Coupling of cavitation with transverse waves through elastic solids

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Coupling of cavitation with transverse waves through elastic solids

Julien Rapet

SCHOOL OF PHYSICAL AND MATHEMATICAL
SCIENCES

2019

Coupling of cavitation with transverse waves through elastic solids

Julien Rapet

SCHOOL OF PHYSICAL AND MATHEMATICAL SCIENCES

A thesis submitted to the Nanyang Technological University
in partial fulfillment of the requirements for the degree of
Doctor of Philosophy

2019

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I hereby certify that the work embodied in this thesis is the result of original research done by me except where otherwise stated in this thesis. The thesis work has not been submitted for a degree or professional qualification to any other university or institution. I declare that this thesis is written by myself and is free of plagiarism and of sufficient grammatical clarity to be examined. I confirm that the investigations were conducted in accord with the ethics policies and integrity standards of Nanyang Technological University and that the research data are presented honestly and without prejudice.

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Assoc. Prof. Rainer Helmut Dumke

Authorship Attribution Statement

The thesis contains materials from 2 papers published in the following journals where I was the first and/or corresponding author.

Chapter 2 was published as Julien Rapet and Claus-Dieter Ohl. Elastic waves generated by laser induced bubbles in soft solids. *In Proceedings of the 10th International Symposium on Cavitation (CAV2018)*. ASME Press, 2018. 10.1115/1.861851_ch68

The contributions of the authors are as follows:

- I designed and conducted the experiments, collected and analyzed the results and wrote the manuscript.
- Prof. Claus-Dieter Ohl supervised the project, provided help and guidance and participated to the writing and revision of the manuscript.

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The contributions of the authors are as follows:

- I designed and conducted the experiments and the simulations, collected and analyzed the results, and wrote the manuscript.
- Prof. Yoshiyuki Tagawa, provided help and guidance for the simulation, data analysis and the physical model and participated to the writing and revision of the manuscript.
- Prof. Claus-Dieter Ohl supervised the project, provided help and guidance and participated to the writing and revision of the manuscript.

Chapter 4 has been submitted and is under revision by *Physics Review Letters*

The contributions of the authors are as follows:

- I designed and conducted the experiments and the simulations, collected and analyzed the results, and wrote the manuscript.

- Dr. Pedro A. Quinto-Su, conducted the streak-photography experiment, provided help and guidance for the physical model and participated to the writing and revision of the manuscript.
- Prof. Claus-Dieter Ohl supervised the project, provided help and guidance and participated to the writing and revision of the manuscript.

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Date

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Julien Rapet

Abstract

Cavitation is nowadays used for many medical applications, however the dynamics of cavitation in solids is not well understood. Liquids and solids can support the propagation of longitudinal / pressure waves. But thanks to their elasticity, solids can also transport transverse / shear waves. In this thesis, we present two discoveries involving coupling between cavitation and transverse waves through solids. We show the first evidences of the emission of shear waves during the collapse of laser induced bubbles in a soft solid and we described a non-yet reported novel mechanisms to generate cavitation from transverse waves in a thin liquid layer confined by two solid walls. Experimental and numerical methods are discussed, and models are proposed to explain the observed phenomena.

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Julien Rapet, August 2019

“Bubbles! Bubbles! My bubbles.” ”

—Bubble the yellow tang (In finding Nemo, 2003)

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Chapter 1

Introduction

Bubbles have for a long time been a subject of fascination and curiosity. They can be found almost everywhere in nature. Produced by natural running water at the foot of a waterfall [67] or at the tip of a breaking wave [29, 109], by thermal or chemical reaction in a kettle of boiling water or in a magma pool [87, 119] but also by living organisms [70]. Their round shape, apparent emptiness and short lifetime have inspired mankind, proverbs and sayings from the ancient Greek [92, 93] - “Πομφολυξ ο ανθρωπος”, “Man is a bubble” -, to the modern French who like to - “buller” or “coincer la bulle”, “to bubble” or “to wedge the bubble” - when they do nothing [51]. Metaphor for the fragility and brevity of human life [8, 93] for the 17-18th Centuries painters. Symbol of an uncertain and ephemeral economic situation in our modern era [72, 102]. But despite the collective imaginary of simple round-shaped bubbles flying with the wind, slowly raising to the water surface and gently popping, bubbles are very complex objects and their behavior from creation to disappearance can lead to dramatic effects. We have all created vapor bubbles by cooking a pot of water and observe a mild simmering turning into an explosive bubbling. There, when the temperature rises above a certain threshold, vapor bubbles start to form, this is referred as boiling [24]. A similar phenomenon is known as “Cavitation”, from the Latin “cavus” meaning hollow [118]. There, vapor bubbles or cavities appear when the liquid pressure locally drops below the

vapor pressure [12, 38]. Figure 1.1 illustrates the two different phase transitions from boiling and cavitation in the water phase diagram.

FIGURE 1.1: Water phase diagram: the red arrow illustrates the phase transition in boiling and the blue arrow indicates the change of phase in cavitation.

Because cavitation bubbles are created by abrupt pressure changes, their later dynamics is mostly dominated by inertia when the liquid temperature is far below the boiling point. It results in strong collapses and dramatic side effects which are of great interest for many fields of research and practical applications.

1.1 Cavitation: from inefficient ships to medicine

The history of cavitation in modern sciences started a bit more than a century ago, when naval engineers realized that a new ship they had designed could not reach the expected performances [108]. They quickly observed that vapor cavities were forming around the propellers [118] disturbing the hydrodynamic flows. This observation and the need to mitigate it opened a new research field on cavitation bubble dynamics.

The nucleation of bubbles around the propellers was explained by the presence of regions of low-pressure in the flow where water was exposed to pressure below vapor pressure [12, 38, 62]. Such areas can also be found in many other hydraulic systems

such as pumps [5], valves [73], turbines [5, 34, 64], artificial hearts [13, 46] but also in trees where drought conditions can lead to cavitation in xylem [112, 113].

Soon it was discovered that the collapse of such bubbles is accompanied by dramatic side-effects. During the bubble collapse, the liquid is rapidly and highly compressed and shock waves are emitted [53, 84]. In the case of a non-spherical collapse, many shock waves can be emitted arising from the complex collapse of the bubble and its splitting into several daughter bubbles [90, 104, 116]. The amplitude of the emitted pressure waves can reach several GigaPascal [1, 88]. When a bubble loses its spherical symmetry during the collapse, parts of the bubble's interface will shrink at different velocities. In particular in the presence of a pressure gradient a high-velocity liquid jet is formed and pierces the bubble [81, 103, 110]. With special geometry and kind of pressure gradient the jet velocities can reach several hundred meters per second [65, 81]. Depending on its content and the presence of non-condensable gases, the bubble may eventually rebound and undergo further and milder collapses where again acoustic transients are emitted and jets can form. These dramatic side-effects are responsible for the observed erosion of the nearby surfaces [4, 90]. Thus in many applications cavitation was first studied by the need to avoid it. Later scientists realized that cavitation could also have beneficial usages. Industrial applications of cavitation include surface [94, 101] and membrane [45] cleaning, water-treatment [6], material synthesis [120] or even processes optimization during brewing [2].

Another area where the characteristics of cavitation have shown useful are biomedical applications [13]. In non-invasive surgery, cavitation is commonly used for the ablation of soft tissues such as in histotripsy [60, 74, 95, 114] where ultrasound pulses of finite amplitude are focused in the tissues to induce intense cavitation which turns the tissue into a paste. To remove hard bodies, for example ureteral or kidney stones, lithotripsy [23, 91] and high intensity focused ultrasound (HIFU) [26, 59] are now standard procedures. The former uses focused shock waves to destroy the stones into pieces small enough to be carried out of the body by blood or urine. The latter is designed to maximize cavitation activities around

the stone to optimize its grinding. Laser pulses and cavitation are also used in cataract, cornea and intraocular surgeries [50, 56, 71, 111, 115] to locally vaporize tissues and produce clean ocular cuts.

1.2 Cavitation generation

We have seen that cavitation can naturally and artificially be created by hydrodynamic flows where sufficient low-pressure regions are formed. However such mechanisms are not always suitable in many engineering or research applications. In many cases, repeatable, consistent, targeted, tunable and often single-bubble cavitation is required. Several techniques have been developed to have that precise control of size, timing and location:

FIGURE 1.2: Frame from the high-speed recording of a plasma created by a pulsed laser in gelatin. The laser pulse (New wave research Orion, $532nm$, $6ns$, $114mJ$) propagates from right to left.

Laser induced bubbles Short duration pulsed laser (femto- to nanosecond) can be focused to create single bubbles [1, 16, 79, 83, 110]. For high intensities the energy is sufficient for multiphoton ionization and amplification through subsequent avalanche ionization [96]. The thereby formed plasma cools quickly down after the end of the laser pulse, recombines and an explosively expanding vapor bubble emerges. Laser induced bubbles are a convenient way to obtain single and repeatable bubbles with controllable dimensions. Indeed, the size of the bubbles are easily tuned by changing the laser energy. Even the shape of the bubble can be altered using different focal geometries which can be modulated with a digital hologram[68]. Fig. 1.2 displays a frame extracted from a high-speed recording, it

shows the double cones of the laser path and the plasma (bright dot) created at the focal point.

Underwater explosions Bubbles are created by the detonation of an explosive charge. The size of the bubbles depends on the amount of explosive used and ranges from centimetric size for small-charge experiments to tens of meters in diameter for example in the case of the explosion of a half a tonne torpedo. [22, 27, 32, 61].

Spark cavitation Electricity might be used to induced cavitation. In spark cavitation, an electric discharge takes place between two electrodes and generate a dielectric breakdown leading to the creation of an explosive bubble, this is similar to the laser bubble described above. [28, 44].

Acoustic cavitation Another very common method to generate cavitation is to use acoustic waves. Different mechanisms can be involved, ultrasound waves can be used to expand pre-existing gaseous nuclei [17, 31, 52] and tensile waves can bring the liquid under tension to rupture and create bubbles [3, 82]. The second case is illustrated in fig. 1.3, where a secondary cavitation event is created by a shock wave reflected as tensile wave at a free surface. The shock wave is emitted during the collapse of a laser induced bubble.

1.3 Cavitation in soft solids

For historical ground as much as simplicity reasons, the study of cavitation has been for a long time mostly focused on cavitation happening in Newtonian liquids and especially in water. Numerous extensive reviews are available [10, 12, 38, 66]. Despite the now long use of cavitation in medical treatments, the understanding of cavitation dynamics in non-Newtonian bio-fluids and bio-tissues [20] remains incomplete. Reviews on previous work primarily focused on non-Newtonian fluids can be found in [40] and [15]. Soft solids have recently attracted more interests and many numerical models have been developed. Yang and Church [121] combined the Voigt model and Keller-Miksis equation for the study of forced oscillating bubbles

FIGURE 1.3: Snapshot extracted from a high-speed recording (162000 fps) of a laser-induced bubble collapsing near a free surface in a 4% gelatin phantom. The image is captured $117.3\mu s$ after nucleation. The laser-induced bubble is rebounding after the first collapse and shows as two ring-shaped bubbles. Between those bubbles and the free surface we can observe a cavitation cloud created by the tensile reflection of a shock wave emitted during the collapse.

in a compressible viscoelastic solid. Nonlinear oscillations following a Rayleigh collapse in a linear viscoelastic medium by coupling the Keller-Miksis equation and the Zener model were considered by Hua and Johnsen [55]. Gaudron et al. [41] used a Rayleigh-Plesset equation, modified to include the Mooney-Rivlin and neo-Hookean models, to account for medium relaxation. Cohen and Molinari [21] proposed analytical solutions for a spherical void expanding in a nonlinear viscoelastic medium. Solano-Altamirano et al. [99] used a modified Young-Laplace equation including elastic effects to study bubble dynamics in soft materials. Warnez and Johnsen [117] used various equations for viscoelastic media with relaxation to model single bubble dynamics. Barajas and Johnsen [7] proposed a model combining Kelvin-Voigt model and neo-Hookean formulation for bubbles in a viscoelastic medium accounting for full thermal effects inside and outside the bubble. Zilonova et al. [122] used a modified Gilmore-Akulichev model to study the dynamics of bubbles in a soft tissue subject to HIFU excitation. However much of those models still lack of experimental verification.

Experimental research on cavitation and bubble dynamics in soft solids can be split in three categories depending on the process used for creating the bubbles.

Cavitation in soft solids can be obtained from mechanical stress for example by the means of a drop tower as Kang et al. [57], [58] used to look at the mechanism of cavitation nucleation in gelatin. The impact of a striker on the test medium has also been used by Canchi et al. [19] to investigate injuries consecutive to the collapse of a single bubble in brain tissues. Ultrasound cavitation commonly used in liquids can also be applied for bubble nucleation in soft solids. Maxwell et al. [75] investigated the possibility of inducing cavitation in tissues and tissue-mimicking materials exposed to single and intense ultrasound pulses. Mohaved et al. [77], [78] observed bubble clouds in tissue-mimicking agar samples subjected to burst-wave lithotripsy-like waves and developed a fracture-based bubble dynamics model. For single bubble observations, laser-induced cavitation has been widely used. The dynamics of bubbles created with laser in gelatin and acoustically driven were found by Hamaguchi and Ando [49] to have good agreement with numerical models combining the Voigt model and linearized Rayleigh-Plesset equation. Acoustic driven bubbles were also used by Shirota and Ando [98] to estimate mechanical properties of gelatin phantoms, while Estrada et al. [35] used high-speed imaging of bubble collapses coupled with numerical models to characterize properties of soft material. Furthermore, it was reported that similar to what happens in liquids, longitudinal or pressure waves at the speed of sound are emitted in soft-solids during the bubble collapse. Brujan and Vogel [14] observed stress-waves emitted by laser induced bubbles in transparent polyacrylamide (PAA) gel phantoms and Oguri and Ando [80] studied cloud cavitation created by a shock-bubble impact in gelatin.

