Preface

This book describes how surface tension effects can be used by engineers to provide mechanical functions in miniaturized products (<1 mm). Even if precursors of this field such as Laplace already date back to the eighteenth century, describing surface tension effects from a mechanical perspective is very recent. The originality of this book is to consider the effects of capillary bridges on solids, including forces and torques exerted both statically and dynamically by the liquid along the 6 degree of freedom (DOF). It provides a comprehensive approach to various applications, such as capillary adhesion (axial force), centering force in packaging (lateral force), and recent developments such as a capillary motor (torque). It devises how surface tension effects can be used to provide mechanical functions such as actuation (bubble-actuated compliant table), sealing, and tightness. Different case studies will also be proposed in the fields of energy harvesting, nanodispensing, self-assembly...

Context and Historical Note

The skeleton of this book concerns the modeling, characterization, and application of surface tension effects in precision and micro-engineering.

This project will therefore quickly recall the dominance of surface tension effects at scales smaller than a few millimeters. This limit is known as the *capillary length* L_C, which expresses the ratio between gravity and surface tension effects:

$$L_C = \sqrt{\frac{\gamma}{\rho g}} (\approx 2.7 \text{ mm for water}) \tag{1}$$

where γ is the surface tension of the liquid (Nm^{-1}), ρ is its density, and $g = 9.81$ ms^{-2}. Moreover, as it can be observed from dimensions, capillary forces linearly depend on length scale ($F \div \gamma \ell$), leading to the dominance of surface tension effects over other physical effects at small scale. Consequently, studying capillary forces is a good starting point to enter micro-engineering since it is a dominant

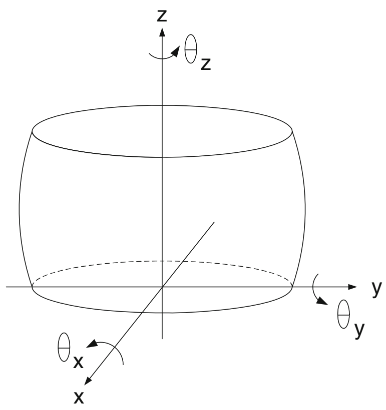

Fig. 1 Liquid joint with 6 DOF: 3 translations x, y, and z, 2 tilts θ_x and θ_y, and 1 rotation θ_z

effect. Additionally, they can be studied from the millimeter and below, i.e., at a scale sufficiently large to be addressed without dedicated experimental material.

The reader will be led from the underlying physics to various case studies, passing through the concept of fluidic joint, i.e., the mechanical description of a liquid bridge linking two solids as a mechanical joint with 6 DOF (Fig. 1). The static study outputs the stiffness and the dynamic study leads to the damping coefficients.

The models presented in this book find their far origin in the theory of capillary effects[1] which has existed for two centuries (Pierre-Simon de Laplace [1]): it used to focus essentially on the description of capillary filling of small gaps with liquids.

Nevertheless, Laplace went beyond phenomenological description and already wrote down the famous Laplace equation introducing the concept of surface tension from geometry (i.e. curvature) and mechanics (i.e. pressure). A few decades later, in 1873, Joseph Plateau (Professor at the University of Ghent, Belgium) described the equilibrium shape of droplets immersed in a bath with identical density [2]. These precursor works were restricted to equilibrium, such as the famous Jurin 's law [3] giving the rising height of a liquid in a thin capillary. Today, these effects can be simulated with powerful finite elements software such as Surface Evolver [4]. As early as 1921, Washburn [5] introduced an equation to model the dynamics of capillary rise. In 1936, Wenzel [6] described the effect of roughness of wettability and in 1944, Cassie and Baxter published their study on wettability of porous surfaces [7]. Nevertheless, dynamic contact angles were not studied before the end of the twentieth century by Voinov [8], Tanner [9], and Jiang [10]. Dynamic contact angles have been under study these last years [11–13].

With the introduction of numerical simulation and high speed cameras, dynamics became easier to study, yet it still focused on the shape of liquid bridges: Orr presented in 1975 a numerical simulation to compute the shape of liquid

[1] In French: 'Théorie des actions capillaires' [13].

bridges at equilibrium [14]; Edgerton published in 1937 the first results on the dynamics of drop formation [15]. Experimental results on liquid bridges dynamics was only published at the end of the twentieth century [16]. Besides the shape of the liquid bridges, another question is to study how these bridges acts on solids, i.e., provide forces which can be used in mechanical systems. The most famous model is probably Israelachvili's equation [17] describing the capillary force exerted by a meniscus linking a flat plane and a sphere.

Based on this background, this book clarifies some aspects of capillary forces calculation, extends the modeling from static to dynamic behaviors, and from axial to radial forces.

It introduces the concept of fluid mechanical joint and various case studies, which are briefly described in the following.

Problem Definition and Goals

This book does not try to address a particular industrial problem. On the contrary, the wide range of case studies proposed at the end of the book illustrates the generic interest of the models presented in the early chapters. Nevertheless, the reader will recognize many illustrations coming from micro-assembly domain and nanoscopic domains. For instance, capillary forces at the nanoscale are illustrated by the case of liquid delivery.

The justification for this proposal originates from the framework of micro-assembly and packaging.[2] Traditionally, the microrobotic community—which applies pick-and-place know-how to downscaled applications—makes use of surface science adhesion and mechanical contact models, because downscaling laws require an adequate understanding of the physical background. This improves design, simulation, haptic feedback, and automation of developed products. Since engineers are usually not familiar with scaling, good models are mandatory to ensure reliability, *sine qua non* condition for industrial perspectives of our research developments.

