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# How asymmetric surfaces induce directional droplet motion

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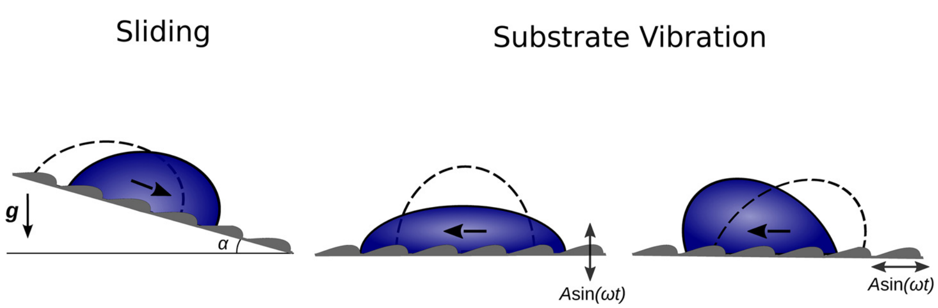
## HIGHLIGHTS

- Mechanisms of droplet motion on asymmetrically patterned substrates.
- How vibrations induce directional droplet motion.
- Effect of solid surface geometry features on droplet velocity.
- Prediction of contact angle hysteresis and droplet speed.

## GRAPHICAL ABSTRACT

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## ABSTRACT

Asymmetrically patterned surfaces appear in many living organisms. An intriguing example is the ratchet-like structures of the *Morpho aega* butterfly wings which help to keep water droplets away from the body of the insect, thus enhancing the flying stability. Here, we investigate the mechanisms of droplet motion on asymmetrically structured substrates and predict conditions that favor preferential droplet transport. To this end, we present a numerical investigation of the droplet dynamics on hydrophobic surfaces. Crucially, our model is able to handle the possibility of air inclusions in the structure of the solid surface (e.g. droplets in Cassie state). Our results indicate that the unbalanced capillary force, developed at the contact line, is the key factor for achieving a preferable liquid motion direction. Thus, a sliding droplet on an asymmetrically structured surface exhibits different migration velocities depending on the direction of the structures with respect to the motion, only when the capillary forces are predominant against the effect of inertia (e.g. this behavior is not observed for a fluid with low surface tension). We also show that the anisotropic wetting properties, due to the structure asymmetry, can be exploited in order to passively transfer a droplet by vibrating the substrate, either vertically or horizontally. A parametric study is presented, varying the vibration amplitude as well as the length scale of the asymmetric roughness to demonstrate the effect of these factors on the migration velocity of the droplet.



## 1. Introduction

Engineering the wettability of solid materials, by means of fabricating surface micro-textures, has attracted the interest of many researchers over the past years [1–3]. In particular, surface patterning enables to transform a hydrophobic material into highly water-repellent (super-hydrophobic surface). A droplet on such an artificially roughened substrate behaves like a "liquid sphere" which can easily roll off in any direction. The above behavior is extremely useful for manipulating droplets in micro-devices, under an external actuation (e.g. lab-on-a-chip [4], fuel cells [5]). The selection of the optimal actuation type for handling a sessile droplet in such micro-devices has been extensively studied. Several techniques have been proposed like the electrowetting effect [6], thermocapillary convection [7], the Leidenfrost phenomenon [8] and acoustic fields [9]. In addition, droplet handling can be achieved

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by a combination of vertical and horizontal substrate vibrations which result, due to their phase difference, in the breaking of the droplet axial symmetry [10–13]. Recently, researchers have also demonstrated that the uni-directional droplet transport can be facilitated on surfaces featuring anisotropic wettability (with asymmetric micro-structures), even if the micro-device is operating under non-stationary conditions [14–17]. The latter case actually requires only one driving oscillation, since the symmetry breaking occurs due to the anisotropy of the solid substrate.

The concept of fabricating surfaces with anisotropic wettability originates from living organisms. In particular, Zheng et al., in a milestone work [18], found that the wings of the Morpho aega butterfly are covered by asymmetric ratchet-like structures enabling a droplet to exhibit both rolling and pinning behavior under different directions. The above characteristic drives the water away from the wings (and not toward its body) in a humid environment, providing flying stability for the butterfly. A plethora of similar structure morphologies, that can directionally control the movement of droplets, have been also discovered in living nature (e.g. shark and lizard skin, spider silk) [19–21], inspiring the design of asymmetrically structured substrates in order to handle small amounts of liquid [22–26].

Determining the preferable motion direction on an asymmetrically patterned surface is, however, still an ambiguous issue in the literature, since it is affected by the local forces applied in the vicinity of the contact line. In particular, different motion directions of droplets on asymmetrically structured, vibrating substrates were considered in published experiments [15] and simulations [17]. Furthermore, despite the fact that a relation between the droplet velocity and oscillation amplitude is fundamental when designing microfluidic applications, it is a still a controversial issue since both linear [27] and non-linear [15] behaviors have been reported in the literature. From the above it is clear that different driving forces may exist, originating from competing mechanisms. Specifically, a droplet moves to the direction toward the corrugations tilt on the butterfly wings [28] whereas it self-propels to the opposite direction when deposited on a hot ratchet due to the vapor escape below the droplet (Leidenfrost phenomenon [8]).

