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Vibration of soap films and Plateau borders, as elementary blocks of a vibrating liquid foam

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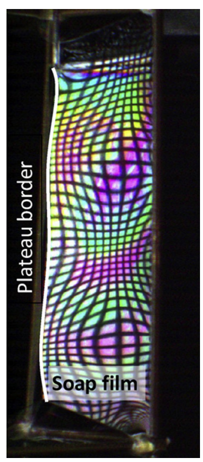
HIGHLIGHTS

- Dispersion relation and attenuation of a transverse wave along a soap film.
- Dispersion relation and attenuation of a transverse wave along a soap film junction.
- Several regimes are identified as a function of the frequency.
- The surrounding gas is essential in the propagation of transverse waves.
- The interfacial and bulk rheology of the liquid plays no role, in our conditions.

GRAPHICAL ABSTRACT



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ABSTRACT

The propagation of an acoustic wave in a liquid foam results from the coupling of a pressure wave in the gas phase and the vibration of the liquid backbone of the foam. At the bubble scale, the foam liquid skeleton is made of soap films connected by liquid channels. We study here the transverse vibration of those constitutive elements. The measurement of the velocity and attenuation of the transverse wave on each element isolated on a rigid frame, compared with an analytical modeling, reveals the main sources of inertia, elastic restoring forces and dissipation, for frequencies ranging from a few tens of Hz to a few kHz. In the case of a transverse wave propagating on a single soap film, we show that (i) the wave velocity is set by the surface tension and the inertial mass of the film loaded by the surrounding air, and (ii) that the damping of the wave is mainly due to the viscous dissipation in the air. In the case of a transverse wave propagating along the junction line between three soap films (Plateau border), the dispersion relation reveals two different scalings at low frequency and at high frequency, which are interpreted by considering the role of the vibration of the adjacent soap films, and the role of the inertia of

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the liquid inside the channel. The attenuation of the transverse wave along the liquid channel is measured in the low frequency regime. In both investigated cases (transverse wave propagating on a soap film as well as on a liquid channel), we show that the surrounding gas plays a dominant role, whereas the role played by the interfacial rheology is negligible.

1. Introduction

Foams are typical examples of complex fluids, whose macroscopic properties depend on the microstructure of the material. A liquid foam is a dispersion of gas bubbles in a liquid matrix, stabilized by tensioactive molecules or particles. The liquid skeleton, organized to minimize its interfacial energy, is structured by a few geometrical rules known as Plateau's rules: the soap films between bubbles meet by three in liquid channels also called Plateau borders, which themselves meet fourfold at the vertices of the liquid network (see Fig. 1) [1,2]. Models at the scale of the bubble are needed to explain the macroscopic behaviour of foams, such as their complex rheological response under shear [3], their electrical conductivity [4], the drainage of the liquid phase out of the foam [5], or the filtration of solid particles by a liquid foam [6].

Amongst the foam physical behaviours, a still little explored domain is the acoustic propagation in foams. Foams are nevertheless used for mitigating blast waves, thanks to their strong acoustic attenuation [7,8]. At smaller acoustic amplitudes, the acoustic velocity and attenuation in the foam have been shown to depend on the liquid content [9] and on the bubble size [10].

It has been recently shown that the acoustic propagation in a foam strongly depends on the frequency and the bubbles average diameter d [11,12]. Several regimes of propagation have been identified: two non-dispersive regimes at low and high frequencies, separated by a resonance, with a maximal attenuation and a negative density behavior. A model at the scale of the bubble successfully explains these three regimes [12]. The propagation of an acoustic wave in a liquid foam couples a pressure wave which propagates in the gas and the vibration of the liquid skeleton. Due to the cellular geometry of the foam, the compression wave generates transverse vibrating waves in the liquid phase. Hence, the relevant length scale for describing the acoustic propagation in foams is not the acoustic wavelength in the foam, which is, in general, several orders of magnitude larger than d,[2] but the wavelength of the vibration wave on the liquid interfaces, at the forcing frequency.

In this article, we investigate the vibrations of the liquid skeleton of a dry foam. We isolate one by one the constitutive elements of the liquid skeleton, and we measure the dispersion relation and the attenuation of a transverse wave propagating on each of these elements. In Section 2, we study an isolated soap film submitted to a transverse vibration (bending wave). We measure the phase velocity and the attenuation of the wave. We develop a theoretical modeling to identify the relevant parameters that contribute to the inertial and elastic response of the vibrating films, and to the dissipative effects.

When the soap films meet at a Plateau border junction, the inertia of the liquid in the channel must be taken into account, as well as the tensile surface forces exerted by the soap films on the Plateau border. Does the Plateau border vibrate like the free border of a liquid membrane, or does it behave as an inertial liquid string? In Section 3, we show that the answer is in between: two regimes are identified as a function of the frequency. In Section 4, we finally

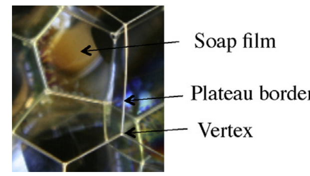

Fig. 1. At the bubble scale, the vibrating skeleton of the foam is composed of coupled soap films and Plateau borders, and four plateau borders meet at a vertex. Here, the bubble size is millimetric and the volume fraction of liquid in the foam is about 1 percent.

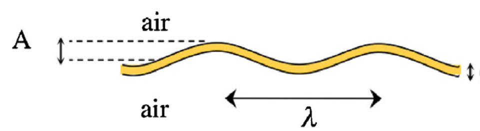

Fig. 2. Antisymmetric wave on a soap film, i.e. with the interfaces of the film vibrating in phase with each other. A is the amplitude of the wave, λ the wavelength, and e the thickness.

replace the results in the light of the recent studies of the acoustic propagation in a liquid foam, and we discuss the outlooks of this work.

This article is a synthesis of results obtained in previous publications [13,14], and complementary results. All those results are explained in this article in order to get a complete picture of the dynamics of the studied systems.

2. Transverse vibration of a single soap film

We consider a horizontal soap film, surrounded by air, which is freely suspended on a rigid frame. When the frame is vibrated vertically using an electromagnetic shaker, a wave is created at the periphery of the soap film and travels up to its center where it is totally reflected (in the linear limit where the amplitude is small compared to the wavelength). Then a transverse standing vibration takes place on the soap film. Several vibration modes are theoretically predicted [15]: a so-called symmetric mode, where the interfaces of the film undulate in anti-phase, and an antisymmetric mode where they undulate in phase with each other. In our experiments, no thickness variation is associated to vibration, which means that the soap film vibrates in the antisymmetric mode, as sketched in Fig. 2. To characterize the antisymmetric wave appearing on the soap film, we develop two experimental setups in order to determine the complete dispersion relation (real part and imaginary part): the first setup gives access to the measurement of the wavelength as a function of the frequency for different thicknesses of the soap film; the second setup allows to measure the dissipation as a function of the frequency, in the case of thin films. The results are compared to the predictions of a model detailed in a previous article [13].

2.1. Wavelength

2.1.1. Setup and measurements

A horizontal soap film is formed upon a cylindrical plexiglas tube of 16 mm of diameter, which is mounted on an electromagnetic

[2] The typical acoustic wavelength in air is about 3 mm at 100 kHz, and about 30 cm at 1 kHz.

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