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Shock waves emitted at the collapse of a laser-induced cavitation bubble in the vicinity of a free surface

Sóng xung kích sinh ra tại thời điểm nổ bóng khí trong điều kiện có bề mặt thoáng gần kề

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Abstract

We investigated the dynamic of a cavitation bubble induced by laser ablation in liquid in the vicinity of a free surface. The observation was conducted using high-speed laser stroboscopic videography in photoelasticity mode. We showed the bubble contracted faster in the vertical direction and formed a flat bubble at the minimum contraction. At the collapse, the bubble emitted multiple shock waves. The dynamics of the bubble during contract phase and the emission of multi shock waves were discussed in details.

Keywords: Cavitation bubble; laser ablation in liquid; photoelasticity images; shock waves.

Tóm tắt

Chúng tôi phân tích động học của bóng khí sinh ra bởi quá trình phá hủy bằng tia laser trong môi trường chất lỏng trong điều kiện có mặt thoáng gần kề. Quan sát được tiến hành sử dụng kĩ thuật quay phim quang đàn hồi tốc độ cao. Chúng tôi chỉ ra rằng bóng khí co lại nhanh hơn theo phương đứng và tạo thành bóng khí phẳng tại kích thước cực tiểu. Khi nổ, bóng khí phát ra đa sóng shock. Động học quá trình co lại của bóng khí và sự phát sinh đa sóng shock được thảo luận chi tiết.

Từ khóa: Bóng khí; phá hủy bằng tia laser trong môi trường chất lỏng; hình ảnh quang đàn hồi, sóng shock.

1. Introduction

When focusing a laser beam on a surface immersed in liquid, the induced plasma initiates a cavitation bubble. In laser machining and surface treatment, laser-induced cavitation bubble is considered a harmful phenomenon that limits the machining effectiveness. Moreover, the shock waves emitted at bubble collapse can cause serious damages to the machined surface. Thus, the dynamics of laser-induced cavitation bubbles have received intensive attention in the past decades.

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In infinite liquid, the dynamics of a bubble has been well studied and has been shown to follow the Rayleigh-Plesset model [1]. However, a spherical cavitation bubble developed near a free boundary results in an asymmetric collapse by that the bubble collapses faster in one direction [1-3]. In the studies on cavitation bubble induced in laser ablation in liquid (LAL), the liquid depth is usually considered infinite. However, LAL is usually conducted under a thin liquid layer in industry. For this reason, investigating the shock emitted at the collapse of a laser-induced cavitation bubble in the vicinity of a free surface is of great importance.

In laser forward transfer of liquids (LFT), the effects of a free surface on the dynamics of a cavitation bubble has been investigated [4,5]. The interaction of bubble and free surface were also considered in the studies on a single spherical bubble [1,2]. In LAL, the cavitation bubble induced is restrained in one direction. Thus, the results for a spherical bubble can not be directly applied. In LFT, the bubble is restrained in one direction like in LAL. However, they uses much smaller energy in LFT in comparison to LAL. Furthermore, the liquid layer is kept much thinner and the emission of secondary shock is not considered in the researches on LFT.

In this research, we aim to observe the collapse and rebound of a cavitation bubble induced by LAL in the vicinity of a free surface. The emission of the shock wave at bubble collapse is observed by high-speed laser stroboscopic videography in photoelasticity mode. The dynamical aspect of the bubble and shock wave are discussed in detail. This knowledge is useful for an optimal parameter choice for applications of under-liquid laser ablation.

2. Material and methods

The cavitation bubble was induced by focusing a 1064 nm laser pulse, with full width at half maximum (FWHM) = 13 ns on a solid target. The target is an epoxy-resin block 20 x 5.8 x 28 mm^3. The ablations were carried out in pure water with the liquid-air interface at 3 mm above the target surface. The pulse energy was 20 mJ. Photoelasticity images were obtained by using high-speed laser stroboscopic videography in photoelasticity mode. Details of the technique and imaging system can be found in our previous work [6].

3. Results and discussion

Figure 1 presents a time-resolved observation of a laser-induced cavitation bubble from the maximum radius until dozens of microseconds after the collapse. The bubble reached its maximum radius at 144 μs. At this time, the bubble has a radius of about 2.8 mm, which is approximate to the depth of the liquid layer. After reaching the maximum radius, the bubble begins to contract. The bubble appeared to contract slower in the horizontal direction compared to the vertical direction, forming a flat bubble. The bubble reaches its minimum radius at around 328 μs. At this time, the bubble has the shape of a dish with the diameter much larger than the height. At 336 μs we can observe the emission of the shock waves, represented themselves as many waves in the water and the stress wave observed in the target. After emitting the shock waves, the bubble burst into a cluster of many smaller bubbles, as can be seen in the frame taken at 384 μs.