1.4 Elastic waves in soft solids

Tissue mimicking materials [18] such as polyacrylamide, agar, gelatin and other hydro-gels are soft-solids possessing rigidity and elasticity. They can transport longitudinal waves their elasticity also supports shearing [11] and therefore transversal waves traveling at a velocity of typically a few meters per second [42], i.e.

FIGURE 1.4: (a): Longitudinal wave (P). The medium deformation is parallel to the direction of wave's propagation. (b): Transverse or shear wave (S). The medium deformation is perpendicular to the direction of wave's propagation.

$1 \text{ m/s} < v_s < 50 \text{ m/s}$. An illustration of these two types of waves, namely longitudinal and transversal or shear waves is sketched in Fig. 1.4. The velocity of the longitudinal (v_p) and transverse waves (v_s) can directly be related to the material's mechanical properties (density ρ , young's modulus E , shear modulus G , and Poisson's ratio ν) [63]:

$$c_p = \sqrt{\frac{E(1-\nu)}{\rho(1+\nu)(1-2\nu)}} \quad (1.1a)$$

$$c_s = \sqrt{\frac{G}{\rho}} = \sqrt{\frac{E}{2\rho(1+\nu)}} \quad (1.1b)$$

Longitudinal acoustic waves are commonly used for medical ultrasound imaging. This non-intrusive imaging technique[54, 105] uses sound waves for diagnostic imaging of the human body. Acoustic (longitudinal) waves are mechanically created generally using piezo-transducer and propagate through the tissues. Their echoes are recorded and processed to display images of the scattered signals from the tissue. It is a well-established method thanks to its simplicity, low cost and capability of real-time observation. However, the technique does not allow obtaining information about the mechanical characteristics of the tissues. Changes of properties, for instance stiffness, of the tissues help to distinguish healthy areas from ill or damaged areas [86]. For example, liver's tissues would become stiffer in the case of liver fibrosis due to hepatitis C infection or cirrhosis [37, 123]. To gain more insight

about tissue properties, elastographic techniques [85] have been developed. There, a deformation / displacement / distortion is exerted on the volume of interest and the response of the medium is observed. This can be done in a quasi-static way, as for example during palpation diagnosis where hand and fingers are used for the mechanical excitation (pressure) and as sensors (stiffness sensation). Dynamic diagnosis can be established, there shear waves are used as displacement source and the tissue's response is captured via acoustic imaging or magnetic resonance imaging [9, 97]. Shear waves can be induced by different methods. It traditionally uses focused ultrasound waves [100], more recently new actuation mechanisms have been presented. One example is the local displacement within the elastic solid by the Lorentz force from a combination of an electric current and a magnetic field [47]. Another method is the displacement of the medium when bubbles are generated from electrolysis in a hydrogel block [76]. Shear waves can also be generated from localized heating [48] of a continuous wave laser beam that is absorbed at the surface of a soft solid. There two regimes are found: a thermoelastic regime where the thermal expansion creates the waves and an ablative regime where the vaporization of the surface leads to tissue deformation and shear waves emission.

FIGURE 1.5: Coup–contrecoup injury adapted from Ref. [33] with permission.

Those diagnostic imaging methods use waves of low amplitude, however if waves of sufficiently high amplitudes propagate through human tissues, they can lead to significant damages. For example, in extracorporeal shock wave lithotripsy (ESWL), the tensile part of the waves can induce cavitation at unwanted position [36]. In contrast positive pressures used for gallstone destruction and interacting with gaseous bodies nearby such as the lungs may cause bleeding [30]. Pressure waves may also be responsible for soft tissue damages observed in traumatic brain injury [33, 69]. There, damages are created by the high-pressure gradients due to the compression wave traveling from the impact (coup) position and by cavitation bubbles due to the tension waves reflecting at the back of the skull (contrecoup). Fig. 1.5 illustrates this injury dynamics.

Impacts can also induce shear waves of large amplitude [25, 107] which may cause damages e.g. blast-induced traumatic injuries [43, 89, 106, 107]. There, extensive shearing of the medium provoked the damages. A similar phenomenon is thought to be responsible for the injuries of tissues treated with repeated shock waves. The cumulative shock-induced shearing could result into lesions if the tissues do not have enough recovery time between repetitive shocks [39].

Starting from the work on cavitation in water, some attention has been given to the pressure waves emitted in soft solids by bubble collapse and laser induced bubbles. However despite evidence of shear induced damages in soft solids and growing interest for shear waves related medical applications, there exists so far only a weak link between the phenomenon of cavitation in soft solids and the generation of shear waves. In this thesis, we show what is to our knowledge the first experimental evidence that the collapse of single cavitation bubbles in a soft solids can not only generate pressure waves but also shear waves.

1.5 Guide to this thesis

Chapter 2 presents the first photoelastic observation of stress patterns around laser-induced bubbles collapsing in the bulk of a gelatin phantom. We consider two kinds of bulk collapses, the spherical collapse, where the bubble remains spherical during shrinkage and rebound and the non-spherical collapse where the bubble deforms and loses its symmetry. An experimental setup is developed that combines high-speed photography with photoelasticity to visualize the stress pattern and its evolution at sufficient frame rates. The theoretical background behind photoelasticity is developed and we produce a test case to assess the potential and limits of our experimental setup.

In **Chapter 3**, we investigate two cases where the bubble collapse in gelatin proceeds non-spherically and demonstrate the importance of jetting for shear wave generation. The two cases are the collapse of bubbles in the vicinity of a solid wall or a free surface. Taking as example the case of the collapse near a free surface, we explain the mechanisms behind the shear wave generation. The theory is supported by a numerical simulation using the Finite Element Method. We also show that the collapse of a bubble near a soft solid / air interface can potentially lead to permanent damage of the interface. We further introduce the possibility of generating transversal waves away from the laser focus and discuss potential experiments to further study those waves.

Chapter 4 presents a new way of generating fast and intense cavitation discovered during experiments discussed in **Chapter 3**. This novel method is based on the excitation of lamb modes in a microscopic liquid gap confined between two hard solids. The mechanisms behind this cavitation event was investigated using sub-picosecond and streak imaging for high-temporal resolution. We also ran Finite Element Method simulations coupling solid physics and acoustics. Using those results, a simple model explaining the phenomenon was produced. Experimental and numerical methods are described and the influence of some parameters such as gap height is discussed.

Chapter 5 concludes the different results developed and we end this thesis by opening perspectives on future work to utilize our discoveries.

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Chapter 2

Photoelastic stress visualization around laser induced bubbles

2.1 Introduction

Unlike liquids, soft solids possess elasticity and a rigid structure supporting shearing [4] and the propagation of transverse waves. Their speed is considerably slower than the longitudinal waves, typically of the order of a few meters per second [10]. In traditional elastography, where mechanical properties of human tissues are measured, such waves are tracked by monitoring the media response using ultrasound imaging or magnetic resonance imaging [10, 16, 20]. If those imaging methods show to be efficient for detecting static damages and abnormalities, they are limited by their acquisition frequencies ranging from tens of Hz to few thousands of Hz for Supersonic Shear Wave Imaging [2], which is insufficient for fast phenomena such as cavitation collapse. For imaging the dynamics of such events and their side-effects, high-speed cameras are widely used [14, 23]. However, while strong pressure waves are visible with shadowgraphy [15] or Schlieren [11] techniques as they typically result in a strong change of index of refraction, transverse stresses

and waves are more difficult to visualize. Thus we combined high-speed photography with photoelastic imaging to observe stresses generated by the oscillations of single bubbles.

In the following Chapter, we introduce the physical principle behind photoelasticity and describe the experimental methods used. A test case of a laser-induced bubble in the bulk of a gelatin phantom is shown and compared against the classical literature problem of a spherical cavity with internal pressure and we debate the validity of our methods. Finally, we present and discuss experimental results for two configurations, the spherical and non-spherical bulk collapses.

2.2 Photoelasticity

The term photoelasticity [8, 9, 12, 13, 19, 21] gathers the ensemble of experimental methods using the principle of birefringence to resolve mechanical stress and strain fields. Birefringence [6] describes the properties that some transparent materials possess of being naturally doubly refractive or to become temporary doubly refractive. The later category being the most commonly use in photoelasticity. Those materials are for example polymers and plastics that are optically isotropic when in no-stress conditions. When stress is exerted, the materials become doubly refractive (optically anisotropic), i.e any ray of light entering the material will be resolved and polarized along two optical axes, the ordinary respecting the Snell's law and the extra-ordinary violating it. Those optical axes coincide with the two local principal stress directions normal to the direction of light propagation. The two transmitted rays are now plane polarized with planes of polarization normal to each other. Thus the light exiting the medium is now polarized according to the state of stress of the medium. Figure 2.1 illustrates the transmission of an unpolarized ray of light through a birefringent material. Figure 2.1A shows the material at rest where the ray of light remains unchanged. Figure 2.1B corresponds to the material under stress where two polarized rays of light will exit the sample.

FIGURE 2.1: A: Illustration of the light passing through an isotropic material, the ray of unpolarized light (yellow) travels through the object without being altered. B: Illustration of birefringence: a ray of unpolarized light (yellow) enters a birefringent material and is decomposed in two polarized rays of lights, one ordinary (orange) and one extra-ordinary (red).

Rays of light passing through the material at rest (isotropic) follow the classical Snell's law (eq.2.1), where θ_A & θ_B are the angles of incidence and refraction, v_A & v_B and n_A & n_B respectively the velocities of light and the refractive indices in the media A & B .

$$\frac{\sin\theta_A}{\sin\theta_B} = \frac{v_A}{v_B} = \frac{n_A}{n_B} \quad (2.1)$$

A ray of light entering the material under stress (anisotropic) is resolved as two polarized rays. Those two rays have different velocities (v_1 & v_2) and leave the media with a phase difference δ (retardation) given by eq. 2.2. Where h is the thickness of the sample and f is the frequency of light and is equal to the velocity of light (c) divided by its wavelength (λ). n_1 & n_2 are the indices of refraction of the two rays.

$$\delta = 2\pi f \left(\frac{h}{v_1} - \frac{h}{v_2} \right) = 2\pi h \frac{c}{\lambda} \left(\frac{1}{v_1} - \frac{1}{v_2} \right) = \frac{2\pi h}{\lambda} (n_1 - n_2) \quad (2.2)$$

The relations between the refractive indices of the material at rest (n) and under-stress (n_1 & n_2) have been established by Maxwell in 1853 [17] and read as follow:

$$n_1 - n = c_1 \sigma_1 - c_2 \sigma_2 \quad (2.3a)$$

$$n_2 - n = c_1 \sigma_2 - c_2 \sigma_1 \quad (2.3b)$$

with σ_1 & σ_2 being the local principal stresses and c_1 & c_2 respectively the direct and the transverse stress-optic coefficients. Using the eq. 2.3, we can rewrite the retardation (eq. 2.2) as follows:

$$\delta = \frac{2\pi h}{\lambda} C (\sigma_1 - \sigma_2), \text{ with } C = c_1 + c_2 \quad (2.4)$$

This equation links the phase difference (retardation) between the two rays and the local state of stress.

2.3 Experimental devices for photoelasticity

In photoelasticity, the stress information are obtained by analyzing the light emerging from the sample. Different optical systems exist for this purpose and are known as polariscopes.

2.3.1 The plane polariscope

The simplest device used in photoelasticity is the plane polariscope. It is composed of a light source, two linear polarizers and a sensor (camera). The first polarizer is placed between the light source and the sample. The second one referred as “analyzer” is placed between the sample and the camera. Polarizer and analyzer have their optical axis oriented 90° towards each other. The working principle of the plane polariscope is depicted in Figure 2.2.

FIGURE 2.2: Optical principle of the plane polariscope; in red the optical axis of the polarizer and analyzer, in blue the principal stress direction of the sample.

The intensity of the light going out of the plane polariscope and captured by the sensor can be calculated using trigonometry and by following the path of the light through the different elements.

The light exiting the polarizer is $I_0 e^{i\omega t}$ and is polarized along its optical axis. For explicit calculation, we consider only the real part [19]:

$$E_p = I_0 \cos(\omega t) \quad , \quad (2.5)$$

here I_0 accounts for the intensity of the light source passing through the polarizer.

