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Soap films under large-amplitude oscillations

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We present observations of the strongly non-linear behaviour of a single circular soap film undergoing large-amplitude harmonic oscillations in the acoustic frequency range. In such a film, liquid is re-distributed towards its centre, which leads to striking mode formations and consequently to the ejection of droplets from the film. Both processes, liquid re-distribution and droplet ejection, finally result in the rupture of the film.

Keywords: films; foams; vibrational properties

1. Introduction

Soap films are elastic membranes of a very special kind: they consist of a thin liquid film of several nanometres to micrometres thickness, which is stabilised by surfactants (most commonly soap-like amphiphilic molecules).

Soap films have served as excellent models of vibrating membranes [1]. Their tension is due to surface tension and an interfacial elasticity, of which the latter is provided by the surfactant dynamics [2]. When analysing the vibrations of soap films, one needs to consider both the inertia of the liquid film and the inertia of the air moving with the film. The viscous dissipation within the oscillating film is, in general, negligible [1].

While the fundamental behaviour of a soap film under acoustic forcing is similar to that of standard elastic membranes, redistribution of liquid within the film and surfactant effects provide a range of physically relevant and esthetically striking effects. As a consequence, several types of acoustic responses are observed in soap films, which depend most significantly on the film thickness and the oscillation amplitude. For example, very thin films display strong and rapid recirculation (counter-rotating vortices) [3–5], while in films of sufficient thickness and oscillation amplitude, liquid is redistributed permanently from the nodes to the antinodes of the film. As a consequence, the oscillation amplitude in thick films is maximal at any forcing frequency. This mechanism is known as “self-adaptation” [6]. In some cases (for instance, for vertical soap films) soap film oscillations have been observed without thickness gradients [5].

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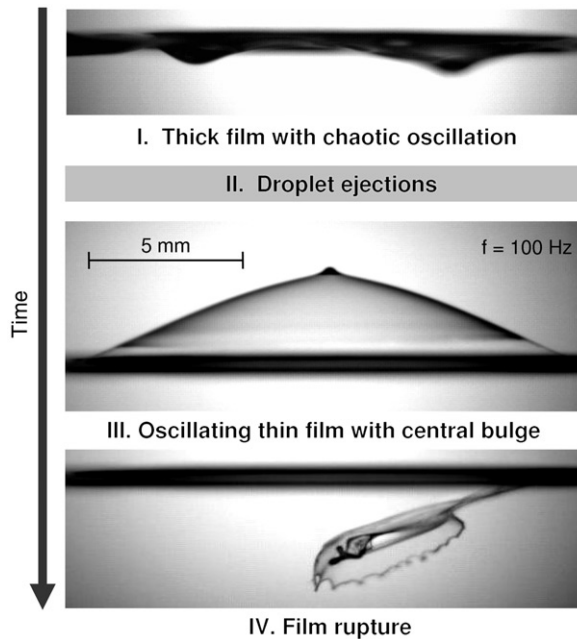


Figure 1. Overall film behaviour with time at constant frequency and amplitude: I. Initially the film is very thick and responds with chaotic oscillations. II. The film thins via the ejection of droplets. III. Once the film is sufficiently thin, large-amplitude oscillations are observed together with the formation of a liquid bulge in the centre of the film. IV. Eventually the film ruptures.

Until now, soap film oscillations have been studied at rather moderate oscillation amplitudes. In this article we report investigations into the strongly non-linear behaviour of soap films undergoing large-amplitude oscillations that lead to striking mode formations, instabilities (droplet ejection) and finally to film rupture.

We submit a horizontal soap film to an acoustic wave of strong amplitude, and we visualise the response of the film using a high-speed camera. Typical side views of the film response are presented in Figure 1. In general terms we observe that, after a transient regime (Figure 1(I)) in which liquid droplets are ejected (Figure 1(II)) from a very thick film, the soap film vibrates in phase with the forcing and is strongly deformed (Figure 1(III)). Furthermore, above a threshold amplitude, a liquid bulge forms in the centre of the vibrating film and oscillates simultaneously perpendicular to and in the plane of the film, displaying striking mode formations (Section 3). If the soap film is stable, the liquid bulge grows in time, and destabilises into droplets which are ejected from the soap film (Section 4). Both mechanisms, liquid redistribution and droplet ejection, finally lead to the rupture of the film (Figure 1(IV) and Section 5). This article focuses on the two latter stages (III) and (IV).