To this aim, we summarized, developed, and present here many capillary forces models that can be used in this field and beyond. For example, we recently published results on lateral dynamics of liquid bridges, which can serve as a basis toward design of flip-chip applications [18].

From an editorial point of view, the goal is to combine the knowledge of many specialists and present their most up-to-date research work in a way that this knowledge will not be out-of-date too quickly. We therefore tailor this book into different parts. The first two parts are expected to have a long-term validity, because they present capillary forces models in a generic way. The last part is

[2] Which includes a large variety of topics such as designing, manufacturing, feeding, positioning, joining, testing.

devoted to case studies, which obviously will be soon replaced by new research development. However, they show nowadays a broad and relevant picture of research trends toward designing micro-engineering applications with surface tension issues.

Methodology, Originalities, and Perspectives

Surface tension is a classical topic but is given many different insights: for example, the surface chemistry engineer is familiar with surface energies, the pharmaceutical industry researcher is familiar with surface tension and surfactant, tribologists know a lot about adhesion, physics teachers present laws as an appendix of their lectures, and so on. We hope to give a basis combining these aspects, actually the underlying concepts, which are required to understand how surface tension effects can be used to exert forces and torques on solids.

The key idea is therefore to write it ‘as a textbook’, even if the topic has not yet become a classical lecture. It will therefore include analytical developments, simulation recipes and results, description of experimental test beds, and, of course, experimental validation. In some case, the effort will be pushed until applicative demonstrators, such as for example in the case of the micro-robotic platform using three fluidic actuators combining surface tension and gas compressibility.

The results and data given in this book rely on literature reviews, mathematical and physical models, digital simulation, and experimental studies.

Its perspectives rely on the scope of the Belgian MicroMAST Network,[3] whose scientific objectives are driven by fundamental questions raised in microfluidics, interfacial science, and micromanipulation. The rational use of surface tension, surface stress, and capillary effects in micromanipulation is expected to be applied to highly relevant case studies, including capillary gripping, capillary filling, capillary alignment, capillary sealing, capillary self-assembly, and droplet manipulation (Fig. 2).

These fundamental questions can be grouped into three categories: the first category is partially addressed in this book while the two other can serve as future developments.

1. Fluid statics and dynamics: How much force is applied on solids by menisci and micro-flows in a given geometry? What happens if the solid bends when subject to these forces? Are the interfaces stable and what if not? What is the effect of an electric field? How can the microscopic description of wetting be translated into an adequate boundary condition at the macroscopic level?

[3] Microfluidics and Micromanipulation: Multi-Scale Applications of Surface Tension, www.micromast.be.

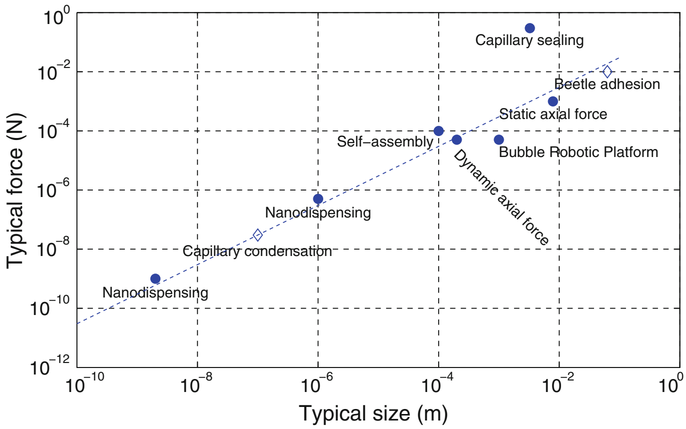

Fig. 2 Orders of magnitude in this book: from nano-dispensing at the nanoscale (Chap. 14) up to capillary-based sealing at the millimetric scale (Chap. 11). Self-assembly at 100 μm is described in Chap. 12, dynamic axial force models and measurements are led in Chap. 7, the bubble robotic platform devised in Chap. 5 and the static axial force in Chap. 2. Finally, capillary condensation and beetle adhesion have been reported elsewhere, respectively in [19] and [20]

2. Surface engineering: How does a contact line move on a rough surface? Can one pattern the surface microscopically to control this motion? How is the motion affected by evaporation, or by the presence of colloid particles in the liquid or at the interface? Do these particles interact with the micro-patterns on the surface? Can one create highly 3D patterns on the surface by using capillary forces?
3. Liquid engineering: How to measure the interfacial properties of complex liquids where apart from surface tension a surface viscoelastic response is present? How to infer macroscopic properties from the dynamics at the molecular scale? And how to engineer liquids and tailor them to the requirements arising from applications? Can one make a liquid that is biocompatible, and has a large surface tension and a low viscosity?

Overview

This book falls into a description of the related physical background (Part I), static and dynamic modeling of capillary forces and torques (Parts II and III), and an overview of relevant case studies (Part IV), such as a capillary micromotor (whose rotor follows a rotating surface energy gradient produced by electrowetting, see Chap. 10), a capillary-based sealing (whose limit is given by the capillary pressure, see Chap. 11), micro- and nano-assembly case studies using surface-tension-driven self-assembly (see Chap. 12), surface tension actuation and energy harvesting through transpiration actuation (Chap. 13) and finally, the illustration of surface tension effects in actuation and liquid nano-dispensing (Chap. 14).

All these case studies are positioned in a log–log diagram plotting the force order of magnitude as a function of the size order of magnitude (Fig. 2).

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