It then propagates through the birefringent medium and results in two diffracted rays. They are resolved along the optical axis of the sample, which coincide with the principal stress directions, and exit with the relative retardation δ .

$$E_{s1} = I_0 \cos(\omega t - \frac{\delta}{2}) \sin(\theta) \quad (2.6a)$$

$$E_{s2} = I_0 \cos(\omega t + \frac{\delta}{2}) \cos(\theta) \quad (2.6b)$$

Passing through the analyzer, only the light component along the analyzer's axis is transmitted:

$$E_a = I_0 \sin(\omega t) \sin(\frac{\delta}{2}) \sin(2\theta) \quad (2.7)$$

The intensity is proportional to the square of the amplitude. Any extinction due to the frequency (ω) would be too fast to be recorded on the camera. Hence the intensity of the light captured by the camera is:

$$I_p = I_0 \sin^2(2\theta) \sin^2(\frac{\delta}{2}) \quad (2.8)$$

This equation possesses two particular solutions for which the intensity is zero. The first one is given by eq.2.9 and provides the *isoclinics*. They correspond to the orientation for which the principal stress directions and the axis of the polarizer and analyzer are coincident and thus the resulting intensity is zero.

$$\sin^2(2\theta) = 0, \quad i.e \quad \theta = 0, \frac{\pi}{2} \quad (2.9)$$

The second one is given by eq.2.10 and gives the isochromatics, which are areas of equal stress important for quantifying stress by fringes analysis. Interested readers can refer to [9, 12, 13, 19, 21] for more information about fringes analysis.

$$\delta = 2m\pi (m = 0, 1, 2, \dots) \quad (2.10)$$

2.3.2 The circular polariscope

FIGURE 2.3: Optical principle of the circular polariscope; in red the optical axis of the polarizer and analyzer, in blue the principal stress direction of the sample.

Another device commonly used in photoelasticity is the circular polariscope. It consists of the same elements as the plane polariscope to which two quarter-wavelength plates are added between the polarizers and the sample. The optical arrangement of the circular polariscope is shown in figure 2.3. The quarter wave plates are generally birefringent crystals and decompose the incident ray of light along the crystal's two optical axis. The thickness of the plate is chosen to induce a retardation of $\frac{\lambda}{4}$, i.e a $\frac{\pi}{2}$ phase-shift. This results in changing the polarization from linear to circular.

The addition of the quarter-wavelength plates suppresses the dependence of the exiting light on the orientation of the polarizers. Therefore, the intensity of the resulting light is independent of θ and as such isoclinics are removed. Hereafter, we derive the expression for the intensity of the light exiting the polariscope, following the trigonometric method used previously.

As previously and considering only the real part, the light exiting the polarizer is:

$$E_p = I_0 \cos(\omega t) \quad (2.11)$$

Passing through the first quarter-wave plate the light is projected along its two optical axis with a retardation $\delta = \frac{\pi}{2}$. The polarization is changed from plane to circular.

$$E_{q11} = -\frac{I_0}{\sqrt{2}}\sin(\omega t) \quad (2.12a)$$

$$E_{q12} = \frac{I_0}{\sqrt{2}}\cos(\omega t) \quad (2.12b)$$

It then propagates through the birefringent medium and each incident ray is resolved along the optical axis of the sample and they exit it with the relative retardation δ :

$$E_{s1} = -\frac{I_0}{\sqrt{2}}\sin(\omega t + \theta + \delta) \quad (2.13a)$$

$$E_{s2} = \frac{I_0}{\sqrt{2}}\cos(\omega t + \theta) \quad (2.13b)$$

Passing through the second quarter-wave plate, the light is projected along its two axis with a retardation $\delta = \frac{\pi}{2}$.

$$E_{q21} = -\frac{I_0}{\sqrt{2}}\sin(\omega t + \theta + \delta)\cos(\theta) + \frac{I_0}{\sqrt{2}}\sin(\omega t + \theta)\sin(\theta) \quad (2.14a)$$

$$E_{q22} = -\frac{I_0}{\sqrt{2}}\sin(\omega t + \theta)\cos(\theta) + \frac{I_0}{\sqrt{2}}\sin(\omega t + \theta + \delta)\sin(\theta) \quad (2.14b)$$

Passing through the analyzer, only the light components along the analyzer's axis are transmitted:

$$E_a = I_0\sin(\omega t + 2\theta + \frac{\delta}{2})\sin(\frac{\delta}{2}) \quad (2.15)$$

The intensity is proportional to the square of the amplitude, thus any extinction due to the frequency (ω) would be too fast to be recorded on the camera. Hence the intensity of the light captured by the camera is:

$$I_p = I_0 \sin^2\left(\frac{\delta}{2}\right) \quad (2.16)$$

The intensity of the exiting light is now independent from the orientation of the polarizers and isoclinics are removed. The only light extinction possible would now be due to isochromatics or absence of stress.

2.4 Methods

2.4.1 Experimental setups

The experimental setups are portrayed from top-view in Figure 2.4. Figure 2.4a depicts the experimental setup with the plane polariscope as defined in 2.3.1. It is composed of a polarizer and analyzer (Thorlabs, Glan-Thomson polarizer GTH10M-A), a light source and a high-speed camera for the recording, the path of the light is colored in yellow. The experimental setup with the circular polariscope is presented in (b), it consists of the same elements as the plane polariscope and two additional $\lambda/4$ plates (Thorlabs, WPQ05M-532) inserted between the sample and the Glan-Thompson polarizers. For both experimental setups, single bubbles were nucleated by focusing a laser pulse into a gelatin sample using a microscope objective (Olympus 10x Plan Achromat, $NA = 0.25$). At the focal point, dielectric breakdown occurs leading to the formation of a sub-millimeter sized bubble. Illumination was provided by a White light LED source (SugarCUBE™ LED Illuminators, Edmund Optics) or continuous wave green laser (Shaan'xi Richeng Ltd, DPSS Green Dot Laser Module, wavelength 532 nm). A green Nd:YAG pulsed laser (New wave research Orion, 532nm, 6ns, and pulse energy between 0.15 mJ and 1 mJ) was used with the white light and an infra-red pulsed laser (Litron Lasers, Nano series, Q-switched Nd:YAG, and pulse energy between 0.15 mJ and 1 mJ) created the bubbles when green monochromatic illumination was utilized.

FIGURE 2.4: Experimental setups used for visualization of elastic waves generated by laser induced bubbles in soft solids. (a): Plane polariscope with systems for bubble nucleation and high-speed recording. (b): Circular polariscope coupled with pulse laser for bubble generation, monochromatic illumination and high-speed camera.

The dynamics of the bubble, i.e expansion, collapse and rebounds and the resulting stresses were recorded with high-speed cameras. The Photron, Fastcam, SA-X2 equipped with a macro camera lens (Nikon, 60mm f/2.8 Micro-NIKKOR AF-D) provided frame rates of up to 400,000 frames per second (fps), exposure times as short as $1\mu\text{s}$ and $20\mu\text{m}$ per pixel spatial resolution. The Shimadzu HPV-X2 equipped with a macro camera lens (Canon MP-E 65mm f/2.8 1-5x) recorded 256 pictures at frame rates at up to 5M fps with a $12.8\mu\text{m}$ per pixel spatial resolution.

2.4.2 Medium preparation

Traditional photoelastic experiments involve polarized light passing through birefringent paints or models made out of birefringent materials. Here we need to use a transparent and birefringent medium with some similarity to biological tissues. Gelatin based soft solids are commonly used for mimicking biological tissues [7] as their mechanical properties can easily be adjusted from quasi-Newtonian liquids to hard elastic solids by changing the gelatin mass ratio during the preparation. Moreover gelatin is transparent to visible light and exhibit excellent birefringent properties with a rather high stress optic coefficient $C \approx 10^8 - 10^9 \text{ m}^2.N^{-1}$ [1, 24]. The soft solid samples are prepared using industrial gelatin from Pork/Beef skin (Gelatin 250 bloom, Yasin Gelatin, China). The powdered gelatin is mixed with deionized water and dissolved on a steering hot plate at a temperature below boiling point to limit liquid loss from evaporation. Once homogeneity is reached, the hot mixture is poured into an optical glass container (Aireka Scientific Co. Ltd, 3.5 ml, QO10204-4) that limits birefringence distortion which are for example observed for plastic containers. Glass also results into smoother interfaces with the container walls required for clear observation and accurate laser focusing. To insure homogeneous gelation and gas content, the samples cool down to room temperature before being stored in a fridge for a minimum of 24 hours. Before using them, we assure they have reached again room temperature. Samples used in the following experiments were prepared with a mass ratio of gelatin to Water of 4%.

2.5 The case of a spherical cavity with internal pressure

To acknowledge the right adjustment of the polariscopes and the validity of our experimental setups, we decided to compare the first experimental results with a typical case from literature; a spherical cavity with an internal pressure. When a laser is focused in gelatin, a dielectric breakdown happens, a plasma appears and recombines forming a pocket of gas under high pressure. Due to the difference in pressure between the bubble and the surrounding medium, the bubble grows quickly. The bubble can be “frozen” by capturing an ultra-short exposure ($t_{exp} < 300$ ns) picture using the high-speed camera.

2.5.1 Theory

The analytic solution (Equation (2.17)) for a spherical cavity with internal pressure was derived by Brethauer [5] as a special result for the case of a spherical container exposed to an external and internal pressure, see Timoshenko and Goodier [22].

$$\sigma_{RR} = \frac{P_i}{R^3} \quad (2.17a)$$

$$\sigma_{\theta\theta} = \sigma_{\phi\phi} = \frac{-P_i}{2R^3} \quad (2.17b)$$

$$\sigma_{R\theta} = \sigma_{R\phi} = \sigma_{\theta\phi} = 0 \quad (2.17c)$$

,

where σ_{RR} , $\sigma_{\theta\theta}$, $\sigma_{\phi\phi}$, $\sigma_{R\theta}$, $\sigma_{R\phi}$ and $\sigma_{\theta\phi}$ are the stress components in spherical coordinates, R is the radial distance to the cavity center, and P_i is the internal pressure.

Thus around a cavity with internal pressure, only normal and radial stress components are non zero. To compare with experimental results, the stress fields as

captured using the plane and circular polariscopes need to be reconstructed. If we consider that the light arriving to the bubble is normal to the camera sensor (see Figure 2.4 for orientations), then only the stresses contained in the plans parallel to the sensor plane will induce a change of polarization of the light passing through the sample. Thus the problem can be reduced to a 2D problem for a plane parallel to the sensor's plane and passing through the cavity center. The stress field expressed in polar coordinates is:

$$\sigma_{RR} = \frac{P_i}{R^3} \quad (2.18a)$$

$$\sigma_{\theta\theta} = \frac{-P_i}{2R^3} \quad (2.18b)$$

$$\sigma_{R\theta} = 0 \quad (2.18c)$$

And finally, the retardation induced is calculated by combining eq. 2.18 & 2.4, which reads as

$$\delta = \frac{2\pi h}{\lambda} C(\sigma_{RR} - \sigma_{\theta\theta}) = \frac{2\pi h}{\lambda} C \frac{P_i}{2R^3} \quad (2.19)$$

2.5.2 Results for the plane polariscope

Experimental and reconstructed analytical results are displayed in figure 2.5. Frames [A], [B] and [D] are recorded during the growth phase of the bubble sufficiently long after the plasma formation for the bubble to be spherical. [A] shows the round “frozen” bubble captured with the high-speed camera without using any polariscope. Frame [B] depicts a similar “frozen” bubble captured with a plane polariscope which polarizers axis are oriented with $\theta = 0^\circ$ & 180° . We can observe a bright “clover”-like pattern with four “stress lobes” around the bubble. The black areas joining the bubble on the horizontal and vertical witness the presence

of isoclinics coherent with the orientation given to the polarizers. This results are in agreement with the results from the analytical solution depicted in [C]. Frame [C] shows the light intensity map reconstructed from the analytical solution as if observed through a plane polariscope. It is obtained by combining the stress field from the analytic solution (Equation (2.19)) and the plane polariscope equation (Equation (2.8)). The optical axis of the polarizer and analyzer are materialized in blue and red. [D] and [E] present experimental and analytic results for a plane polariscope oriented with $\theta = -45^\circ$ & 45° . The stress lobes and isoclinics observed are in agreement with the optical axis of the polarizer and analyzer oriented along the frame diagonals.

FIGURE 2.5: Frozen captures of an expanding bubble in gelatin. [A] is the bubble observed without polariscope, [B] and [D] are experimental results obtained for $\theta = 0^\circ$ & 90° and [C] and [E] are numerical results with the same values of θ . Bright areas indicates areas of stress.

2.5.3 Results for the circular polariscope

The same procedure was repeated for the circular polariscope, the results are presented in figure 2.6. [B] shows the experimental result for a bubble captured during its growth using a circular polariscope. [C] depicts the intensity map from the analytic solution (Equation (2.19)) reconstructed as if observed with the circular polariscope (Equation (2.16)). They are in good agreement and show that the “clove” of the plane polariscope has been replaced by a “ring” around the bubble. The extinction due to the isoclinics has disappeared which is coherent with the utilization of a circular polariscope.

FIGURE 2.6: Stress patterns around an expanding bubble. [A] is the bubble observed without polariscope, [B] and [C] are respectively experimental and numerical results for an expanding bubble observed with a circular polariscope. Bright areas indicates areas of stress.

2.5.4 Summary

Intensity maps where brightness indicates stress fields, are reconstructed using the solution from the literature and the theory for photoelasticity. “Frozen” bubbles were also observed using the experimental methods described above. Good agreement was found between the positions and shapes of the “stressed” areas. For the plane polariscope “cloved” like patterns were observed with light extinction due to the isoclinics coherent with the orientation of the polarizer and analyzer. Using the circular polariscope the isoclinics were removed and the stressed area materializes as a ring around the bubble.

2.6 Photoelastic observation of the spherical collapse of a laser induced bubble

We have shown that the experimental methods combining high-speed photography and photoelasticity allows to observe the stress around “frozen” bubbles in gelatin. We now investigate the cases of laser-induced bubbles collapsing in the bulk of the gelatin, i.e far from any boundary and other bubble. Two categories of bulk collapses can be distinguished. The “spherical bubble collapse”, which is the ideal case where the bubble keeps a quasi spherical shape during its lifetime; expansion

- shrinkage - collapse - rebound. The second category is the non-spherical bubble collapse, where the bubble loses its roundness during its expansion or shrinkage.