2. Experimental set-up and procedure

The main elements of the set-up are presented in Figure 2. A circular soap film of 16 mm diameter is created in a flat metallic frame (height 1 mm), which is placed 8 cm below

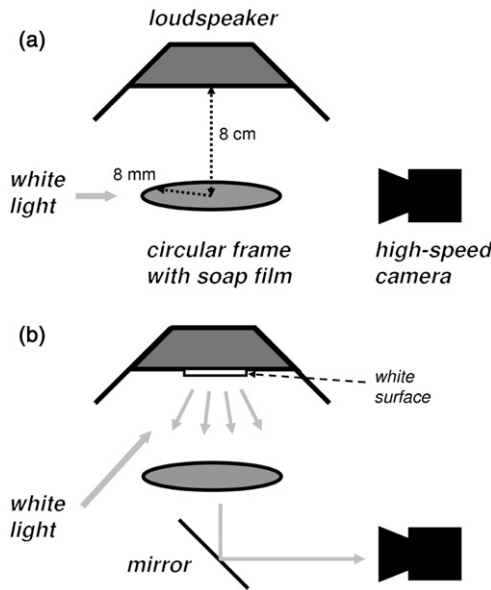


Figure 2. Sketch of the experimental set-up (not to scale) for the (a) side view and (b) bottom view of the film.

a loudspeaker (MONACOR SP-90, 60 Hz-2.5 kHz). The latter is connected to a low-frequency generator via a 10 dB home-made power amplifier. The film response is recorded either from the side (Figure 2a) or from the bottom (Figure 2b) using a high-speed camera (Photron Fastcam) running at 1000 frames per second. The illumination is provided by a halogen bulb and is homogenised by a diffusing screen.

We create the soap film by pulling the frame out of a soap solution containing 1% (volume) of commercial dish-washing liquid (Fairy), which is known to make highly stable films. The initially thick film (10–100 μm) is placed horizontally under the loudspeaker, whose radius is 10 times larger than the one of the soap film, which ensures spatially homogeneous forcing. The frequency f is set to a fixed value.

Under acoustic forcing, the soap film undergoes the highly reproducible sequence of events I–IV shown in Figure 1 and described in the Introduction. We began our observations once stage III was reached.

Performing a frequency sweep, we found that the response of the soap film was maximum at $\sim f_0 = 100$ Hz. This value guided not only further measurements but also provides a mean of estimating the average film thickness e . Assuming that f_0 is the first resonant frequency of the soap film on the circular frame, we have $f_0 = \omega_0/2\pi = m_0 c/2\pi a$, where $m_0 \approx 2.4$ is the first zero of the Bessel function J_0 of order zero [7] and c is the phase velocity of the wave on the membrane. c is given in [3] for the antisymmetric mode of undulation of a soap membrane, taking into account the inertia of the air moving in the film. We therefore obtain

$$f_0 = \frac{m_0}{2\pi a} \sqrt{\frac{2\sigma}{\rho e + 4\rho_{\text{air}} a/\pi}}, \quad (1)$$

where $\rho = 10^3 \text{ kg m}^{-3}$ is the liquid density, $\rho_{\text{air}} = 1 \text{ kg m}^{-3}$ is the density of air, $a = 8 \text{ mm}$ is the radius of the soap film, and $\sigma \approx 0.03 \text{ N m}^{-1}$ the surface tension. This gives the average film thickness $e \approx 13 \text{ }\mu\text{m}$.

3. Liquid bulge formation and modes

Observing the film from the side (Figure 3a), we find that despite its large amplitude it oscillates in a linear manner:

- (1) the variation of the oscillation amplitude (measured at the centre of the film) is perfectly sinusoidal, as shown for one period in Figure 4a;
- (2) All film shapes collapse on the same curve when normalised by the amplitude of the film centre, as shown in Figure 4b.

Both graphs of Figure 4 present the analysis of the example shown in Figure 3a.

However, at the same time, a very pronounced liquid bulge (size of the order of 1 mm) is formed at the centre of the film and oscillates in phase with the film (Figure 3b). Because of this additional weight, the shape of the oscillating film deviates clearly from being spherical, which would be the case for a film in which inertial forces are negligible with respect to surface tension forces.

