A STUDY OF IMPULSIVE PRESSURE DISTRIBUTION OF CAVITATION GENERATED BY A HIGH-FREQUENCY VIBRATIONAL PROBE

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ABSTRACT

The cavitation is always known as a very harmful phenomenon to the hydraulic systems and equipment. But the collapse of cavitation micro-bubbles can be used as a knifeless cutter due to the highly erosive pressure. In order to make usage of this phenomenon, the present study investigated experimentally the characteristics of the 47 kHz-ultrasonic cavitation by several techniques, such as, particle flow visualization; impulsive pressure and acoustic emission (AE) measurement. As the result, the cavitation phenomenon induced by the 47 kHz vibrator has been visualized and the impulsive pressure performance is established. The collapsed frequency and erosive intensity of cavitation bubbles which induced by the 47 kHz vibrational field is analyzed. The effects of parameters, such as, vibrational intensity; stand-off distance are estimated with the aim of cavitation control for realizing a micro knifeless-surgical tool.

TÓM TẮT

Xâm thực được biết đến là một hiện tượng có tác hại rất lớn trong máy và hệ thống thiết bị thủy lực. Tuy nhiên, sự phá vỡ của các bọt khí xâm thực kích cỡ micro có thể sử dụng như một công cụ cắt không dao nhờ vào xung áp suất cao có thể gây ăn mòn kim loại. Nhằm phát triển ứng dụng xâm thực như một công cụ hữu ích, nghiên cứu này đã tiến hành đo đạc thực nghiệm đặc tính của xâm thực tần số cao 47 kHz bằng các kỹ thuật như: quan sát dòng chảy hạt; đo đạc xung áp suất SPF và sự truyền sóng âm (AE). Kết quả nghiên cứu đã quan sát được hiện tượng xâm thực và khảo sát đặc tính phân bố xung áp suất của nó. Tần số phá vỡ của đám mây xâm thực và cường độ phá hủy của xâm thực cao tần ở tần số phát động 47 kHz đuwocj phân tích. Các thông số ảnh hưởng như: cường độ rung động; khoảng cách tấm chắn được đánh giá theo mục đích xây dựng khả năng điều khiển xâm thực để hiện thực hóa công cụ mổ không dao kích cỡ micro.

I. INTRODUCTION

The cavitation is always known as a very harmful phenomenon with the hydraulic system and equipment because of causing erosion, vibration, noise and failing system [1, 2]. But what can we deal with cavitation in an useful way? Cavitation bubble collapse can produce an extreme condition in order of some thousands Celsius degree and up to 1000 *bar* pressure. Recently, the possible application of cavitation is one of a very interested topics of researchers in biomedical engineering, water treatment, manufacturing technology. In the field of biomedical engineering, the usage of ultrasonic cavitation were carried out with the High Intensity Focused Ultrasound - HIFU technique and cavitation control lithotripsy - CCL technique in kidney stone lithotripsy with the research works of Ikeda et al. [3,4]. By the cycle of pressure transmission thought a liquid media, local compression and refaction of acoustic pressure waves causes the cavitation bubble appeared and collapsed which can produce an extreme condition in the order of thousands Celsius degree and up to 1000 *bar* pressure [5]. The induced impulsive pressure of buble can cause erosion of kedney stone. So that the controlability of ultrasonic cavitation becomes very important for study. In HIFU therapy, cavitation appearance can impede acoustic propagation that affecting to the focal temperature of HIFU source as well as the prediction of lesion shapes and focal location. Generally, we have to control the intensity of cavitation for the particular purposes. In other way to be approached of lithotripsy method, the CCL technique combining of the two-range frequency (low and high range) that has been introduced by Matsumoto group [6] by experimentally simulating the kidney stone lithotripsy. This method allows us to control cavitation effects more flexibility.

Both of the two method CCL and HIFU are used the ultrasound wave generator and no need to touch to the patient body. In our approach, we aim to use the vibrational probe as a knifeless surgical tool by generating closed-range cavitation bubbles. By the way, we can creat a micro-scale cutter with a low power.