2.6.1 Spherical bulk collapse

Figure 2.7[1] depicts selected frames of a high-speed recording showing the dynamic of laser-induced bubble created in the gelatin's bulk recorded in the absence of the polariscope. The dynamics of the same bubble from nucleation to 5th collapse is plotted in figure 2.8, the blue curve shows the evolution of the bubble equivalent radius and the green one the displacement of the center of mass compared to its original position.

FIGURE 2.7: Dynamics of a spherical bubble collapse in the bulk, [1] recorded without polariscope with the Shimadzu HPV-X2 at 2M fps , [2] observed using a plane polariscope with $\theta = 0^\circ$ captured at 75 kfps with a Photron, Fastcam, SA-X2, [3] seen using a circular polariscope. [2] and , the recording speed was 200k fps.

In the first frame (Figure 2.7[1]), the bright dot indicates the dielectric breakdown happening at the lens focal point. Following nucleation the bubble grows and reaches a maximum ($r_{max} \approx 300\mu m$) after $t \approx 26\mu s$, it then shrinks before collapsing after $t \approx 53\mu s$. After the first collapse, the bubble rebounds and collapses a second time around $t \approx 76\mu s$. The bubble remains mostly spherical during the two

first collapses and rebounds. At the collapses, a small displacement of the bubble center of mass is observed, it is however negligible in regard to the bubble radius and the spatial resolution of the camera.

FIGURE 2.8: Dynamics of a spherical bubble collapse in the bulk, time evolution of the bubble radius.

Figure 2.7[2] depicts a similar bubble collapsing in the gelatin bulk now observed through a plane polariscope with $\theta = 0$. A bright “clover” pattern similar to the one observed in Section 2.5.2 is visible around the bubble. The dark lines along the horizontal and vertical match are isoclinics coherent with polarizer and analyzer oriented with $\theta = 0^\circ$ & 90° .

The lobes extends further away from the bubble when the bubble reaches a maximum radius. This can be explained as the gelatin tends to resist to deformation and thus the stress is more important when the gelatin is more deformed hence when the expansion of the bubble is maximum. It is to be noted that the stress pattern is present and similar during growth and shrinkage of the bubble.

The same configuration of a single bubble growing in the bulk is then investigated using a circular polariscope to see the full stress pattern around the bubble. Selected frames are presented in figure 2.7[3]. The plasma is visible in the first frame at $t = 0\mu s$, the bubble then expands until reaching a maximum radius at $t \approx 25\mu s$ where the bright ring appears the biggest. Then the bubble shrinks and the bright

stress rings fades down until collapse happens at $t \approx 50\mu s$, the bubble then rebounds. We observe that from the first collapse, the bright stress pattern becomes fainter and even disappears after some time, witnessing the bubble's loss of energy and the smaller rebounds. The stress pattern has remained attached to the bubble and was coherent with the instantaneous shape of the bubble.

2.6.2 Non-spherical bulk collapse

Spherical collapse represents an ideal case often studied for symmetry and simplicity. However, perfect spherical collapse is seldom reached, the presence of interfaces or heterogeneities in the vicinity often contributes to the deformation of the bubble and/or the apparition of instabilities leading to the asymmetrical collapse of the bubble. Merging of multiple bubbles or imperfect focus of the energy source necessary for the bubble nucleation are other ways to create non spherical bubbles and induce a non-spherical collapse. Here, the case of a such non-spherical collapse is investigated.

FIGURE 2.9: Bubble collapsing aspherically in the bulk, [1] observed without polariscope, [2] observed using a plane polariscope with $\theta = 0^\circ$, [3] seen using a circular polariscope.

In the experiment depicted in Figure 2.9[1], we created a slightly elongated plasma at $t = 0\mu s$ by increasing the laser energy. The bubble will grow in a quasi spherical shape until its maximum radius (at $t \approx 29.5\mu s$) before shrinking and slowly losing its roundness ($t = 59.5\mu s$). The collapse is highly asymmetrical ($t = 60.5\mu s$) and highly oriented, it is followed by a rebound where the bubble never achieves roundness ($t = 73.5\mu s$). The second collapse is also non-spherical and generally oriented in a direction opposite to the first collapse and followed by more non-spherical rebounds and collapses eventually leading to bubble necking and splitting. In figure 2.10, the green curve shows the displacement of the center of mass of the bubble compared to its original position and the blue curve tracks the equivalent bubble radius. We observe that when the bubble reaches a minimum radius, i.e during collapses, the center of mass of the bubble undergoes a strong displacement. This is explained by the conservation of Kelvin Impulse during the bubble's lifetime [3]. As the bubble grows it acquires Kelvin Impulse by "added mass" due to its change of volume [18]. When it shrinks, the "added mass" decreases and as a result of the conservation of Kelvin Impulse, the bubble is accelerated. As the bubble rebounds and collapses again, similar non-spherical collapse and displacements are observed. After the bubble's oscillation is damped, the bubble moves back towards its original position due to the restoring force, however it never reaches it, showing the presence of damage into the gel structure which appeared during the early stage of the bubble's life.

The same experiment was repeated using a linear polariscope to see if the non-spherical collapse leads to stress patterns similar to the one observed above. Figure 2.9[2] shows selected frames of a similar collapse. The two first frames corresponding to the time of the bubble nucleation ($t = 0\mu s$) and of its shrinkage ($t = 80\mu s$), they display the previously seen "clover" pattern coherent with the $\theta = 0$ orientation. At the collapse ($t \approx 80\mu s$) the "clover" pattern is lost and more blobs of light appear. Even more appear during the bubble rebound and second collapse ($t = 110\mu s$). On a longer timescale ($t = 240\mu s$), the blobs of light leave the edge of the bubble and propagate away from it. The presence of dark fringes due to the

FIGURE 2.10: Dynamics of an non-spherical bubble collapse in the bulk, in blue time evolution of the equivalent bubble radius, in green displacement of the center of mass compared to its original position.

isoclinics inherent to the linear polariscope further complicates the comprehension of what is happening. Figure 2.9[3] depicts selected frames from an non-spherical collapse observed using the circular polariscope. The frame sequence starts at the time of first collapse ($t = 77.5\mu s$), this collapse is non-spherical as the non-spherical light pattern indicates. The bubble rebounds quasi-spherically and reaches a second maximum size at $t \approx 130\mu s$ before collapsing a second time at $t \approx 137.5\mu s$. The second collapse and the following rebound ($t = 160\mu s$) are highly non-spherical and lead to parts of the stress pattern to separate from the bubble surface, this is particularly visible at the time of the third collapse ($t = 165\mu s$) when the bubble reaches a minimum. During the third rebounds the stress propagates further away while a second bright blob is observed separating from the other side of the bubble ($t = 242.5\mu s$). Strong non-spherical collapses induce important displacement of the bubble, they also are responsible for the emission of what seems to be stress waves of low velocities, i.e. shear waves as will be discussed in Chapter 3.

2.7 Conclusion

In summary, this Chapter shows the possibility of investigating stress around laser-induced bubbles in a birefringent soft solid. The experimental methods combine high-speed photography and photoelasticity and have been tested against a literature case. Good agreement is reached for qualitative observations. However no quantitative measurements could be done without a thorough calibration not yet available. Nonetheless, it was used for the observation of the classical case of single bubbles collapsing in the bulk. Two different regimes were found. An “attached” regime and a “wave” regime. In the first, the bubbles grow, collapse and rebound while keeping their round shapes. There the stress created over the bubbles lifetime remains confined in a quasi symmetric ring attached to the bubble surface. In the second case, the bubbles undergo a non-spherical collapse where they lose their roundness and important translational motions are observed. During expansion, the stress remains limited to the ring observed in the previous case, however during collapse and rebounds, asymmetry of the stress appears and we observe what appears to be a stress wave, identified as shear waves in Chapter 3, propagating away from the bubble at a low velocity of few $m.s^{-1}$.

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Chapter 3

Elastic waves generated by laser induced bubble collapse

3.1 Introduction

In chapter 2, we demonstrated the possibility of visualizing stress around laser-induced bubbles in a birefringent soft solids by combining photoelasticity and high-speed photography. We investigated the case of bubbles collapsing in the bulk of a gelatin phantom. We found that two different stress regimes exist depending on the kind of collapse. In the first case, the bubbles collapse while keeping a spherical symmetry, the stress field remains confined to a spherical shell “attached” to the bubble surface. In the second case, the collapse is aspherical, i.e after a mostly spherical first expansion the bubbles deform during shrinkage and collapse non-spherically. There the initially radial symmetric stress field becomes asymmetrical and propagates away from the bubble. In other examples, the presence of pressure gradients, inhomogeneities in the material, and boundaries even at rather large distant can induce perturbations to the spherical shape that are amplified during the bubble shrinkage [3, 9, 12].

In this chapter, we extend our observations of stress fields emitted during bubble collapse to the case of bubbles collapsing near boundaries. For this, we chose two different boundaries, namely the free surface and the rigid wall. For water both are known to induce jetting away (free surface) or towards the boundary (wall). For the case of a free boundary we argue that the motion of the bubble and jet are responsible for creating a localized volume of stress which is radiated as a shear wave. The radiation pattern of this shear wave is compared with a numerical simulation supporting above argument.

3.2 Methodology

Here, the experimental methods for measuring the stress patterns in the solid, which were developed in Chapter 2 are used. The experimental setup shown in Figure 3.1 allows recording the cavitation bubble dynamics and the stress wave emission through photoelastic imaging with a high speed camera. Single laser induced cavitation bubbles are created by focusing a laser pulse (Litron Lasers, Nano series, Q-switched Nd:YAG, 6 ns, wavelength 1064 nm, and pulse energy between 0.15 mJ and 1 mJ) into the gelatin with a microscope objective (Olympus 10× Plan Achromat, N.A. = 0.25). In the focal volume of the lens the bubble is created by optical breakdown. The dynamics of the bubble (expansion, collapse and rebound) and the stress waves are recorded either with a high speed camera (Shimadzu HPV-X2) equipped with a macro lens (Canon MP-E 65mm f/2.8 1-5× Macro) or with a Photron Fastcam SA-X2 equipped with a macro camera lens (Nikon, 60mm f/2.8 Micro-NIKKOR AF-D). White light illumination is provided by a LED illuminator (SugarCUBE, Edmund Optics) and single wavelength illumination is provided by a continuous green laser (Shaan'xi Richeng Ltd, DPSS Green Dot Laser Module, wavelength 532 nm). The orientation of the different elements of the circular polariscope (see Section 2.3.2) are depicted in Figure 3.1(b).

The soft solid samples are prepared from powdered gelatin (Gelatin 250 bloom, Yasin Gelatin, China). It is mixed with deionized water at a mass ratio of 4%

FIGURE 3.1: Experimental setup for bubble generation and observation. (a) Top view of the setup with the circular polariscope. The recording path is shown in green and the bubble generation path in red. (b) Optical axis of the elements of the circular polariscope, S is for the slow axis and F for the fast one, σ_1 and σ_2 are the gelatin local principal stress directions.

(gelatin to water) and dissolves in a flask on a hot plate with a magnetic stirrer. The hot mixture is poured into an optical grade glass cuvette (Aireka Scientific Co. Ltd, 3.5 ml, QO10204-4) that minimizes birefringence distortion from the container. The flat container walls insure a good optical access to the gelatin-glass interface needed for imaging and accurate laser focusing. After the samples cooled down to room temperature they are stored in a fridge. Before use, we assure that the samples have reached room temperature again.

3.3 Stress waves induced by non-spherical collapse near a free surface

3.3.1 Dynamics of a bubble collapsing near a free surface

FIGURE 3.2: Selected images of the dynamic of a bubble nucleated in gelatin near a free surface (on top) observed at 2M fps with a Shimadzu HPV-X2 camera

A simple way to induce a strongly jetting bubble in water is to create the bubble near a free surface. The same works for gelatin. Figure 3.2 presents selected frame from a typical run. The evolution of the bubble equivalent radius and the distance of its center of mass to the free surface are plotted in Figure 3.3.

The bubble created near the free surface reaches a maximum volume while remaining quasi-spherical ($t = 29.2 \mu\text{s}$). It then shrinks and collapses a first time away from the free surface ($t = 58.2 \mu\text{s}$) before rebounding without regaining its round shape ($t = 76.7 \mu\text{s}$). It undergoes two more collapses away from the interface (2^{nd} collapse at $t = 84.2 \mu\text{s}$) before it is pulled back. The 3^{rd} and 4^{th} collapses occur

FIGURE 3.3: Dynamics of a bubble collapsing near a free surface. The blue symbols depict the time evolution of the equivalent bubble radius, and the green symbols the distance of the center of mass from the undisturbed air-gelatin interface.

then close to the interface. On a longer time scale, the bubble will be slowly pulled back towards its original position mitigated by the gelatin's elasticity. Overall the dynamics has some similarity to that in a low viscous fluid such as water. A clear distinction is the pull back of the bubble's center of mass to the location where it was created. This does not occur in liquids.