We believe that the bulge formation is a manifestation of the self-adaptation of vibrating soap films [6], i.e., a result of the competition between inertial forces and elastic restoring forces. Although Boudaoud et al. [6] observed a much smoother variation of the film thickness with the distance from the centre of the film, the formation of the bulge in our case could be due to the strong amplitude of the forcing which leads to further

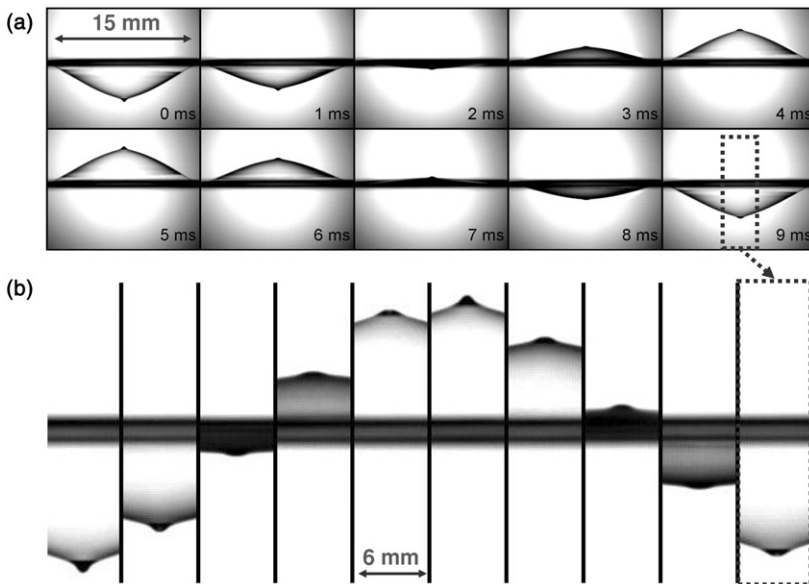


Figure 3. (a) One period of the large-amplitude oscillations of the entire film viewed from the side. (b) Zoom into the centre of the film to show the formation of a pronounced liquid bulge ($f = 100 \text{ Hz}$).

non-linear effects. We observe that these pronounced bulges are formed above a threshold amplitude.

Figure 3b also shows that the bulge itself undergoes an oscillation in thickness which is synchronised with the film oscillation. The bulge reaches its maximum thickness when the film reaches its maximum amplitude. With time, we generally observe a gradual increase of the oscillation amplitude of the bulge relative to the film. This ultimately leads to an instability and the ejection of droplets which is described, in more detail, in Section 4.

Looking at the bulge from the bottom (as shown in Figure 2b) reveals an additional effect: the bulge oscillates also within the plane of the film in the form of beautiful surface modes, which break the axisymmetry of the system. We were able to record modes $n=2$ (Figure 5a), $n=3$ (Figure 5b) and $n=6$ (Figure 5c), the mode number n being the number of “bumps” along the contour of the bulge. We never observed mode $n=4$ or $n=5$. Although we did not make a systematic study of the conditions of appearance of these modes, it is worth noting that we observe different mode numbers for the same forcing frequency and amplitude (compare Figure 5b and Figure 5c). This may be due to the continuously varying size of the bulge.

The same kind of oscillation modes have been observed and studied in the case of vibrating liquid droplets suspended in air [8]. For a drop of radius r , the natural frequency f_n of a mode n is given by

$$f_n = \frac{1}{2\pi} \sqrt{\frac{\sigma n(n^2 - 1)}{\rho r^3}}. \tag{2}$$

Taking here $f_n = 140$ Hz, $\sigma = 0.03$ N m⁻¹ and $\rho = 1000$ kg m⁻³, one obtains $r = 0.6, 1$ and 2 mm for modes $n = 2, 3$ and 6 , respectively. These radii are of the same order of magnitude as those observed for the liquid bulge.

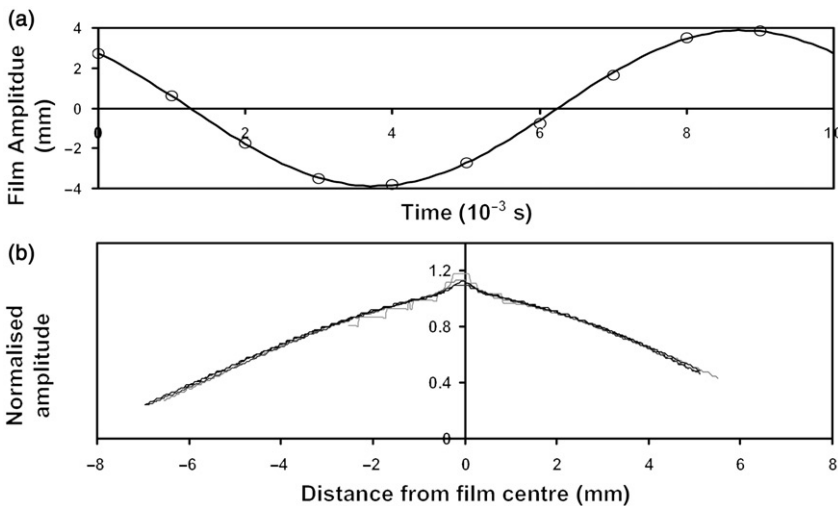


Figure 4. Analysis of the film oscillation displayed in Figure 3. (a) The film amplitude follows a perfect sinusoid. (b) All film shapes collapse on the same curve when normalised by the amplitude of the film centre.