The dynamic modeling, using continuum-level approaches, of a droplet moving on such complex substrates is tedious due to the contentious issue of the boundary condition imposed at the contact line (where the three different phases meet). In particular, an *a priori* unknown number of contact lines can be created due the presence of air inclusions trapped between the liquid and the solid. In order to tackle the above limitation, we have recently presented a sharp-interface, continuum-level formulation where the liquid–vapor and the liquid–solid interfaces are treated in a unified context (one equation for both interfaces) [29,30]. In particular, by employing a disjoining pressure term, modeling the liquid–solid micro-scale interactions, we avoided the implementation of any boundary condition at the contact line(s). With this approach, we examined cases of droplets impinging on complex solid surfaces, in good agreement with experimental measurements [29,30].

The aim of the current work is to extend our understanding regarding the driving mechanism and the dynamic behavior of a droplet on asymmetrically micro-structured substrates. In particular, we provide predictions regarding the migration velocity and the (dynamic) contact angle hysteresis under the effect of gravity or a periodic force induced by oscillating the bottom plate either in the horizontal or vertical direction. The effect of the solid structure length scale on the droplet motion is also investigated. Understanding the role of the structure asymmetry on the liquid transfer process has a great practical importance since it could enable the control of the droplet's speed and motion direction in modern miniaturized devices.

The present article is organized as follows: in Section 2, we describe the system of governing equations and outline the numerical scheme that is used for the simulations. Next, our numerical results regarding droplets moving on tilted as well as oscillated solid substrates are presented and discussed in Section 3. Concluding annotations are made in Section 4.

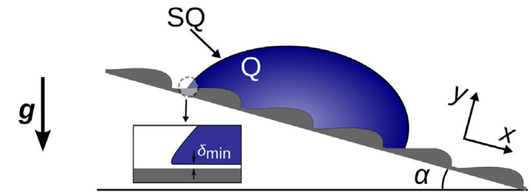


**Fig. 1.** Schematic of a droplet sliding on an asymmetrically structured substrate inclined at angle *a* (notice that droplet and surface features are not shown in the same scale).

## 2. Mathematical formulation

We study the dynamics of a droplet sliding on a solid substrate which can be tilted by an inclination angle, *a*, or vibrated (horizontally or vertically). We consider that the droplet is a Newtonian incompressible fluid with nominal radius, $R_0$, density, $\rho$, viscosity, $\mu$ and surface tension, $\gamma$. Assuming that the viscosity of the ambient phase is negligible, the Navier–Stokes equations are solved only for the droplet interior (Q in Fig. 1). In our formulation the liquid–solid and liquid–vapor interfaces are treated uniformly, therefore the solution of the above set of equations is determined subject to a single stress balance boundary condition applied at the whole droplet surface (SQ in Fig. 1) referred as the liquid–ambient interface from now on [30]:

$$\boldsymbol{n}\cdot T_{\text{tot}} = (\boldsymbol{n}\cdot T_{\text{ext}}\cdot\boldsymbol{n})\boldsymbol{n} + (\boldsymbol{n}\cdot T_{\text{ext}}\cdot\boldsymbol{t})\boldsymbol{t} + 2\gamma\kappa\boldsymbol{n}. \tag{1}$$

In the above equation, $\boldsymbol{n}$, and, $\boldsymbol{t}$, are the unit normal and the unit tangent of the liquid–ambient interface, respectively; $T_{\text{tot}}$ and $T_{\text{ext}}$ are the total stress tensor and the stress tensor of the ambient phase, respectively, and, $\kappa$, is the mean curvature of the interface ($\kappa = -(\nabla_s\cdot\boldsymbol{n})/2$, where $\nabla_s$ is the surface gradient operator). In the above equation we have neglected any surface tension gradients that can be induced either by surfactant adsorption on the droplet surface [31,32] or by the presence of temperature gradients along the substrate [7], since such phenomena are out of the scope of this specific work.

Since the liquid–ambient interface is a closed curve, the droplet and the wall are always separated by an intermediate layer which is stabilized by the presence of normal micro-scale liquid–solid interactions [29,30]. The above is achieved by introducing a disjoining (Derjaguin) pressure term [33] which expresses the excess pressure on the interface due to the liquid–solid interactions. In this work the disjoining pressure is approximated by a Lennard–Jones type potential (alternative formulations could also be employed, see e.g. Kavousanakis et al. [34]):

$$p^{\text{LS}} = \frac{\gamma w^{\text{LS}}}{R_0}\left[\left(\frac{\sigma}{\delta/R_0+\epsilon}\right)^{C_1} - \left(\frac{\sigma}{\delta/R_0+\epsilon}\right)^{C_2}\right], \tag{2}$$

where, $\sigma$, and, $\epsilon$, are model parameters and, $\delta$, is the distance between solid and liquid phases (see also below). The parameters $C_1$ and $C_2$ regulate the cut-off distance (where, $p^{\text{LS}} \to 0$) of the liquid–solid interactions. The depth of the potential well is proportional to the wetting parameter, $w^{\text{LS}}$, which is directly related with the solid wettability (the Young contact angle, $\theta_Y$), as described in our previous work [29]. The disjoining pressure is finally introduced in the Navier–Stokes equations via the normal stress component of the interface force balance (Eq. (1)).

The distance of separation, $\delta$, between the liquid and the solid phases determines whether the disjoining pressure is attractive