3.3.2 Photoelastic imaging

Figure 3.4 presents a typical result from the experimental setup (Figure 3.1). It consists of selected frames from a high-speed recording of a bubble expanding and collapsing in gelatin near a free (air) boundary. The time $t = 0$ denotes the time of bubble nucleation. Then the bubble expands and compresses the gelatin nearby resulting in a bright area around the bubble ($t = 5 \mu\text{s}$). Upon reaching the maximum size, the bubble pushes and deforms the free surface ($t = 35 \mu\text{s}$) before it shrinks. Thereby its upper wall bulges in and forms a funnel while the position of the interface at the bottom of the bubble remains approximately static ($t = 65 \mu\text{s}$). Between the bubble and the free surface, two vertical dark lines

FIGURE 3.4: Selected images of the dynamics of a bubble nucleated in gelatin near a free surface (on top) observed with a circular polariscope. The yellow dot at $5 \mu\text{s}$ indicates the nucleation site, red arrows at $85 \mu\text{s}$ show the shear waves propagation directions, and a blue arrow at $155 \mu\text{s}$ points to the crack dynamics.

develop on top of the brighter stressed area. These two lines mark the presence of isochromatics. The dark lines extend vertically following the bubble collapse with a velocity of $V_v = 25 \text{ m/s} \pm 1 \text{ m/s}$, which roughly also is the velocity of the upper bubble interface. Their horizontal position changes, too. They move outward with a velocity of $V_s = 2 \text{ m/s} \pm 0.2 \text{ m/s}$. Using equation (1.1) and gelatin properties from literature [6, 7] ($\rho = 1000 \text{ kg/m}^3$, $\epsilon = 0.45$), we can estimate the Young's modulus of the medium, $E \approx 11.6 \text{ kPa}$. This velocity and rigidity compares with values in previous work using a similar recipe for the gelatin[10].

After reaching the minimum size the bubble rebounds ($t = 85 \mu\text{s}$) and its volume oscillations cease shortly after the second collapse at $t = 119 \mu\text{s}$ (not shown), while it remains moving downwards with a velocity of $V_r = 5 \text{ m/s} \pm 0.2 \text{ m/s}$. At $t = 155 \mu\text{s}$, a conical-shaped crack appears starting from the air-gelatin boundary and follows the path of the downwards translating bubble ($t = 225 \mu\text{s}$).

3.3.3 Model and numerical simulation

We speculate that the shrinking and moving bubble is the source for shear stress generation. The speed of the upper bubble interface is considerably high compared to the surrounding medium. This asymmetric motion in the solid leads to the generation of shear stress within the region bounded by the air interface and the bubble. Later the shear stress propagates as a shear wave into the surrounding medium.

FIGURE 3.5: Finite element simulation of the wave generation. Simulation domain. The region F indicates a rectangular source of force moving downward from the free surface along the axis of symmetry with a velocity of V_Z .

This hypothesis is tested with a numerical simulation of the stress generation and propagation using the Finite Element Method solver COMSOL Multiphysics . We used the Solid Mechanics module (*solid*) [5], where the displacement field $\mathbf{u}$ is calculated from the equation of motion:

$$\rho \frac{\partial^2 \mathbf{u}}{\partial t^2} = \nabla \cdot \mathbf{S} + \mathbf{F}_V \quad , \quad (3.1)$$

where ρ is the density of the medium, $\mathbf{F}$ is the volume force vector and $\mathbf{S}$ the Cauchy stress. Figure 3.5 depicts the 2D axisymmetric simulation domain with

the geometry and boundary conditions as specified in COMSOL Multiphysics. The gelatin is defined as a linear elastic material following linear Hooke's law. The gelatin's properties are taken from literature[6, 7] ($\rho = 1000 \text{ kg/m}^3$, $\epsilon = 0.45$, $E = 10 \text{ kPa}$, $C_p = 1500 \text{ m/s}$, $C_s = 1.8 \text{ m/s}$). The simulation is *time dependent* to reflect the dynamics of the bubble. For the sake of simplicity, the stress field resulting from a body force moving downward with a constant velocity is modeled. The boundary conditions are stress free on the top, an axis of symmetry, and to the right and bottom of the domain impedance matched boundaries. At $t = 0$, a rectangular source of force¹ (body load, $F = 3 \cdot 10^{-3} \text{ N}$) moves downward from the free surface along the axis of symmetry with a velocity of $V_Z = 25 \text{ m/s}$ for a duration $\Delta t = 32 \mu\text{s}$. To compare the simulations with the photoelastic images we split the axisymmetric model into slices perpendicular to the line of sight. In each slice of finite thicknesses, the retardation is calculated assuming a constant stress along the depth. Then we compute the light intensity as if the model was observed by a camera.

FIGURE 3.6: Finite element simulation of the wave generation. Selected frames of the numerical results after light intensity calculation. The white features are the wave from the simulation and black is the sketched bubble shadow taken from the experiment.

Figure 3.6 presents selected frames from the numerical results. Black areas correspond to the gas/vapour domains (bubble and free surface are drawn from the experimental results and added on the numerical results), dark gray (low light intensity) shows the unstressed gelatin and areas of stress are depicted with gray

¹We estimate the magnitude of the force on the gelatin assuming that the bubble creates a stagnation pressure of $1/2\rho u^2$ acting on an area of approximately $(100 \mu\text{m})^2$ and a speed of $u = 25 \text{ m/s}$. This results to a force of $F \approx 3 \cdot 10^{-3} \text{ N}$, which is used in the simulation.

scales, with higher brightness indicating areas of higher stress. Overall the simulation results show good agreement considering the coarse simplifications. In particular we observe a bright region which extend vertically following the rectangular source of force with a velocity of V_z and slowly expands radially. The main difference between simulation and experiment is that the extinction due to the isochromatics is not reproduced. We explain this by the fact that the pre-existing stress fields from the earlier bubble dynamics are not considered in the simulations, i.e. there the body force moves within an unstressed solid. The simulation supports the explanation that shear waves can be induced with a source of stress moving with the bubble upper interface.

3.3.4 Interface deformation

FIGURE 3.7: Side view of the experimental setup for two-views recording, it shows the orientation of the cameras used for synchronized recording of the bubble and surface dynamics.

The motion of the bubble collapsing away from the free surface (Figure 3.4) is also reported for liquids, i.e. in water where a jet pierces through the bubble [11]. It suggests that the emergence of a jet penetrating through the bubble in gelatin

could be the source of the shear waves. To obtain a better photographic evidence we repeated the experiment in absence of the polariscope optics, see Figure 3.7 for the experimental setup. Now two high-speed cameras (Photron, Fastcam, Mini AX200) equipped with camera lenses (Canon MP-E 65 mm f/2.8 1-5× Macro) record simultaneously the bubble and the surface from the side and top.

Figure 3.8 presents selected frames from a bubble with very similar size and position as shown in Figure 3.4. Again the bubble expands and pushes the free surface ((b): $t = 6 \mu\text{s}$) resulting in an upward displacement visible on the surface with a gelatin jet pointing upward ((a): $t = 15 \mu\text{s}$) and expanding laterally as the bubble grows ((a): $t = 44 \mu\text{s}$, (b): $t = 37 \mu\text{s}$). The bubble then collapses and moves away from the free surface. During collapse, a jet is penetrating through the center of the bubble with a velocity of $V_j = 19 \text{ m/s} \pm 1 \text{ m/s}$ ((b): $t = 68 \mu\text{s}$). Then the jet impacts on the lower bubble interface while the bubble continues to translate downward ((b): $t = 86 \mu\text{s}$ and $t = 167 \mu\text{s}$). These observations indicate that the jet formed by the bubble moving away from the air-gelatin boundary is causing the shear wave. At a later time, due to the elastic restoring force, the deformed gelatin relaxes and attempt to recover its initial shape. Thus, the remains of the bubble are pulled back towards the nucleation site (see (b): $t = 222 \mu\text{s}$), however they never reach it showing that the gel structure has been altered during the early stage of the bubble's life.

The crack originating from the air-gelatin boundary indicates that the upwards pointing tip of the jet on the gelatin-air interface ((a): $t = 15 \mu\text{s}$) retracts first towards the original level and then penetrates into the gelatin, visible as a conical crack in (a): $t = 178 \mu\text{s}$. The opening angle of the crack remains while the crack tip propagates into the gelatin trailing the cavitation bubble ((b): $t = 222 \mu\text{s}$). The oscillations of the free surface result in surface waves (Figure 3.8 sketch and (a)) traveling radially with a velocity of $V_r = 1.9 \text{ m/s} \pm 0.5 \text{ m/s}$. This crack was not reported for the bubble collapse in Section 3.3.1, its presence depends on the position of the laser focus and its energy, i.e if the bubble grows big and close enough to the interface. In most cases, the crack / deformation of the free surface

FIGURE 3.8: Selected images of the dynamic of a bubble nucleated in gelatin near a free surface taken by the setup shown in Figure 1(b). (a) Top view. (b) Side view. The blue arrow reflects the crack dynamics. Frames were taken from a single experiment and were selected to show the event at similar time step. The variation in time is due to the different recording speeds ((a), 67.5 kfps - (b), 162 kfps). Sketches above show the profile of the air-gelatin interface for some of the presented frames.

closes after some time. However in extreme cases, the deformations exceed the elastic limits of the medium and permanent damages might appear. Figure 3.9 shows before/after pictures of a free surface captured with the 2-views setup where permanent damage (ruptures) due to the bubble collapse is clearly visible.

FIGURE 3.9: Selected images showing the permanent damage due to the collapse of a laser-induced bubble near a free surface. (a) and (c) show respectively the top and side views of the interface before the experiment. (b) and (d) show the same interface one minute after the bubble creation.

3.4 Non-spherical collapse near a rigid wall

Another way to obtain a strongly non-spherical collapse is to create the bubbles near a rigid boundary. Here, we move the sample so that the lens focuses the laser beam near the wall of the glass cuvette that acts as solid boundary.

FIGURE 3.10: Bubble collapse near a rigid wall observed without polariscope recorded at 2M fps with a Shimadzu HPV-X2 camera

Figure 3.10 presents selected frames of a typical high-speed recording of a laser-induced bubble expanding and collapsing near the cuvette wall without polariscope but with white light illumination. The dynamic of the bubble is tracked and displayed in Figure 3.11. The blue curve shows the evolution of the equivalent bubble radius, while the green curve follows the distance between the bubble center of mass and the wall (materialized as a black line at the bottom). The bubble created at $t = 0$ reaches a maximum radius at $t = 20.2 \mu s$ with a nearly spherical shape. It then shrinks and undergoes a strongly non-spherical collapse at $t \approx 44.7 \mu s$ where the gas pocket moves toward the wall. The bubble then rebounds and grows again yet it does not regain the spherical shape ($t = 49.2 \mu s$). It shrinks again ($t = 57.7 \mu s$) and a second collapse occurs at $t \approx 58.2 \mu s$. This time the bubble moves away from the wall. The bubble then undergoes several oscillation cycles while being “pulled back” toward its original position. This process is driven

by the elasticity of the gelatin. Here also, the bubble collapse in gelatin shares some similarity with the collapse in water [9] except for the elastic restoring force.

FIGURE 3.11: Dynamics of a bubble collapsing near a rigid wall, in blue time evolution of the equivalent bubble radius, in green displacement of the center of mass compared to the wall.

Figure 3.12 presents selected frames from a similar collapse, this time observed using a circular polariscope as described in Figure 3.1. Upon reaching its maximum volume ($t = 26.6 \mu\text{s}$), the bubble is surrounded by a quasi-spherical bright “stress” ring similar to the one observed in Chapter 2. At $t = 56.6 \mu\text{s}$, bright lines emerge from the gelatin-glass interface at the wall. From the velocity of propagation we identify them as shear waves. They may be generated by the reflection at the glass wall of the shock wave emitted during bubble generation. The stress pattern around the bubble changed into a half-ring facing the wall. At the back where a jet develops a faint stress region is visible, too. This bright blob of the jet becomes more pronounced during the bubble collapse ($t = 59.9 \mu\text{s}$ before and $t = 76.6 \mu\text{s}$ after the collapse). From this region a v-shaped stress wave is emitted that propagates with a few meters per second. The alternating bright and dark parts of the wave are caused by the isochromatics (Section 2.3). This shape of the wave resembles a Mach cone, i.e. similar to the “shear-wave Mach cone” created by rapidly moving an acoustic focus in in supersonic shear imaging [2]. Once the velocity of the acoustic focus exceeds the shear wave velocity of the elastic medium

the cone is formed. With the material's shear wave velocity of $c_s = 3 \text{ m/s}$ and a cone angle of $\alpha = 30^\circ$, we obtain a velocity of deformation near the jet region of about $v = c_s / \sin \alpha \approx 6 \text{ m/s}$ and a shear wave Mach number $M_s = \frac{1}{\sin \alpha} = \frac{v}{c_s} \approx 3$. While the picture do not allow to pin-point the precise mechanism we can speculate from the shape of the v-shape, that it is formed shortly after the collapse, starting from the rigid boundary and moving away from it. One mechanism could be a fast recoil of the bubble away from the surface.

FIGURE 3.12: Bubble collapse near a rigid wall observed using a circular polariscope.

3.5 Creating stress waves away from focus

In the previous section, we have observed that the interaction of shock waves with rigid walls leads to the excitation of shear waves. In cavitation, another classical collapse configuration is the passing of a pressure wave over preexisting bubbles [4]. This is a common phenomenon in shock wave based therapy such as shock wave lithotripsy [8].

FIGURE 3.13: Creation of elastic waves away from the laser focus.