In present study, the impulsive pressure distribution of cavitation around a 47-kHz vibrational probe are investigated for clarifying the cavitation control in surgical purpose. The pressure measurement technique here used Pressure Sensitive Film (PSF) and Acoustic Emission (AE) sensor. The results carrided out some parameters' effect for application purpose.

II. EXPERIMENTAL SET-UP

The experimental system is shown as in figure 1. The test is carried out by simply putting vibrator on a water small tank with the dimensions of h×b×l = 150×150×150 mm. The target is an aluminum flat plate. The source of vibration supplies a constant 47 kHz oscillating motion with a maximum displacement 100 μm. The intensity of vibrator is controllable digitally at different values from 10% to 100% that corresponding to the displacement from 10 μm to 100 μm. The flow pattern and cavitation aspect are visualized by laser light sheet (LLS) technique and instantaneous photo by a 8-Megapixel digital camera (Dh1-Nikon). When observing cavities, the 1 μs-xenon flash lamp is employed instead of laser sheet. The important parameters have to control during experimental work are the depth D [mm]; the distance, so-called stand-off H [mm] and the intensity of vibrator I [%]. The vibrator is a titan-coating probe with a diameter d = 2 mm. Acoustic emission (AE) sensor is fixed on the chamber wall. The depth D of probe's submergered part is kept by 5.d = 10 mm. The stand-off distance H is changed from 1 to 3 mm for detecting of impulsive pressure distribution.

For measuring impulsive pressure of cavitation collapse, we cover the specimen a very thin pressure sensitive film (SPF) by a vacuum packing machine. There are 3 types of SPF are used in the measurement, such as, ultrasuper low- (USL); low- (L) and high-pressure (H) type of SPF. The water temperature is kept around 20^0 C.

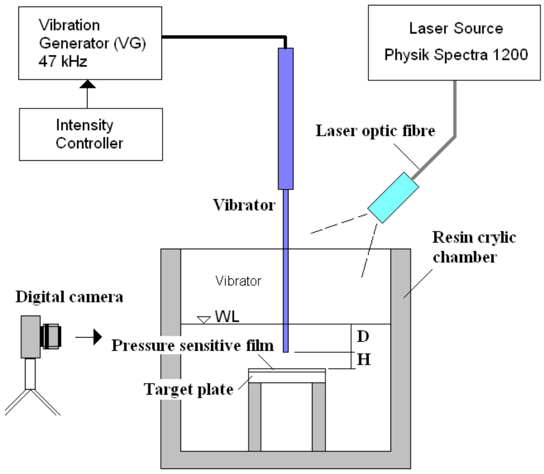


Fig.1 Experimental system diagram

III. RESULTS AND DISSCUSION

3.1 Visualization of cavitation aspects

The aspects of the vibrational ultrasonic cavitation are shown in figures 2 and 3. The shutter speed of camera is 1/500. The interval time 0.2 s which is much longer than the cycle of vibrational motion (47000 cycle per second), so that we can only observe instantaneously the cavitation bubble propagation. In the case of without target plate with 100% intensity (Fig.3), the cavitation appeared as a mushroom-shape cloud cavities with the foot is formed by the downward flow.

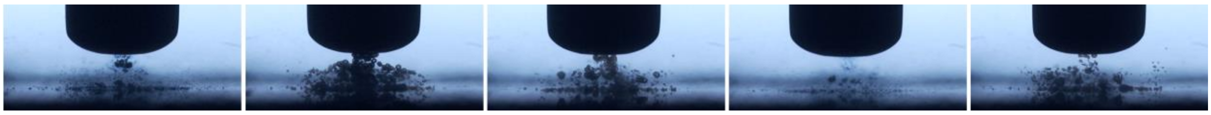
At a different moment of vibrational progress as shown in figures 3a to 3d. Under a high intensity in order of 70% and 100 %, the cavitation is in sevearl type: (i) a bulk of bubble attached on the vibrator's surface and (ii) bubble cavitation at peripheral location of the probe. When reducing the intensity of vibrator, the attached cavitation are on the ways to disappear from the vibrator's surface and the cloud cavitation of micro-scale bubble is formated and disperses into the target plate surface. This is a jet flow of cavities (type (iii)). At 30 % intensity, the bulk cavitation bubble attached on the vibrator's surface is disappeared. At the range of 10% to 20 % intensities, cavitation is not occurred.

