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Elastic waves generated by laser induced bubbles in soft solids

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Abstract

We experimentally investigate the generation and propagation of elastic waves in gelatin occurring during the collapse of laser induced bubbles. Sub-millimeter sized bubbles are generated with a pulsed 6ns laser within the tissue mimicking material. The stress fields and wave propagation is visualized with elastography, a method where the polarity of a polarized light is altered by the state of stress of the medium. High-speed photography captures the fast dynamics of the bubbles and is used to describe the succession of events leading to the wave emission. 4 configurations of bubble collapse are studied; spherical and non-spherical collapses in the bulk, collapse near a wall and collapse near a free surface.

Keywords: elastic waves; cavitation; laser induced bubble; soft-solids; gelatin; stress waves

Introduction

Cavitation is commonly utilized for numerous medical procedures [2]; still there is considerable lack of knowledge on the mechanisms of cavitation and the complex bubble dynamics in biological tissues. Most biological media have viscoelastic properties and as such they possess both liquid (viscous) and solid (elastic) behaviors. In experiments, it is frequent to replace the tissue with a mimicking phantom such as a gelatin-based mixture [4] which allows to cover a wide range of mechanical properties from quasi-Newtonian liquids to soft-solids by varying the gelatin/water ratio. Experiments on cavitation in soft solids have shown that longitudinal waves traveling at the speed of sound analogous to those found in liquids are produced during bubble collapse [3, 6]. But unlike liquids, soft solids elasticity allows transversal waves of much slower speed (few $m.s^{-1}$) to propagate [5].

In this paper, we experimentally study the generation and propagation of these elastic waves in gelatin created by the collapse of laser induced bubbles. The waves are made visible using elastographic methods where the polarity of a polarized light is altered by the state of stress of the medium through which they propagate. High-speed photography captures the fast dynamics of the bubbles and describes the succession of events leading to the wave emission. We describe 5 typical configurations of bubble dynamics leading to spherical and non-spherical collapse, the later are causing an emission of stress waves.

Method

Soft solids preparation

Gelatin was chosen as base to prepare the soft samples for its optical properties; i.e optical transparency and birefringence allowing high-speed recording for monitoring the bubbles dynamics and the resulting stress waves. The soft solids samples are prepared using industrial gelatin (Industrial Gelatin 250bloom, Yasin Gelatin CO.,LTD). The powdered gelatin is mixed with deionized water and is dissolved on a steering hot plate (T = 70°C, steering force = 3) until no grains are visible. Then the hot mixture is poured into a glass container and is let to cool down at lab temperature before being stored in a fridge for at least 24 hours before usage. The mass ratio of Gelatin to water so far studied can be varied between from 2% to 16%.

Bubble nucleation and recording system

The experimental setup is portrayed in a side-view in figure 1. A green Nd:YAG laser (New wave research Orion, $532nm$, $6ns$) emits a single laser pulse which is focused into the gelatin using a microscope objective (Olympus $10x$ Plan Achromat, $NA = 0.25$). At the focal point, optical breakdown occurs generating a sub-millimeter sized bubble. The dynamics of the bubble, i.e expansion, collapse and rebounds, is recorded at frame rates of up to 400,000 frames per second (fps) using a high speed camera (Photron, Fastcam, SA-X2) equipped with a macro camera lens (Nikon, 60mm f/2.8 Micro-NIKKOR AF-D).