We will here use the pulse laser to emit a shock wave near a pre-existing bubble. Stable bubbles were obtained by focusing a laser pulse in a gas supersaturated gelatin [1]. Selected frames from the experiment recorded with the circular polariscope are presented in Figure 3.13. A bubble (bubble A) is created using the same laser setup next to a preexisting bubble (bubble B) ($t = 0 \mu s$). A shock wave is emitted from the dielectric breakdown at the focal point. The shock wave reaches bubble B leading to a shock induced collapse (not shown here due to the low frame rate). The two bubbles will then successively expand and collapse leading to the emission of multiple shear waves both at and away from the laser focus. One can imagine that in tissues bubble clouds can be present and interact in similar way once excited by passing shock waves, i.e. the conversion of longitudinal waves into shear waves due to the presence of gaseous bodies.

3.6 Conclusion

In conclusion, we have demonstrated that shear waves can be generated from non-spherical bubble collapse in soft elastic media. We connect the wave emission with the translation and thus jetting of the collapsing bubbles confining shear stress in a cylindrical volume near the bubble. We compare those observation with a simple Finite Element Model simulation. For the collapse near air/solid interface, we report on that strong collapse may lead to the opening of a cone-shaped crack and

to permanent damages to the free surface when the bubble is sufficiently big and created very near. This may also occur in high power ultrasound therapy settings. There, non-spherical collapses are caused by inhomogeneities in the tissue, bubble-bubble interaction and pressure gradients from shock waves. We also report on the possibility of generating multiple shear waves away from the laser focus due to the interaction of shock waves with pre-existing bubbles.

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Chapter 4

Cavitation inception from transverse waves in a thin liquid gap

4.1 Introduction

Water exposed to a pulling force may yield and rupture thereby forming cavitation bubbles. In the presence of nuclei already a few bars of tension suffices [2, 6, 10, 16], yet to induce cavitation in small volumes filled with pristine water much higher forces are necessary. These extreme tension between -100 bar and more than -1000 bar can be created with a quasi-static thermodynamic process such as isochoric cooling of the water [3, 5, 7, 14, 29] or by focused acoustic waves [8]. Rarefaction waves also form by acoustic diffraction [4, 13] or upon sound soft reflection of a shock front, e.g. from laser generated plasmas [1, 22, 25, 27]. In general these laser generated shock waves are used to compress matter and probe high density states [15, 17, 19, 21, 23] with pressures of several hundreds of Giga-Pascals.

In this chapter, we report on a novel way of generating cavitation, first observed during failed attempts at using cylindrical bubbles for calibration of our photoelastic experiment (see Section 3.6). If observation with the circular polariscope did not allow to see stress patterns, experiments with a water-filled gap and normal high-speed photography produced unexpected and interesting results. There, when the energy laser of the laser is sufficient, high pressures are generated within the glass plates. At the solid-liquid interface transverse waves propagates and because of the high surface normal acceleration the yield strength of water is easily overcome and intense cavitation is generated. This method has some similarity to laser based ultrasonics [24] where the substrate is irradiated with a short and focused laser pulse to excite surface waves, e.g. for non-destructive testing of the substrate. While laser ultrasonics is done on dry and wet substrates, we add a second substrate to sandwich a $10 - 20 \mu\text{m}$ thin water film. Upon laser irradiation of the solids intense acoustic waves yield the liquid through transverse modes travelling between the two glass plates (Lamb wave).

4.2 Methods

The experimental setup consists of three parts: a microfluidic gap, a bubble nucleation system and a recording system.

4.2.1 Microfluidic gap preparation

The microfluidic gap is obtained by sandwiching $\approx 15 \mu\text{m}$ thick aluminum foil spacers between a pre-cleaned microscope slide (Marienfield soda lime glass slides, $1 \text{ mm} \pm 0.05 \text{ mm}$) and a pre-cleaned cover-slip (Roth, #1). The gap is filled with deionized (DI) water by capillarity, a drop of DI is placed near the gap opening and is sucked into it due to capillary forces. Figure 4.1 presents the geometry of the microfluidic gap. The yellow dots indicates the position where the laser will

FIGURE 4.1: (a) Top view of the microfluidic gap, SL represents the position of the streak camera's slit (see Section 4.2.5). (b) 3-D view of the microfluidic gap, showing laser's path. On both figures, the yellow dot indicates the position of the laser focus.

be focused. And the position of the slit of the streak camera (see Section 4.2.5) is indicated by the dash line (SL).

4.2.2 Bubble nucleation

Sub-millimeter bubbles are nucleated using a pulsed laser as described in the previous chapters. A microscope objective focuses the laser pulse into the thin gap and the dynamics is imaged through it, too. Illumination comes from the top, passes through the microscope objective and is reflected by a half-mirror into one of three different cameras used (see after). A frequency doubled Nd:YAG laser (Q2-1064 Series, pulse duration ≈ 10 ns, wavelength 532 nm, and pulse energy between 0.1 mJ and 1.5 mJ) is expanded with a telescope consisting of two lenses ($f_1 = -30$ mm, $f_2 = 100$ mm) to fill the entrance pupil of the microscope objective. The laser beam passes through the half-mirror and is focused into the gap with a $10\times$ microscope objective (UPLFLN10X2, Olympus, NA 0.3). The position of the focus is controlled by adjusting the length of the telescope. By focusing the laser onto the microscope slide a dielectric breakdown is obtained that induces a rapid rise in pressure from the expanding plasma. We estimate a maximum

intensity of $2.6 \cdot 10^{12} \text{ W/cm}^2$ when focusing on a diffraction limited spot with a diameter of $2.2 \mu\text{m}$. The size of the light emitting plasma region has a diameter of about $20 \mu\text{m}$. An expanding vapour bubble (primary cavitation) is created once the plasma recombines [28]. The energy is controlled using a Pyroelectric Energy Sensor (ES145C, Thorlabs); part of the beam ($\approx 4\%$) is reflected into the sensor using a glass slide and measured. The bubble nucleation system is shown in Figure 4.2 and Figure 4.3, the laser path appears in green. A photodiode (DET10A2, Thorlabs) is used to time the moment of laser's emission.

4.2.3 High-speed imaging

FIGURE 4.2: Schematic side view of the experimental setup used for high-speed and streak imaging (not to scale). The path of the nanosecond laser used for the bubble nucleation is colored in green. The path of the flash illumination is depicted in yellow.

For the relative slow events a high speed camera (HPV-2, Shimadzu Corp., Kyoto, Japan) recording with up to 1 million fps with 250 ns exposure time and $5.6 \mu\text{m}$ pixel resolution was sufficient. The illumination is provided by a single 1 ms duration camera flash (Auto 3075g, Sunpak, Saitama, Japan) through a condenser lens. A digital delay generator is used to control the synchronization between the pulsed laser, the flash lamp and the high-speed camera. Figure 4.2 shows a sketch of the experimental setup with the high-speed camera, imaging path is represented in yellow.

4.2.4 Sub-picosecond imaging

In cavitation studies some events present a very fast dynamics and would require very short exposure time to be resolved without being motion blurred. Also higher spatial resolution is often needed for observation of small bubbles. However it is not always possible to have access to cameras with such specifications. Another solution is to use stroboscopic illumination with high resolution cameras. The imaging is done with a sensitive CCD camera (PCO.1600, PCO AG, Kelheim Germany) synchronized to a fast laser strobe (FemtoLux 3 SH, EKSPLA, Vilnius, Lithuania, pulse duration 213 fs at max. 50 MHz repetition rate, wavelength 515 nm,). A narrow band-pass filter (FL514.5-3 Laser Line Filter, Thorlabs) is placed in front of the camera that lets pass the strobe and reduces the bright continuum emission from the laser plasma. The experimental setup is depicted in Figure 4.3 with the stroboscopic illumination's path colored in light blue. The short illumination time can freeze fast events such as the cavitation bubble dynamics but also the waves traveling in the gas, liquid and solid. Equipped with the microscope objective presented above, a higher magnification of now $1.1 \mu\text{m}/\text{pixel}$ is obtained. Figure 4.4 shows an example of picture obtain with the stroboscopic illumination. The pulsed laser is focused in the air, a dielectric breakdown occurs (bright spot at the center of the frame) and a shock wave is emitted in the air. Here, the stroboscopic illumination is triggered to illuminate the sensor twice with 20 ns in between. This results in “two apparent waves” to be visible (1 and 2), corresponding to two

FIGURE 4.3: Schematic top view of the experimental setup used for sub-picosecond imaging (not to scale). The path of the nanosecond laser used for the bubble nucleation is colored in green. The path of the femtosecond laser for the illumination is depicted in light blue.

successive positions of the same shock wave. From the distance separating the wave, the wave's velocity is retrieved, $V_w \approx 330 \text{ m.s}^{-1}$, which is equal to the speed of sound in the air.

4.2.5 Streak imaging

Another type of imaging allowing a high temporal resolution, and particularly suitable for axisymmetric configuration, is the streak imaging method. There the time variation of light intensity across a slit is deflected across the length of the

FIGURE 4.4: Shock waves in the air captured with stroboscopic illumination. Exposure time of the camera is 500ns and two pulses of light of duration 213fs are produced 50ns apart.

camera sensor to form a spatial profile of the light intensity. In our experiment, we align the streak slit of the streak camera (SC-10, Optronis, Germany) with the center of the sample, see the dashed lines in Figure 4.1(a). It is illuminated with a flash-lamp (Hamamatsu L12745-02) with a pulse duration of $2\mu\text{s}$. The experimental setup is similar to the one presented in Figure 4.2.

4.3 Experimental results

Figure 4.5 presents a typical run obtained after focusing the laser pulse into the thin gap, recorded at 500 kfps with 250 ns exposure time. The intriguing features are the annular rings of cavitation bubbles formed shortly after the laser induced plasma. The bright spot in the center at $t = 0$ (the time the laser is triggered) is the location of the focus and is caused by the plasma radiation from the dielectric breakdown¹. It will be replaced by a permanent dark spot in the center of each frame caused by the ablation of the glass. During the exposure of the first frame lasting 250 ns

¹This overexposure leads to two artifacts: a brighter area at $t = 2\mu\text{s}$ in Fig. 4.5 and two differently shaded regions separated by a “line”.

FIGURE 4.5: Secondary cavitation activity within a $15\mu\text{m}$ thick liquid gap following a laser-induced dielectric breakdown: selected images from a high-speed recording taken at 500 kfps with 250 ns exposure time. The central bright spot on the first frame is from the plasma emission.

a cavitation bubble is emerging from the recombined plasma, yet remains hidden in the overexposed image center. The bubble becomes visible after $t = 1\mu\text{s}$ and grows to $\approx 500\mu\text{m}$ in radius in the first $6\mu\text{s}$. It reaches a maximum radius after $\approx 34\mu\text{s}$ and starts to shrink thereafter until collapse at $\approx 126\mu\text{s}$. We will hereafter refer to this bubble as the primary cavitation bubble and contrast the annular rings as secondary cavitation. The formation of these rings is already visible at $t = 0$, yet due to the finite exposure time and their small size they are captured motion blurred. Within $2\mu\text{s}$, the cavitation bubbles have become prominently visible and have colonized the entire frame to the exception of a ring around the primary cavitation bubble. This ring thickens until the secondary cavitation has completely disappeared after $8\mu\text{s}$. From $10\mu\text{s}$, some of those bubbles rebound and disappear again (after $34\mu\text{s}$).

FIGURE 4.6: Cavitation activity within a $15\ \mu\text{m}$ thick liquid gap following a laser-induced dielectric breakdown: Selected images from the first $8\ \mu\text{s}$ from one high-speed recording taken at 1 million fps with 250 ns exposure time. The central bright spot is from the plasma emission.

Figure 4.6 shows the 8 first frames of another run recorded at 1 million fps. With this higher frame rate, we observed that the dynamics of the secondary cavitation is even faster than observed previously as the full frame is populated in less than $1\ \mu\text{s}$. Bubbles are captured with motion blurred on the first frame during the time interval of 180 ns between the optical breakdown and the end of the exposure of frame $t = 0$ bubbles at a distance as far as $r \approx 560\ \mu\text{m}$ are observed. If those bubbles are created very quickly after optical breakdown, they also disappear in a relatively short time. After $1\ \mu\text{s}$, an area of $\approx 440\ \mu\text{m}$ radius around the focus position has been cleared of bubbles. While the primary cavitation bubble expands the region of secondary cavitation steadily shrinks and disappears starting from the inner rim until most of the image is cleared of bubbles.

This dense and fast secondary cavitation event has to our knowledge not been reported in literature and is rather startling. Cloud cavitation previously observed generally arises from tensile waves pulling and rupturing the liquid [1]. But here after an optical breakdown in liquid, one would expect a pressure spike rather than a tension wave [18, 26, 28]. Thus the question is what causes the nucleation of cavitation bubbles?

FIGURE 4.7: Cavitation activity within a $15\mu\text{m}$ thick liquid gap following a laser-induced dielectric breakdown: Selected images from the first $8\mu\text{s}$ from one high-speed recording taken at 1 million fps with 250 ns exposure time. The central bright spot is from the plasma emission.