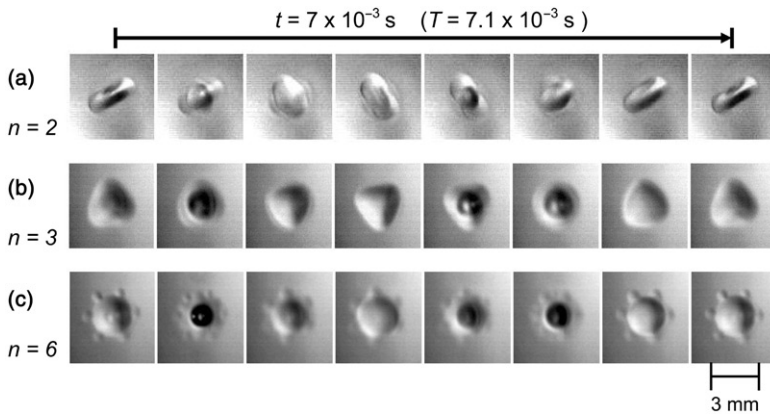


Figure 5. Examples of one period of different oscillation modes n of the liquid bulge viewed from the bottom at an excitation frequency $f = 140$ Hz and a peak-to-peak forcing amplitude (a) $A \approx 0.8$ mm; (b) $A \approx 0.5$ mm; and (c) $A \approx 0.5$ mm.

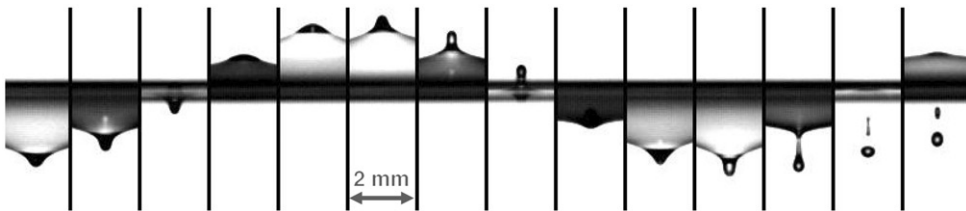


Figure 6. At constant forcing amplitude and frequency ($f = 100$ Hz), the bulge grows continuously and becomes unstable, which leads to the ejection of droplets.

Interestingly, the observed shapes oscillate at the forcing frequency. This contrasts with most of the surface mode phenomena observed for individual drops [9], which oscillate sub-harmonically as the result of a parametric resonance driven by a spherical oscillation [10]. In our case, the surface modes are probably coupled in a nontrivial way to the vertical oscillations of the bulge reported above. The signature of these vertical oscillations can be seen in the second and fifth or sixth images from each sequence in Figure 5: the dark circular spot in the centre of the bulge represents a thicker part of the bulge. Furthermore, unlike in the case of isolated liquid drops, the bulge here can exchange liquid with the film; and also surfactant effects may play a role.

4. Droplet ejection

The film oscillations with a central bulge, as described in Section 3, do not proceed indefinitely. As shown in the image sequence of Figure 6, the bulge grows continuously and finally becomes unstable, which leads to the ejection of droplets. These can in some cases be re-captured by the film or even cross the film without breaking it.

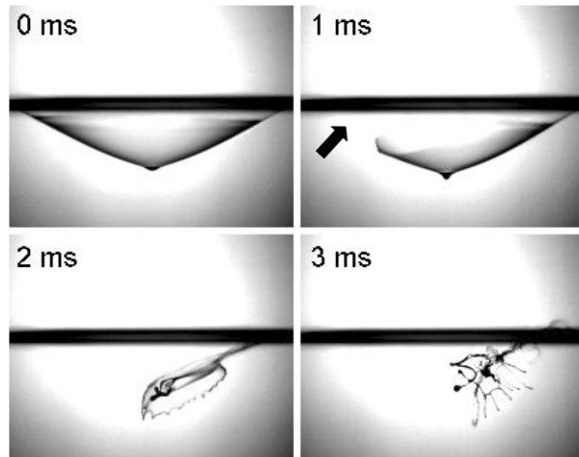


Figure 7. The continuous decrease of film thickness finally leads to the rupture of the film, starting from the boundary, where the film is particularly thin ($f = 100$ Hz).