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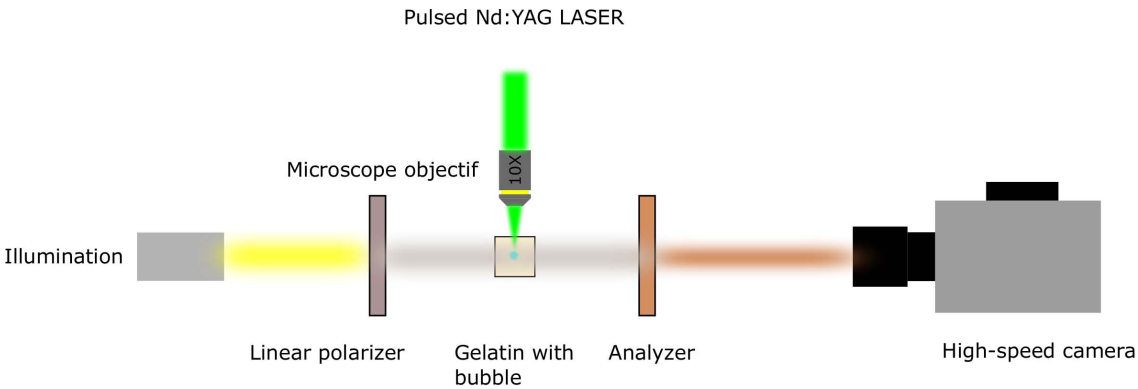

Figure 1: The experimental setup used for visualization of elastic waves generated by laser induced bubbles in soft solids

Plane polariscope

The plane polariscope is a classical device used in photoelasticity [7] to observe changes of mechanical properties of a birefringent material under mechanical deformation. It is composed of a coherent light source, a polarizer and an analyzer. The gelatin phantom is placed between the polarizer and analyzer, as shown in figure 1. Figure 2 illustrates the working principle of the plane polariscope: The light polarized by the polarizer enters and propagates through the transparent sample. Due to the birefringent properties of the gelatin, the light propagates along the principal stress directions. The light passes then through the analyzer with the optical axis oriented perpendicular to the analyzer's axis. In the absence of stress, the gelatin behave as a non-birefringent medium and the polarization is unchanged, thus the light passing through the phantom is blocked by the analyzer. If stresses are present in the gelatin, the birefringence rotates the polarization and as a result some of the light passes through the analyzer and blobs of light are recorded with the high-speed camera.

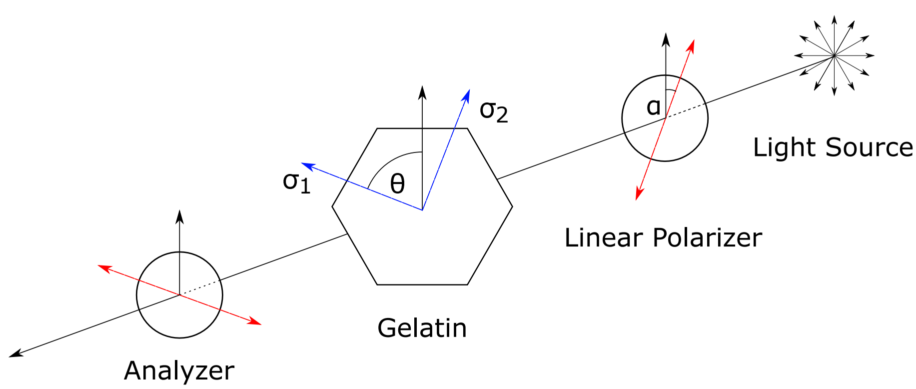

Figure 2: Optical principle of the plane polariscope; in red the optical axis of the polarizer and analyzer, in blue the principal stress direction of the gelatin

Using trigonometry, we can express the intensity of the light exiting the analyzer:

$$I = k^2\, sin^2(2\theta)\, sin^2(\frac{\delta}{2})\, cos(\alpha) \tag{1}$$

where α is the angle of the polarizer with respect to the vertical axis. Polarizer and analyser are kept at $90°$, θ is the angle between the fast axis and the vertical axis, and δ is the phase difference (retardation) between σ_1 the fast axis and σ_2 the slow axis. For white light, this equation possesses one solution for which the intensity is zero:

$$sin^2(2\theta) = 0, \quad i.e \quad \theta = 0, \frac{\pi}{2} \tag{2}$$

For this case, the principal stress directions and the axis of the polarizer and analyzer are coincident and thus the resulting intensity is zero. Those are the *isoclinics*, they indicate the stress principal directions.