Sub-picosecond imaging as described in 4.2.4 is used to gain more insight into what happens during the first microsecond after the pulsed laser is shot. Fig. 4.7 depicts two instant of times where secondary cavitation bubbles are nucleated during the exposure time, $t = 80\text{ ns}$, and shortly afterwards, $t = 232\text{ ns}$, of the first frame of Figure 4.6a. At those instants, all dynamics are frozen thanks to the short illumination time. The primary cavitation bubble is visible in the center, its outline shows some deviation from a cylindrical cross-section. Besides the expanding primary cavitation bubble, intense thermoelastic waves [11, 24] are emitted from the focal volume into the glass and back into the liquid (see Section 4.7.1). They are visible as concentric rings surrounding the focal point. The outermost ring labeled with B is caused by the modulation of the index of refraction in the glass by a fast wave originating from the focal point and propagating radially outward. The speed of $v_B = 5380 \pm 51\text{ m/s}$ indicates that B is a bulk longitudinal wave in the glass spreading as a spherical wave. The velocities are obtained from multi-strobed images with 20 ns delay as explained in 4.2.4. The bulk wave is trailed by a surface wave which we identify as a leaky Rayleigh (L-R) [30] wave traveling at a prominently slower speed of $V_{LR} = 3240 \pm 36\text{ m/s}$. Closer to the focus we observe an annular ring of microscopic cavitation bubbles C . The region between this ring and the primary cavitation bubbles is filled with a patterned region, which under close inspections is composed of many overlapping spherical waves. These waves

are emitted from bubbles that collapse at the inner rim of the ring C . Shortly later at $t = 232$ ns (from a different run) the diameter of the ring increased, i.e. it propagates outwards. The velocity of the inner rim of the annular cavitation ring is $v = 1510 \pm 82$ m/s, which is of the order of the speed of sound in liquid. The acoustic waves emitted from C towards the primary cavitation bubble already indicate that the cavitation bubbles undergo violent collapses. If the sub-picosecond imaging reveals the formation and collapse of the secondary cavitation within the gap and the emission of thermoelastic waves following the dielectric breakdown, the question remains what induces the necessary tensile stress for the cavitation nucleation?

FIGURE 4.8: Streak camera image with a height of 1.2 mm and a width of 1500 ns. The events are illuminated with a flashlamp (Hamamatsu L12745-02) with a pulse duration of $2\mu\text{s}$. The bright spot is the plasma, followed by the primary bubble and secondary bubbles.

Figure 4.8 presents a typical streak image of this secondary cavitation event as a radius-time ($r-t$) diagram. The vertical axis spans a distance of 1.2 mm and the time on the horizontal axis from $t = 0$ to $t = 1500$ ns which covers approximately the first 2 frames in Figure 4.6. The bright spot $r = 0$ is from the plasma, out of which

the primary cavitation bubble expands. Below the primary bubble we observe horizontal stripes (secondary cavitation). Their length increases quickly with time and after about 300 ns they remain for the duration of the streak recording. The slope by which the horizontal stripes appear is the phase velocity of the wave generating the cavitation region. Here we measure a maximum initial velocity of 1712 ± 107 m/s, similar to the expansion velocity obtained with the single frame camera as shown in Fig. 4.7. The magnitude of this phase velocity suggests an acoustic wave. Other experimental results hint towards the propagation of a tensile wave. In Figure 4.13, the pulsed laser is focused near two pre-existing bubbles. Between the first and the second frame ($dt = 2\mu\text{s}$), the bubbles expand before shrinking ($t = 4\mu\text{s}$) and collapse at $\approx 6\mu\text{s}$. This cycle of expansion-shrinkage-collapse is typical of the interaction between bubbles and tension wave.

4.4 Finite element method simulation

Experiments suggest that the nucleation of the secondary cavitation is due to the propagation of a tensile wave emitted by the impact of the pulsed laser within the microfluidic gap. However, to nucleate bubbles this wave should provide sufficient tension. Besides, the front of bubble nucleation propagates at a considerably slower velocity as compared to the waves observed by using sub-picosecond imaging. Thus a different wave should be at work which we could not observe experimentally. Hereafter, we propose a numerical simulation using the Finite Element Method solver COMSOL Multiphysics [20] to reveal this wave.

The problem is defined as axisymmetric and consists in two layers of glass (borosilicate, elastic modulus $E = 63$ GPa, Poisson ratio $\nu = 0.2$) sandwiching a liquid layer (water). Geometry and boundary conditions as defined in COMSOL Multiphysics are depicted in Figure 4.9

FIGURE 4.9: Sketch of the geometry used for the FEM simulation.

Glass layers are defined as linear elastic material (Solid Mechanics, *solid*) where the transverse waves in the elastic solid are described by the deformation field $\mathbf{u}(\mathbf{x}, t)$ calculated with the equation of motion:

$$\rho \frac{\partial^2 \mathbf{u}}{\partial t^2} = \nabla \cdot \mathbf{S} \quad , \quad (4.1)$$

where ρ is the density of the medium and $\mathbf{S}$ the Cauchy stress. For elastic materials $\mathbf{S} = \mathbf{C} : \epsilon$, with $\mathbf{C}$ the 4th order elasticity tensor and ϵ the strain tensor.

The water is represented as a linear acoustic material (Pressure acoustics, Transient, *actd*) with the acoustic pressure $p(\mathbf{x}, t)$ and the wave equation is solved:

$$\frac{1}{c^2} \frac{\partial^2 p}{\partial t^2} - \nabla^2 p = 0 \quad , \quad (4.2)$$

where ρ_f is the density of the fluid.

The coupling is done at the interface (Acoustic-structure boundary) through the linearized Euler equation:

$$-\frac{1}{\rho_f} \nabla p = \frac{\partial^2 \mathbf{u}}{\partial t^2} \quad , \quad (4.3)$$

The fluid pressure is coupled into the solid mechanics as a normal force. The spatial and temporal localized high pressure zone from the dielectric breakdown is abstracted with a symmetric pressure pulse with a duration and radius of that of bright emission region from the plasma. In particular the pressure lasts for $\Delta t = 10$ ns and is modeled as

$$p(r, t) = \begin{cases} \hat{P} \cos\left(\frac{\pi r}{2R}\right)^2 \sin\left(\frac{\pi t}{\Delta t}\right)^2 & \text{for } 0 < t \leq \Delta t \\ 0 & \text{otherwise} \end{cases} \quad (4.4)$$

The pressure amplitude of $\hat{P} = 10$ GPa is motivated by Ref. [11]. While we have no measurement of our own to justify this value, the magnitude is a reasonable choice. In particular, a similar pressure value was found to give good agreement when comparing the shock wave emission and expansion of a bubble in a microfluidic channel [1] with numerical simulations. Choosing a different amplitude $\hat{P}$ will scale the reported pressure values but not change the quantitative picture because all equations and boundary conditions involved are linear.

Figure 4.10 presents results of the simulation. Positive pressures are depicted in red and rarefaction waves in blue. The snapshots at the times of $t = 20, 29, 59$, and 89 ns reveal the formation of a rather complex sequence of waves originating from the central region. At $t = 20$ ns, that is 10 ns after excitation the rightmost wave with a small amplitude is caused by the longitudinal wave in the bulk that is leaking into the liquid (B). This wave is trailed by the leaky Rayleigh wave (L-R) creating Mach-cones in the liquid and is starting to separate from the central region at $t = 29$ ns. At $t = 59$ ns a third wave can be distinguished that is resulting from the reflections of waves between the glass boundaries. This wave creates symmetric deformation on the glass boundary while traveling at a much lower velocity than the L-R wave. The separation of this symmetric Lamb wave traveling with an acoustic velocity in the liquid from the L-R wave is clearly visible at $t = 89$ ns. These three waves are also visible in the $r - t$ diagram in Fig. 4.10b, where the pressure in the center of the gap ($z = 10 \mu\text{m}$) is plotted as a function of r and t . The first rather weak

FIGURE 4.10: Simulations of the acoustic wave propagation in a 20 μm thick water filled gap. a) Side-view of the waves with tension (blue) and compression (red) for 4 instances of time. b) $t-r$ diagram of the pressure at the center of the channel. The three distinct waves are the leaking longitudinal bulk wave (B), the leaky Rayleigh wave (L-R) and the Lamb wave.

wave is caused from the driving of the liquid by the longitudinal wave traveling in the solid at a speed of $v_B = \sqrt{E(1-\nu)/(\rho(1+\nu)(1-2\nu))} = 5602 \text{ m/s}$ and leaking into the liquid (B). It is trailed by a leaky Rayleigh (L-R) wave traveling at $v_{LR} = \sqrt{E/(2\rho(1+\nu)(0.862 + 1.14\nu)/(1+\nu))} = 3116 \text{ m/s}$ radiating into the liquid gap as a Mach cone. The third wave is excited by the bending of the boundaries of the thin gap forming a symmetric Lamb-mode. We find a velocity close to the speed of sound in water similar to the wave front velocity found in the experiment.

Similar symmetric Lamb modes were reported in thin liquid gaps before. There the liquid was sandwiched by two layers of soft rubber [12] and the modes were excited by bubbles undergoing stable volume oscillations. Yet due to the considerably lower elastic modulus the propagation velocity reported was two orders of magnitude smaller than for the present case, while more rigid materials such as glass result into waves traveling in the liquid at much higher velocities. Derivation of Lamb-type waves both symmetric and anti-symmetric following the derivation from this article and corresponding dispersion curve are shown in Section 4.7.2. Resulting velocities for the Lamb waves are similar to those obtained experimentally and with the simulation.

4.5 Discussion

4.5.1 Laser-induced bubbles in thick gaps

With the aid of different kinds of imaging and numerical simulations, we have proposed a model to explain the secondary cavitation activity observed when a pulsed laser is focused in a microscopic gap bounded by two solid walls. Thermo-elastic waves result in a Lamb-type wave which nucleates the bubbles. However, for the Lamb-wave to exist, the gap needs to be thin enough in comparison to the energy of the laser pulse. In the case of a thick gap or if the energy is too low to excite the Lamb modes, a single “classical” cavitation bubble is observed arising from the plasma recombination. Its growth-shrinkage-collapse cycle presents a

FIGURE 4.11: Cavitation activity within a $\approx 125\mu\text{m}$ thick water filled gap following a laser-induced dielectric breakdown: selected images from a high-speed recording taken at 500 kfps with 250 ns exposure time. The central bright spot on the first frame is from the plasma emission.

quasi-symmetry where the time from nucleation to maximum volume almost equals the time from maximum radius to collapse. This differentiates to the thin gap case where secondary cavitation is observed. There, the time from maximum volume to collapse significantly predominates in the bubble life cycle (see Figure 4.5). Figure 4.11 shows the recording of a typical run in a $\approx 125\mu\text{m}$ gap created by using $125\mu\text{m}$ thick Mylar foils, the bubble is nucleated at $t = 0$, grows to reach maximum volume at $t \approx 26\text{ ns}$ and collapses at $t \approx 56\text{ ns}$.

4.5.2 Influence of different parameters on secondary cavitation

We have seen that the gap thickness and the energy of the laser pulse are key conditions in generating secondary cavitation. The medium used is also of significant importance. Indeed, if experiments with water and water based hydrogels have shown dense secondary cavitation, those using ethanol as liquid layer resulted

FIGURE 4.12: Selected frames showing the dynamics of the secondary cavitation when the pulsed laser is focused near a hard wall.

in very few bubbles being nucleated. To the opposite, provided that the energy deposited at the focal point remains sufficient, the thickness of the glass plates does not play a role, similar results were obtained with thickness ranging from $t \approx 130 \mu\text{m}$ to centimetric size. Also presence of a rigid wall nearby does not hinder the appearance of secondary cavitation though the ring pattern is disturbed near it. Figure 4.12 shows selected frame from a run where the pulsed laser is focused near a hard wall. But a gas pocket would block the propagation of the lamb Wave as shows the absence of secondary cavitation bubbles right behind the pre-existing bubbles in Figure 4.13.

FIGURE 4.13: Selected frames showing the dynamics of the secondary cavitation when the pulsed laser is focused in-between two pre-existing bubbles.

4.5.3 Surface erosion

In another experiment, we added a thin paint layer on the bottom glass of the gap. In Fig. 4.14, we show the smooth dark stripe on the left of the frame before the cavitation activity (left frame) is pictured with the bubbles present at $t = 1 \mu\text{s}$ and long after ($t = 210\text{s}$) the collapse in the right frame of Figure 4.14. The latter image reveals many bright spots at the locations where bubbles have appeared. The cavitation bubble collapse is sufficiently intense to remove locally the film from the surface.

FIGURE 4.14: Demonstration of cavitation erosion: at the locations of cavitation activity ($t = 1 \mu\text{s}$) bright spots appear (*after*), indicating the removal of thin film from a water-proof marker.

4.6 Conclusion

In summary, we have demonstrated that cavitation in liquids can be induced from intense surface waves in a thin liquid gap. Most prominently, a Lamb-type wave nucleates cavitation bubbles of up to $\approx 10 \mu\text{m}$ in diameter that last for several microseconds. Their collapses are sufficiently strong to erode the surface. These surface waves can only be nucleated if the initial pressure disturbance is sufficiently strong and confined. For the present experiments the plasma pressure from the laser-induced breakdown is generating several gigapascal on an area of a few micrometers in diameter.

4.7 Appendix

4.7.1 Waves generation upon laser pulse impact

FIGURE 4.15: Elastic waves generated by focusing of a laser pulse in a single glass plate captured with stroboscopic illumination. Exposure time of the camera is 500ns and two pulses of light of duration 213fs are produced 50ns apart.

When a laser pulse is focused into an elastic solid such as glass, intense thermoelastic waves [11, 24] are emitted from the focal volume. One can further observe ablation of the glass [9] and for sufficiently high energies even cracks. Fig. 4.15 shows an example of waves generated upon laser impact on single glass slide. A double illumination similar to 4.2.4 is used. We observed on the outside, two high contrast rings (B1 and B2), those correspond to the positions of the bulk wave generated in the glass and traveling with a velocity $V_w \approx 5800 \text{ m.s}^{-1}$. Closer to the center, two other rings are present (R1 and R2), they correspond to the Rayleigh / Surface wave emitted and traveling at the surface of the glass plate with a velocity $V_w \approx$

3200 m.s^{-1} . At the center, the black area shows the damage (ablation and crack) done to the glass by the laser impact. Non-centered surface waves are also observed, probably created by the cracking of the glass after the laser impact.

