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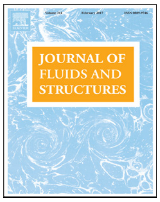

# Vibrations of micron-sized fluid membranes induced via pulsed laser excitation

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## HIGHLIGHTS

- Pulsed optical laser employed to generate vibrations of micron-sized liquid membranes.
- Rapid thermal expansion of the metallic frame generates Taylor vibrations-Finite element simulations denote the highest excited vibration modes.
- Inclusion of carbon nanofibers into the membrane leads to surface tension gradients.
- Surface tension gradients couple Marangoni vibrations with bending Taylor modes.

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## ABSTRACT

We study the acoustic vibrations of three different micron-sized square fluid membranes induced by means of a nanosecond pulsed laser. Several vibration modes in the kHz range are excited when the metallic frame, on which the fluid membrane is suspended, undergoes rapid thermal expansion after absorption of the pulsed laser light. The vibration frequencies detected are compared with a model based on bending vibrations of the fluid film similar to those in a solid membrane. Finite element method based simulations are employed to calculate the membrane deformation for different excitation cases of light absorption, as well as the highest excited modes. In addition we explore the effect on the film vibrations due to the inclusion of carbon nanofibers in the fluid membrane. The carbon nanofibers affect the surface tension in a way that couples bending modes to Marangoni waves in the membrane.

## 1. Introduction

Since the XIX century, free-standing thin fluid membranes have attracted the attention of the scientific community owing to the two-dimensional (2D) nature of the system. This behavior has allowed the study of hydrodynamic phenomena such as vortex formation (Afenchenko et al., 1998; Couder, 1981), turbulent flow (Chomaz, 2001; Rivera et al., 1998), and acoustic vibrations (Taylor, 1878; Bergmann, 1956; Boudaoud et al., 1999) in a two-dimensional framework. In modern experiments, where millimeter size membranes have been studied (Afenchenko et al., 1998; Boudaoud et al., 1999; Rutgers et al., 2001; Kim and Mandre, 2017; Acharige et al., 2014; Gaulon et al., 2017; Yablonskii et al., 2017), a certain concentration of surfactant is required to stabilize the fluid film and avoid rupture. This provides the fluid membrane with an elastic behavior (Couder, 1981; Chomaz, 2001) that consequently enables transverse vibrational modes similar to those in a solid film (Afenchenko et al., 1998; Boudaoud et al., 1999).

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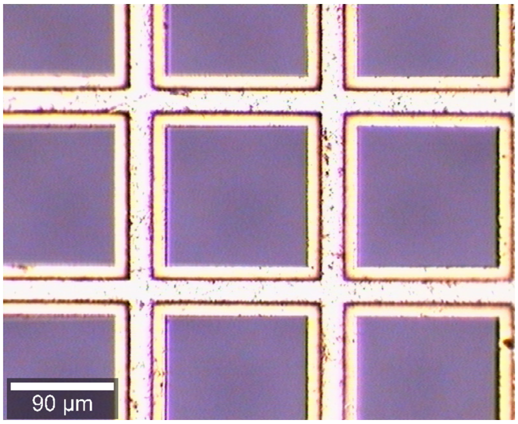

**Fig. 1.** Microscope image of a TEM grid of pitch 165 μm, 132 × 132 μm dimensions.

Optical probing methods are the most often employed approach to visualize the membrane vibrations; taking advantage of optical interference between front and back surfaces of the film (Afenchenko et al., 1998; Boudaoud et al., 1999; Couder, 1981), backscattered light from optical interference fringes (Durst et al., 1981), interaction with modulated light sources (Emile and Emile, 2014, 2016), etc. With the advancement of micromechanical technology, many devices and applications involving fluid components have been scaled down to the micron range. This has lead to an increased interest in optofluidics topics, such as the use of liquid–air and liquid–liquid interfaces as reconfigurable optic lenses by undergoing surface deformation caused either by external mechanical forces (Berge and Peseux, 2000; Ren and Wu, 2005) or by laser excitation (Emile and Emile, 2011; Rosenauer and Vellekoop, 2009).

The purpose of this work is to induce vibrations in micron-sized fluid membranes by using a nanosecond pulsed laser and to optically detect the frequency modes induced in these membranes. We show that several natural modes of the liquid membrane can be excited and probed in this configuration. Measured frequency modes are compared with those predicted by the surface displacement equation derived by Taylor (1959). Furthermore, finite element method (FEM) based simulations are used to show the highest excited modes due to the impulse-like excitation.

In addition, we also present vibration analysis of fluid membranes containing a dispersion of carbon nanofibers (CNFs). The inclusion of micron-sized particles into microfluidic systems further widens the scope of possible applications. For example, recent studies have shown great potential for the use of CNFs as bio-membranes in order to mimic and study chemical processes of biological cells (McKnight et al., 2003; Fletcher et al., 2004); other studies have taken advantages of the semipermeability of CNFs arrays and have employed them to selectively control the transport of nanometric particles through microfluidic channels (Zhang et al., 2002; Fowlkes et al., 2008). CNFs have also been used in microfluidic systems to aid the fabrication of electrically conductive composite fibers in order to enhance their tensile and electrical properties (Lu et al., 2017). This has motivated us to study the observed effects that a dispersion of CNFs can produce on the vibration modes of a composite fluid membrane. In particular, we show that the presence of CNFs can lead to the generation of Marangoni waves in the membrane.

## 2. Experiment description and sample preparation

In order to create a thin micron-sized fluid membrane, we used a copper frame made from TEM grids (purchased from Sigma-Aldrich), Fig. 1 shows a microscope image of the TEM grid. A single drop (∼ 5 μl) of ethylene glycol (EG, purchased from Jalmek E6835-13) was placed into the grid, which results in a meniscus forming in every square of the grid. We used three different grids with a pitch (periodicity) of 250, 165, and 125 μm that corresponds to a hole size of 208, 132, and 97 μm, respectively. All three grids are 12 μm thick. Both the edge length and thickness were measured using an optical microscope.

We employed a pulsed laser (532 nm, 8 ns pulse width, 260 μm spot diameter, ∼ 100 μJ pulse energy) in order to induce vibrations on the fluid membrane. The copper grid undergoes heating due to the absorption of the laser light. Sudden heating will induce thermal expansion creating a stress response which subsequently results in membrane vibrations. We consider that the vibration amplitude is small enough that the EG membrane is not destroyed and that temperature rise in the grid is very low, enough to not evaporate the membrane.

In order to probe the membrane vibrations we used a CW He–Ne laser (632 nm, 2 mW, 200 μm spot diameter) referred to as "probe". A schematic diagram of the experimental setup is shown in Fig. 2. The probe and excitation laser are focused at the sample using a lens of 15 cm focal length. The square shape of the grid diffracts the probe laser light, and the membrane vibration modulates the intensity of the beam. Consequently, changes in the light intensity induced by the membrane vibrations were monitored using a photodiode (Thorlabs PDA100A) connected to an oscilloscope (Tektronix DPO7000). The