Figure 3 depicts experimental and numerical examples of isoclinics. Patterns with four "stress lobes" are observed due to the presence of isoclinics along the horizontal and vertical [A][B] or at 45° [C][D].

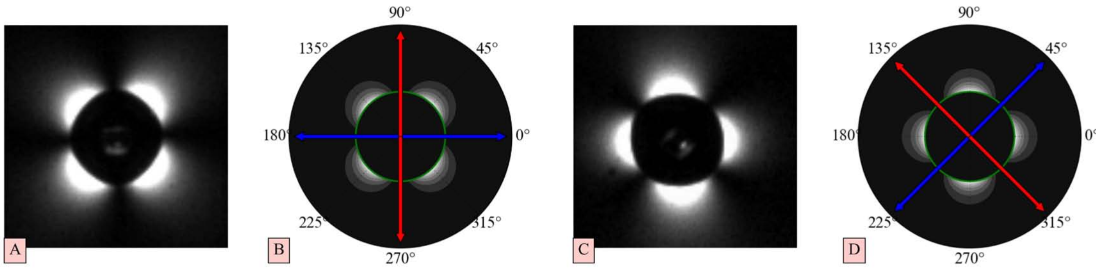

Figure 3: Stress patterns around an expanding bubble. Bright areas indicates areas of stress, red and blue lines illustrate the positions of the optical axis: $\theta = 0$ for [A] (experiments) and [B] (model), $\theta = 45$ for [C] (experiment) and [D] (model)

Results

Spherical bubble collapse

We show first the bubble dynamics in absence of polarizers before we discuss the stress patterns observed. Figure 4 shows selected frames of the dynamics of a single bubble created in the bulk, i.e far from any wall or pre-existing bubble. The time between two frames is $\Delta t = 13.3\mu s$. In the first frame, the bright dot shows the optical breakdown preceding the bubble. After $t \approx 26.67\mu s$ the bubble reaches maximum radius ($r_{max} \approx 325\mu m$), then starts to shrink before symmetrically collapsing after $t \approx 53.34\mu s$. After the first collapse the bubble rebounds and collapses a second time around $t \approx 133.3\mu s$. The bubble in figure 4 remains mostly spherical during the two first collapses and rebounds.

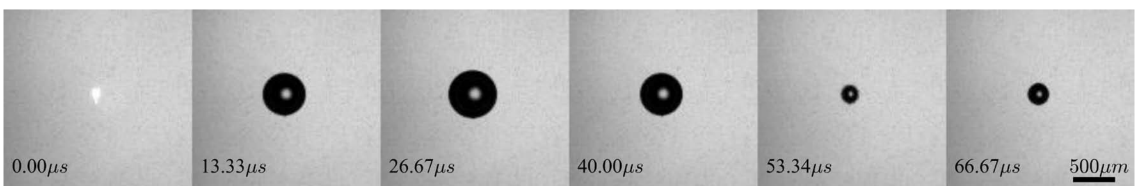

Figure 4: Dynamics of a laser-induced bubble in 4% gelatin

Figure 5, depicts a similar bubble collapsing symmetrically but now observed through the plane polariscope with $\theta = 0$. The use of the polariscope unveils the "bright lobes pattern" around the bubble. The intensity of the lobes can be related to stress intensity using equation 1. As expected the size of the lobes and thus the stress is maximum when the bubble reaches its maximum size. The experiment was repeated for different Polarizer/Analyzer orientations and demonstrates that the stress around the bubble is purely radial, i.e the gelatin near the bubble is compressed during the bubble oscillations. From recording, no apparent elastic waves are created during a symmetric collapse.