4.7.2 Lamb waves in a thin liquid gap

Here we are following the derivation of Lamb-type waves from A. Doinikov et al. [12]. They obtained the dispersion relation for a symmetric excitation, in particular, they calculated the phase velocity of the Lamb wave in a microfluidic channel bounded by two slabs of PDMS (polydimethylsiloxane). The low elastic modulus of PDMS results in Lamb waves travelling at tens of meters per second while we expect much higher velocities for the considerably higher modulus of glass. A second difference is the excitation. We may expect that besides a symmetric mode, also asymmetric modes may be excited. Therefore we present below a brief derivation of the Lamb mode which follows the scholarly paper from Doinikov et al. [12] yet include the anti-symmetric mode, too. And third we expect frequencies of the Lamb mode corresponding to the round trip time in the gap, i.e. $f = c/(2h) \approx 40 \text{ MHz}$, where $c \approx 1500 \text{ m/s}$ is the Lamb wave phase speed and h the gap height of approximately $20 \mu\text{m}$.

A sketch of the geometry solved for is provided in Fig. S1.

The system is axisymmetric with the center, $r = 0$ and $z = 0$ located in the liquid in the center of the channel. $z = h/2$ is the upper boundary between liquid and solid, and $z = -h/2$ is the lower. The indices H_0 and H_1 indicate that the Hankel transforms of order 0 and 1 is used. While for the calculations of the deformation the inverse Hankel transform is needed, we do not need this additional complexity to calculate the wave velocity as a function of ω and h . The notation and details are provided in Ref. [12]. The upper sign refers to the symmetric and the lower sign to the anti-symmetric case. The boundary conditions are:

FIGURE 4.16: Sketch of the geometry glass-solid-glass. Axisymmetry is assumed. A symmetric and anti-symmetric Lamb mode of the two glass plates is depicted below.

$$u_{1r}^{H_1}(z = h/2) = u_{2r}^{H_1}(z = -h/2) \quad (4.5)$$

$$u_{1z}^{H_0}(z = h/2) = \mp u_{2z}^{H_0}(z = -h/2) \quad (4.6)$$

$$\Phi_2(k) = \pm \Phi_1(k) \quad (4.7)$$

$$\Phi_{f2}(k) = \pm \Phi_{f1}(k) = \pm \Phi_f(k) \quad (4.8)$$

$$\Psi_2(k) = \mp \Psi_1(k) \quad (4.9)$$

We can then write Eqs. (2.41)-(2.46) from Doinikov with 3 Equations for Φ_1 , Ψ_1 , and ϕ_f as the unknowns, thus

$$q_l \Phi_1 - k \Psi_1 + q_f (1 \mp e^{-q_f h}) \phi_f = 0 \quad (4.10)$$

$$2k q_l \Phi_1 - (2k^2 - k_f^2) \Psi_1 = 0 \quad (4.11)$$

$$(2k^2 - k_t^2) \Phi_1 - 2k q_l \Psi_1 + \frac{\rho_f \omega^2}{\mu} (1 \pm e^{-q_f h}) \phi_f = -\frac{Q}{2\pi\mu} \quad (4.12)$$

where the upper sign refers to symmetric and the lower sign for anti-symmetric excitation. Using Cramer's rule these in-homogeneous linear systems of equations can be solved. Solutions to the dispersion equation $D(k) = 0$ where $D(k)$ is the determinant of above equations result to the dispersion curves $c(\omega)$ for the symmetric and anti-symmetric Lamb waves:

$$D(k) = (2k^2 - k_t^2)^2 - 4k^2 q_l q_t + \frac{\rho_f k_t^4 q_l}{\rho_s q_f} \frac{1 \pm e^{-q_f h}}{1 \mp e^{-q_f h}} \quad (4.13)$$

For the definition of $k, k_t, q_l, q_t, q_f, \rho_f$, and ρ_s please see Ref. [12].

FIGURE 4.17: Dispersion curve as a function of elastic modulus.

Next we present the solutions to Eq. (9). Fig. S2 demonstrates the dispersion relation $c(f)$, where c is the phase velocity of the wave and $f = 2\pi\omega$ the frequency

FIGURE 4.18: Dispersion curve as a function of gap height.

for the symmetric (solid lines) and anti-symmetric (dashed lines) waves. The three pairs of curves are for selected elastic modulo $E = 63, 40, 20$ GPa and a gap height $h = 20 \mu\text{m}$. The other parameters are $\rho_s = 2230 \text{ kg/m}^3$, $\rho_f = 998 \text{ kg/m}^3$, and the speed of sound in the liquid $c_f = 1481 \text{ m/s}$. In the limit of $f \rightarrow \infty$ the wave velocity approaches to the Scholten wave velocity, i.e. $h \rightarrow \infty$ for the symmetric and antisymmetric wave. The speed of sound in the liquid c_f is the upper limit of the Lamb-wave velocity. We find that the symmetric wave can propagate at the expected frequency range of 40 MHz for the elastic modulus of glass $E = 63$ GPa, while the anti-symmetric wave may propagate only for smaller modulo. The second dependency of the dispersion curve is the gap height, see Fig. S3.

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Chapter 5

Conclusions and outlook

While there is large body of research available on cavitation in liquids many of the therapeutical applications occur in a tissue. The major difference between liquids and an elastic solid is the restoring force and therefore the ability to propagate transverse waves. The thesis' main focus was how these waves are generated and propagate. While it is far from these fundamental studies, we hope that this increase our understanding of the interaction of bubbles with tissue so existing therapy and diagnostic methods could be improved.

Below the main chapters 2 to 4 are summarized before an outlook on the possible future research paths is given.

5.1 Conclusions

In **Chapter 2**, the stress field surrounding a laser-induced bubbles created in the bulk of a gelatin phantom can be observed with high-speed photography in combination with photoelasticity. The experimental result for a “frozen” spherically expanding bubble was tested quantitatively against the expected results for stress around a spherical cavity owing to internal pressure found in literature [3, 14] with good agreement. The laser-induced bubbles collapsing in the bulk of the tissue

mimicking phantom may result to either an attached stress field or emission of stresses from the bubble, the “wave” regime. In the first regime, the bubble grows, collapses and rebounds while remaining mostly spherical. There the stress created over the bubble’s life-time remains confined in a thin spherical shell and attached to the bubble’s surface. In the second case, the bubble undergoes a non-spherical collapse with strong surface deformation or even splitting. During the first expansion, the stress remains attached to the bubble similar to the first regime, but during collapse and rebound we observe a non-spherical stress field surrounding the bubble which will eventually propagate away from the bubble.

In **Chapter 3**, the non-spherical collapse was induced intentionally by placing the bubble near solid walls or free boundaries. As a result shear waves traveling with a speed of a few meters per second are emitted from the bubble. For the case of a bubble collapse near a free surface, we connect the emission process with the lateral translation of the bubble during collapse and the thereby induced jet. This process confines shear stress in a cylindrical volume bordered by the free surface and the bubble. This observation is compared with a Finite Element Method simulation. There a simple stress source traveling away from the free surface is introduced. The time dependent simulated shear stress field overall agrees with experimental observations. Due to the bubble jetting away from the free surface material is dragged along. Owing to the rigidity of the gelatin, the air/solid interface is pulled behind the bubble leading to the opening of a cone-shaped crack. Strong jets, i.e when the bubble is sufficiently big and created very near to the free surface permanent damage may occur. We also introduce experimental observations of shear waves emitted far from the position of laser focus.

In chapter, **Chapter 4**, the situation is reversed. Instead of the generation of a transverse wave from cavitation, cavitation is generated by a transverse wave. We present a new way of generating intense cavitation. This phenomenon was discovered while studying cylindrical laser-induced bubbles in a microfluidic gap to calibrate our photoelastic experiments. Surrounding the primary laser-induced cavitation bubble fast and intense secondary cavitation bubbles are formed. Using

sub-picosecond and streak imaging, we show that the laser pulse excites elastic waves in the glass plates confining the liquid layer. A Finite Element Method simulation coupling linear elastic and linear acoustic model was run to understand the complex interaction of waves. It reveals that Lamb modes are excited. The symmetric mode expands/stretches the liquid resulting in outward propagating low pressure volume sufficient to rupture the liquid and form cavitation bubbles.

5.2 Outlook and perspectives

5.2.1 Cavitation induced shear waves in soft solids

FIGURE 5.1: Tissue velocity maps acquired on in vivo human liver at four successive times after the shearwave generation. Adapted and reproduced from [7], © [2008] IEEE

We have now evidence that shear waves can be generated by non-spherical bubble collapse in soft solids and proposed a mechanistic model. Yet open questions remain: one is the amplitude of the waves created and at which magnitude they may cause damages. Those could be to the structural integrity of the elastic tissue, but also to individual cells or complex networks of cells found for example between neurons. This is particularly important for medical applications where bubbles are present in tissues either as active treatment agents or as side-effects. In some cases, the potential tissue alteration induced by the shear waves could improved efficiency of the treatment. In others, it would be important to remain below the damage threshold to avoid tissue destruction or propagation of the damages outside of the targeted area.

The experimental methods used in Chapter 2 and Chapter 3 combining high-speed photography and photoelasticity were useful to reveal the waves and their generation mechanisms but do not allow as of now to quantify the stress magnitude. They also limit the choice of study's media to optically transparent and birefringent materials and thus deny in-vivo experiments. Another measurement methods is required. As discussed in Section 1.4 and Section 2.1, acoustics imaging as already established in elastography could be a solution. It is used to monitor tissues responses to shear waves and measure the mechanical properties of the medium. For example tissue velocity maps such as the ones presented in Figure 5.1 can be obtained. There shear waves were created by ultrasound focusing and captured by ultrasound imaging, i.e the local tissue velocity is measured and changes compared to reference highlight the propagation of the transverse waves. The limited acquisition frequencies offered by this imaging technique was not ideal for understanding the mechanism behind the shear waves emission following bubble collapse. However they are plenty sufficient for tracking deformation induced by the waves propagating at low velocities of few $m.s^{-1}$, especially with the development of acoustic high-speed cameras. Xi et al. [12] proposed for example to use a research ultrasound platform (Verasonics 64LE) with a 64 channels transmit/receive transducer to build an acoustic high-speed camera. Figure 5.2 depicts an experiment where the acoustic camera is used to track the diameter of a spark-induced bubble. It shows good agreement with the measurement obtained with an optical high-speed camera.

This method would present the advantage of being able to directly quantify shear waves emission in medical procedures such as histotripsy. One could also imagine tracking the shear wave emitted during medical treatment to map the mechanical properties of the targeted medium and monitor the efficiency of the treatment.

We have also observed that strong stress conditions may result into deformation of solid / air interface and appearance of a crack. This phenomena should be investigated as it may occur in medical ultrasound where neighboring bubbles could

FIGURE 5.2: (A): Test setup of the acoustic camera. (B): Acoustic camera's frames acquired during the life-time of a spark bubble. (C): Comparative graph of the bubble diameter as captured by the high-speed camera and reconstructed from the acoustic camera. Adapted and reproduced from [12]

act as a free surface and could be a potential source of permanent damage in the tissues.

5.2.2 Cavitation inception from transverse waves in a thin liquid gap

In Chapter 4, we have described a novel method of generating cavitation from transverse waves in a thin liquid gap. In this method, a strong tension is generated by the propagation of Lamb-type waves at the solid/liquid interfaces which nucleates a dense cloud of bubbles.

Their collapses are sufficiently strong to erode the surface, this could present interest for cleaning of biofilms in confined geometries, sonoporation of cells in microfluidic devices [9] and surface treatment by cavitation peening [11].

FIGURE 5.3: (A): Micro-channel for nanobubbles nucleation by water-ethanol exchange. (B): Principle of nanobubbles nucleation by water-ethanol exchange, channel is flush with water, then with ethanol and finally again with water, after the last exchange nanobubbles start to form on the glass surface. (C): Bubbles nucleate gradually over several minutes. The exchange flow is from left to right. The scale bar is $10\mu\text{m}$, adapted and reproduced from [5]

It could also provide a way to test for cavitation nuclei and their stability on substrates. In classical cavitation theories [1, 2, 6, 8], cavitation arises either from rupture of the pure liquid under strong tension, or from preexisting nuclei. Those are pockets of gases trapped in crevices of nano-, micro-particles or present at nanoscopic scale in the liquid bulk which become apparent as cavitation after being excited by acoustic waves. The existence of such nanobubbles is paradoxical as the large Laplace pressure would predict their dissolution in a few microseconds. However, recently the existence and stability of surface nanobubbles has been demonstrated [10, 13]. But the question remains whether or not cavitation could nucleate from nanobubbles. With the methods developed in Chapter 4 we now have a method to conduct this investigation. One could imagine an experiment where nanobubbles would be created in a microchannel with classical methods such as water-ethanol exchange [5] (see fig. 5.3) and where tension would be induced in the channel exciting Lamb-type waves. Furthermore, the precise timing of the cavitation event with respect to the ns-duration laser pulse may offer an alternate route to explore sonochemistry from cavitation bubble collapse spatially and

temporally resolved [\[4\]](#).

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