement [15]. Still, the bridge can be influenced to move horizontally using mechanical actuations, e.g. by moving one of the surfaces vertically. For example, as shown in Fig. 1a and b, the contact points on the wide side of the bridge remains pinned during the compressing, while the contact points on the narrow side advance towards the cusp of the surfaces, causing bulk of liquid to move towards the cusp. Similarly, during the stretching phase, the contact points on the narrow side remains pinned while the ones on the wide side recede toward the cusp (see Fig. 1b and c). Due to the asymmetric advancing and retreating of the contact lines during the compressing and stretching phases, a net movement in the bulk liquid takes place. Unlike the spontaneous horizontal movement of the bridge when $\psi \geqslant \psi_c$ [15], this method of drop actuation enables horizontal movement of the bridge in a controllable fashion.

The pinning of contact points is essential for such horizontal movement to exist; it allows one side of the bridge to remain pinned, while the other side is advancing or receding. Such pinning is a result of Contact Angle Hysteresis (*CAH*), which allows the contact points to move, only if their local contact angle (CA) attain certain values i.e., they can only advance if their local CA attain a maximum value known as the advancing contact angle (θ_a); or recede, if their local CA attain a minimum value, known as the receding contact angle (θ_r). The difference between these two bounding values is known as *CAH* (i.e. $CAH = \theta_a - \theta_r$). For any value of CA inside the *CAH* range, the contact points remain pinned.

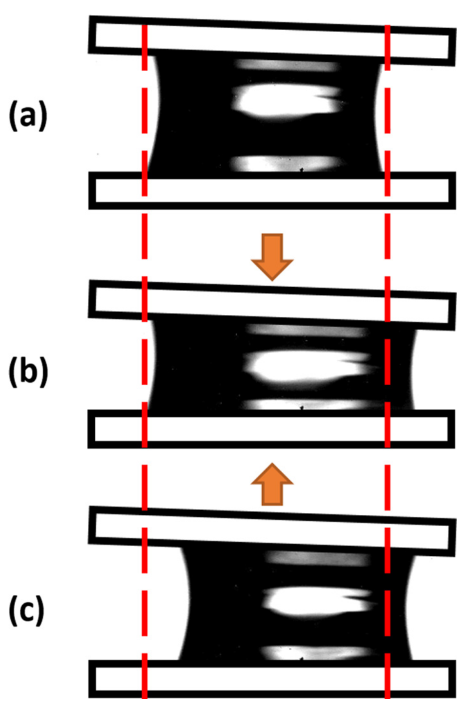

Fig. 1. (a) A water bridge between two identical nonparallel surfaces (PMMA). (b) When compressed, the bridge spreads on its narrower side, while the contact points on the wider side remain pinned. (c) In the stretching stage, the bridge recedes on its wider side while the contact points on the narrower side remain pinned. The asymmetric advancing and receding of contact lines lead to bulk bridge motion in a compression-stretching cycle.

In the literature, such horizontal movement of a liquid bridge due to compressing and stretching has been reported in several studies [9–12,14,15]. Prakash et al. [9] first reported that a certain type of Phalarope shorebirds uses this method to transfer their prey inside a bridge from their beak tips towards their month [9]. They studied quasi-static movement of the bridge in the absence of gravity, where the pressure inside the bridge remains uniform during the movement. Accordingly, the radii of curvature on the narrower and wider sides of the bridge had to be equal, a condition that requires the CAs on the narrower side of the bridge to be larger than that on the wider side [9]. This explains the movement of the bridge discussed in Fig. 1 i.e. in compressing, the CAs on narrower side of the bridge reach θ_a and their contact points advance earlier than that on the wider side, and in stretching, the CAs on the wider side reach θ_r and their contact points retreat first [9].

Despite the reported results on the horizontal movement of the bridge, there are several unsolved issues in the literature. First, there has not been any systematic understanding of the governing parameters controlling the horizontal movement. These governing parameters can be categorized into three classes: mechanical parameters, i.e. the amount of compressing and stretching of the bridge (Δh); geometrical parameters, i.e. the dihedral angle between the two surfaces (ψ); and material (wettability) parameters i.e. θ_a, θ_r, and *CAH* of the surfaces. To apply this method of drop manipulation in practice, one needs to understand how the horizontal movement is influenced by these parameters. In addition, several key elements of the horizontal movement have not been thoroughly studied. For example, if the amount of compressing or stretching is not sufficient, the pinning of contact lines cannot be overcome, so the bridge will not move [9,10]. In the studies to date the bridge was always amply squeezed and stretched such that the pinning of contact lines was overcome [9,10]. However, it is unclear what minimum amount of compressing and stretching is necessary to initiate the motion. Furthermore, in a favorable condition, depinning of the contact lines occur asymmetrically, as explained earlier. Still, the bridge may undesirably regress backwards by advancing on the wider side during compression, and/or receding on the narrower side during stretching [9–10,12]. Under such a condition, the mechanical energy given to the liquid is used to move the bulk of the liquid away from the cusp, which may not be desirable. Thus, the liquid motion is regarded more efficient if asymmetric depinning occurs in both compression and stretching stages. In one study [12], instead of smooth surfaces, lopsided saw-tooth surfaces were used to obstruct the inefficient backwards movement of the bridge [12]. Though, using saw-tooth surfaces could not enhance the movement if the surfaces were hydrophilic, because the bridge motion towards the cusp was obstructed by the liquid being trapped inside the saw-tooth cavities [12]. There has not been any understanding on how one can prevent backward movement of the bridge when the surfaces are hydrophilic.

There are also seemingly contradictory experimental results in the literature. To move the drop to the desired position, the bridge can undergo several sequential compressing and stretching, i.e. loading cycles. Luo et al. [10] showed that when the surfaces are hydrophilic (with CA < 90°), the distance traveled in one cycle increases, as the bridge gets closer to the cusp of the surfaces. This

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