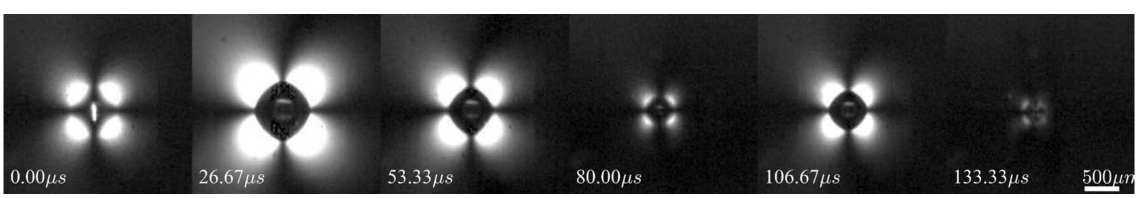

Figure 5: Spherical collapse of laser-induced bubble in 4% gelatin observed using a plane-polariscope, $\theta = 0$

Non-spherical bubble collapse

The mostly spherical collapse as observed in the previous pictures is rarely happening. Most of the times mild asymmetries in the laser breakdown, inhomogeneities of the material (e.g. from previous bubble experiments) or boundaries even far away result in non-spherical dynamics. One of these cases is depicted in figure 6. Interestingly, although the bubble reaches a spherical shape during expansion, surface modes are amplified during the collapse and it moves slightly towards the right while losing its spherical shape. During the second collapse the bubble moves back to the left.

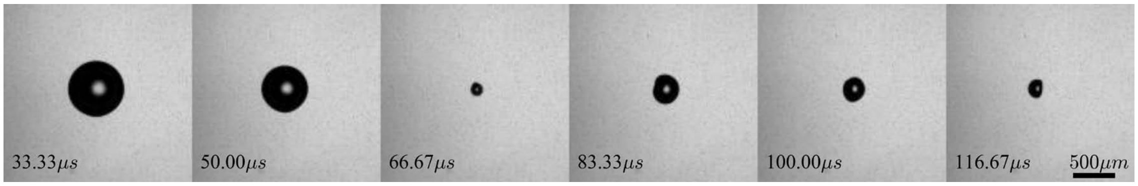

Figure 6: Non-spherical collapse of a bubble in 4% gelatin

The stress patterns during the non-spherical collapse of a different but similar oscillating bubble is depicted in figure 7. Before collapse, the pattern of four quasi-symmetric bright lobes is similar to the previous case. However, during collapse, after $t = 80\mu s$, the bubble moves toward the right by about $\approx 100\mu m$. This movement starts a faster inflow at the left bubble wall, which creates shear-stresses along the translational direction. Although we do not observe a jet piercing through the bubble, some indentation is developing on the left side of the bubble, see also in the fourth frame of figure 6. This stress propagates outwardly from its initial position with a speed of $\approx 3m.s^{-1}$, the two last frames of figure 6 show its position at later stages.

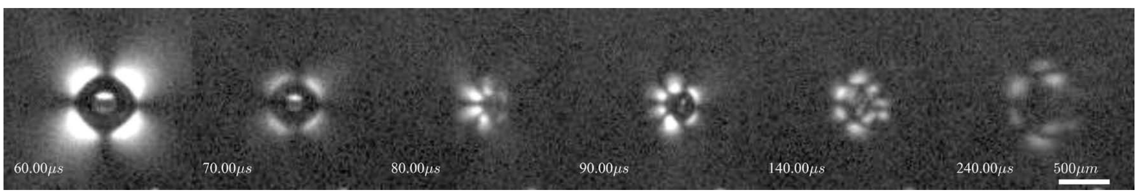

Figure 7: Non-spherical collapse of a laser-induced bubble in 4% gelatin using plane-polariscope, $\theta = 0$

Bubble collapse near a rigid wall

The experiment was repeated for a bubble created close to a solid wall. In this case, observations have shown that the bubble collapsing in gelatin resembles to some extend the bubble collapsing in water: during collapse, the bubble moves towards the wall and a deformation occurs on the wall opposing side leading to the development of a jet. In contrast to water the bubble moves back to its original position due to the elasticity of the medium.