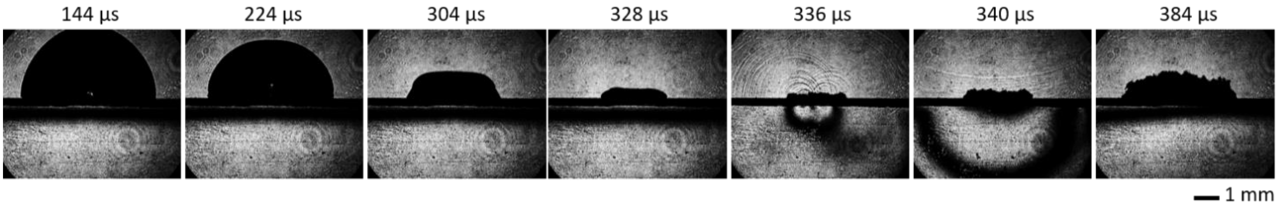

Figure 1. Time resolved observation of laser-induced cavitation bubble in the contract phase. Liquid depth is 3 mm. The pulse energy was 20 mJ. The first frame is demonstrated bubble at the maximum radius. The emitting of the shock waves can be observed at 336 microseconds.

A detailed observation of shock wave emitted at the collapse of the laser-induced cavitation bubble near a free surface is presented in Figure 2. Differ from the bubble in infinite liquid which tends to emit a single shock wave, the flattened bubble emitted several shock waves. These shock waves look non-concentric, i.e. like being originated from the two sites of the bubble within some hundreds of nanoseconds.

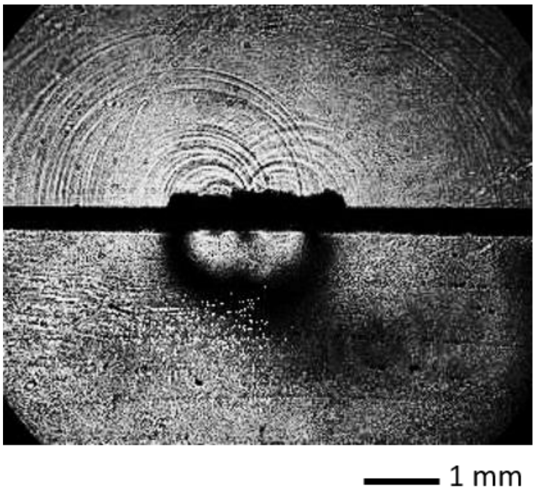

Figure 2. Detail observation of shock wave emitted at the collapse of laser-induced cavitation bubble in the vicinity of a free surface. The images was obtained at 336 microseconds after irradiation, pulse energy was 20 mJ. The liquid layer thickness was 3 mm. .

To explain the multi emission of shock waves, we need to consider the effect of a free surface on the collapse of the bubble. If the liquid is infinite, the expansion and collapse of a bubble can be described by the Rayleigh-Plesset model. However, in the vicinity of a free surface, the bubble is restrained by a non-symmetry environment: the liquid resistance in the horizontal direction is larger than the vertical direction (Fig. 3 (a)). This non-symmetric makes the cavitation bubble elongate in the vertical direction. Since the difficulty in displacing the liquid layer is reduced as the bubble approaches the free surface, the bubble elongation is dominating. In response to the expansion of the bubble, the free surface is lifted and a liquid dome is formed. This dome moves upward following the expansion of the bubble as being shown in Fig. 3 (b) and (c). When the bubble contracts, between the free surface and the bubble forms a high-pressure area. This high-pressure area pushes the bubble and the air-liquid interface in two opposite ways: the dome is pushed upward, while the bubble surface is pushed downward and a liquid jet is formed inside the bubble. In this manner, the hemispherical bubble becomes concave and finally develops into a toroidal shape near its contraction. The compression of a toroidal bubble leads to the collapse and rebound happens at many discrete points along the torus. As a result, the emission of multiple shock waves can be expected [7].

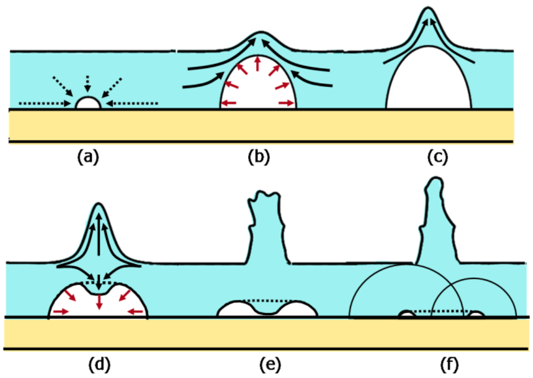

Figure 3. Schematic of the expanse and collapse of a cavitation bubble near a free boundary.

In our photoelasticity images, the bubble has a dish shape near the contraction. This dish-shaped bubble is the 2D projection of the concave bubble mentioned above. Because the shock waves were emitted from different locations along the torus bubble, their projection on a plane looks like many discrete semicircles originating from two sites of the bubble. If the liquid depth is increased, the non-asymmetric of liquid environment causes less effect on the bubble expansion. Thus, the formation of the concave bubble is marginal. The bubble will contract as a hemispherical and emit a single near-circular shock wave, as being reported in our previous [8].

4. Conclusion

We investigated the dynamic of laser-induced cavitation bubble from the maximum radius until several microseconds after collapse. The observation showed that, in the vicinity of a free surface, the bubble collapsed asymmetrically and formed a flat bubble. At the collapse, the bubble emitted multiple shock waves rather than a single one. The observed dynamics aspect of the bubble during contract phase and the emission of multi shock waves can be explained by considering the asymmetric resistance of the liquid against the bubble expansion.

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