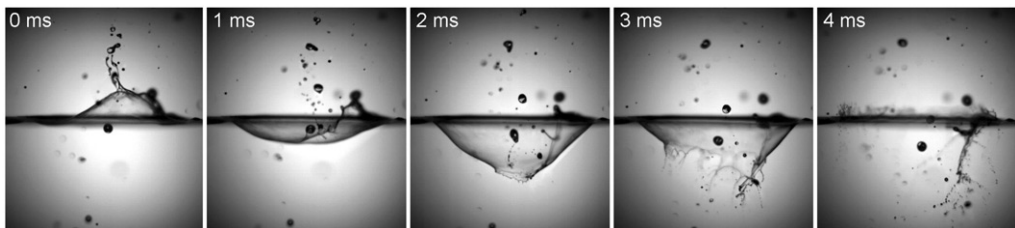


Figure 8. At very large acoustic amplitudes, the film ruptures from the centre after the ejection or impact of large droplets ($f = 100$ Hz).

Our recordings show that the creation of the droplets is very similar to the formation of drops from a dripping faucet (see, e.g. [11]), with a fast pinch-off followed by the formation of at least one visible satellite droplet. However, an interesting feature of the droplet ejection from an oscillating film is that it is controlled by surface tension and an *inertial force*, contrary to the usual case of a faucet where drops detach when *gravity* exceeds stabilising surface tension forces.

5. Film rupture

As a result of liquid redistribution, ejection, evaporation and severe agitation, the lifetime of a soap film undergoing large-amplitude oscillations is generally rather short (order of a minute). The rupture mechanism in this case is very reproducible and shown in Figure 7: The film thins, particularly, strongly close to the boundary until it becomes a black film (typical thickness of a few tens of nanometer) and breaks. The rupture itself is very fast and of the order of a milli-second.

However, at very large applied acoustic amplitudes we observe a different rupture mechanism which is shown in Figure 8: The initial thick film undergoes very violent and

chaotic oscillations which are accompanied by the ejection of big droplets and strong local distortions. In this case, the film breaks from a hole opening in its centre. The overall lifetime of the film is very short (order of a few seconds). The opening of the hole proceeds more slowly than in the previous case and generally takes a few milliseconds.

Although the location of the rupture is different in both cases, we believe that the rupture mechanism is fundamentally the same and originates in the local thinning of the soap film. In particular, the film breaks when its internal Marangoni elasticity does not balance the external stresses due to the fluctuation of the interface. At large amplitudes (Figure 8), the violent ejection of droplets in the centre of the film (i.e., at the antinodes of the vibration – see Section 3) induces strong and fast fluctuations of the film thickness. If Marangoni restoring stresses do not have time to build up, the soap film breaks in the weakest region, i.e., in the centre. At low amplitudes (Figure 7), the fluctuations of the film interfaces induced by the droplet ejection are weak enough (or slow enough) to be balanced by Marangoni stresses, therefore the centre of the film is stable. However, the re-distribution of the liquid slowly thins the film at its edges from where it consequently breaks.

In both cases, we can explain the timescale of the film rupture by considering the opening velocity v of a hole in a film of thickness e , which is given by $v = \sqrt{2\sigma/\rho e}$ [12,13]. We find opening velocities of $v > 8 \text{ m s}^{-1}$ and $v > 3 \text{ m s}^{-1}$ for the case of moderate and large amplitudes, respectively. This corresponds to an approximate average film thicknesses of $e < 1 \mu\text{m}$ and $e < 10 \mu\text{m}$.

6. Conclusion

We have reported here a range of physical phenomena observed in soap films undergoing large-amplitude oscillations in the acoustic frequency range. For a clearer understanding of these mechanisms, much more systematic investigations are needed to determine the role of parameters such as the forcing frequency, the forcing amplitude, the initial film thickness, the waiting time after the soap film has been created, and the physico-chemical properties of the soap films, i.e., the role of the surfactants.

Studies of this type tackle a plethora of physical phenomena governing the hydrodynamic properties of soap films, but also of liquid foams. Of particular importance may be questions concerning foam stability. For example, several studies have shown that the collapse of foams can be initiated and controlled using ultrasonic waves [14,15]. Coupling such kind of investigations with those of the rupture mechanisms of an individual soap film, carries the promise of providing important ingredients for the theoretical modelling; in particular for the influence of the physico-chemical properties of the system. Equally, investigations of the rupture of soap films under an acoustic forcing may allow to better understand the absorption of shock waves by liquid foams [16].

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