The figure 8 shows the collapse of a bubble created at a distance $L \approx 900\mu m$ from the wall, the standoff parameter is $\gamma = \frac{L}{r_{max}} \approx 1.5$. The bright lines (indicated with arrow) propagating from the top are elastic waves created during the bubble nucleation due to the interaction of the shock-wave induced during optical breakdown and the wall. The translational motion of the bubble towards the wall launches a shear wave starting from the site opposite of the wall, which propagates outward to the left and right initially as a cylindrical wave. The amplitude of the stress waves quickly ceases with distance, likely due to symmetry and viscous dissipation in gelatin.

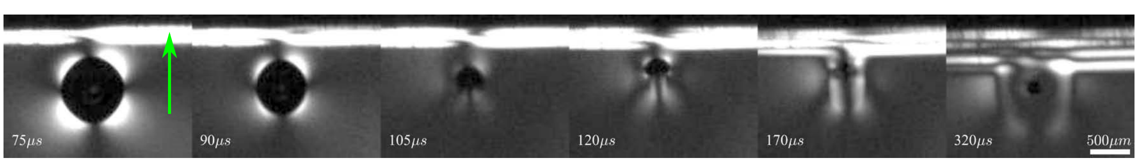

Figure 8: Bubble collapsing near a wall in 4%- gelatin using plane-polariscope with $\theta = 0$

Bubble collapse near a free surface

A bubble collapsing in water near a free surface will translates and jets away from the interface. In gelatin we observe similar behavior, here the bubble initially moves towards the interface during expansion but is "pulled back" to its position of generation during collapse. Figure 9 displays selected pictures of a bubble collapsing in 4%-gelatin near a free surface observed with a plane-polariscope ($\theta = 0$). Due to the presence of the curve soft boundary the gelatin is in a pre-stress condition and appears bright. Compared to the previous collapse near a wall, the situation is inverted, the bubble collapses away from the free surface and the quasi-jetting happens on the free surface side and the shear wave "tail" appears between the interface and the bubble.

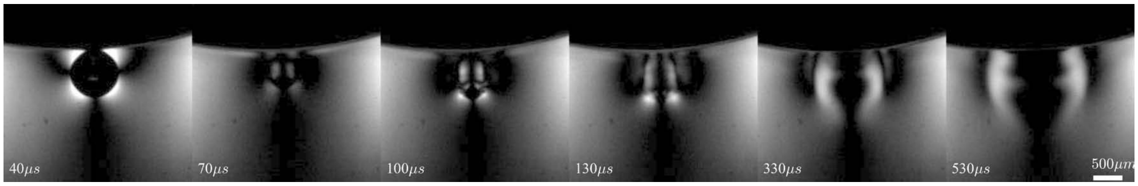

Figure 9: Bubble collapse near a free surface in $4-\%$ gelatin using plane-polariscope with $\theta = 0$

Discussion and conclusion

The present study is to our understanding the first report of elastic waves generated from non-spherical bubbles collapsing in a tissue-mimicking material. While spherical bubbles generate a stress field, non-spherical bubbles create stress waves due to center-of-mass translation. There we expect that the bubble moves with a speed much faster than the elastic wave velocity. The resulting wave pattern thus are Mach cones, resembling the wave generation in supersonic shearwave elastography [1]. Besides the four demonstrated cases of spherical, non-spherical, rigid and free boundary collapses, we expect also for the shock wave-gas bubble interaction the formation of stress waves. Although not shown here, the stress wave may not be generated at the location of bubble nucleation but at the location of the gas bubble impacted by the shock thus far from the origin of nucleation. This may have important consequences for medical applications of shock waves. The research presented here is only a starting point and demands for a quantitative analysis and simulations of the wave propagation. Monitoring biological cells at various distance from the bubble may allow to evaluate the importance of stress waves for cell viability or drug delivery. At last we expect that the strength of the elastic waves may be strong function of the gelatin concentration and bubble size and have some optimum at intermediate values. This again needs more experimental and numerical work.

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