Fig. 2 Cavitation induced as a mushroom cavity propagated under the vibrator (I = 100 %, without target plate, probe's depth D/d = 5, interval time 0.2 μs)

(a) Cavitation aspect at 100 % vibration amplitude

(b)Cavitation aspect at 70 % vibration amplitude

(c) Cavitation aspect at 50 % vibration amplitude



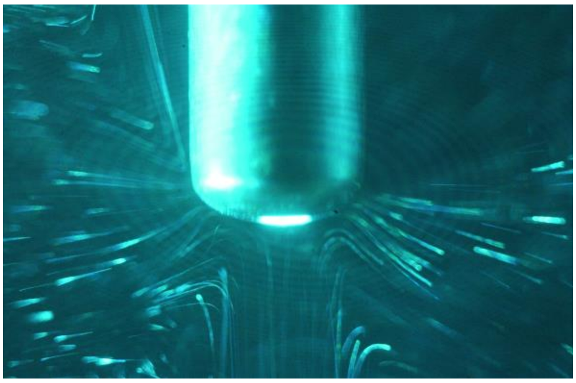
(d) Cavitation Aspect at 30 % vibration amplitude

Fig. 3 Ultrasonic cavitation aspects at a different vibration amplitudes (target plate placed at stand-off H= 1 mm, probe's depth D = 10, interval time 0.2 μs)

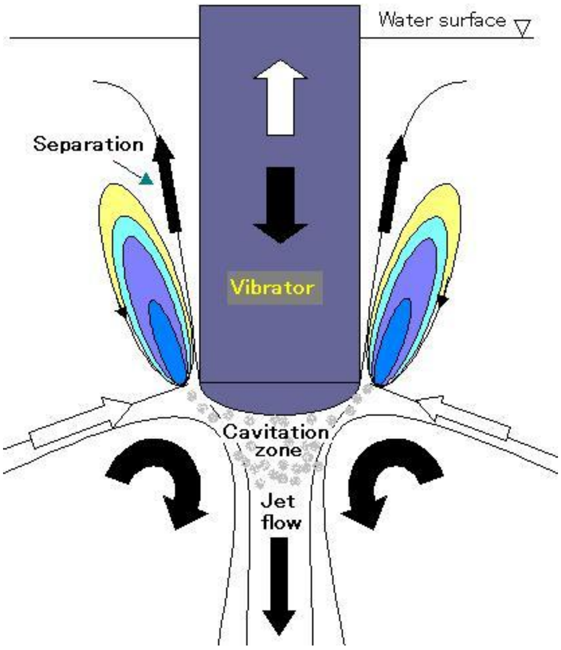
For understanding the mechanism of cavitation formation, the LLS technique is employed to capture the motion of Aluminum fine power put on the observed zone.

The photographs shown in Fig.4 illustrate that when the vibrator moves up, the water will occupy the leaving volume of the probe and the moving orientation is described by white arrows. When the vibrator moves down, the water will be pushed by the probe and the moving orientation is described by black arrows. The separation flow is generated from peripheral line of the probe and combining with the motion of moving-up process to propagate vortices peripherally around the probe. The bulk of fluid under the probe's end is pushed to form a jet flow as observed by LLS technique. The mechanism of flow propagation proved that the moving up motion of the probe gives a local low-pressure zone on the tip of the probe where the cavitation bubble firstly appeared. The peripheral vortex flow also can generate a vortex cavitation when the vortex intensity strong enough, that clarify the appearance of peripheral bubbles as observed by instantaneous capture.

The visualization result proved that the cavitation status much depends on the intensity and stand-off distance H when we place the target plate at a closed position.



(a) Visualization of flow pattern by LLS technique



(b) Diagram of flow mechanism

Fig. 4 Flow pattern generated by the vibrator

3.2 Spatial distribution of impulsive pressure of 47-kHz vibrational ultrasonic cavitation

The impulsive pressure of cavitation is measured by mean of the sensitive pressure film of Fuji Film. The measurement is set-up at a different condition of stand-off distance H, vibrational intensity I, and exposed time 5 s.

In figure 5, the effects of vibrational intensity as well as the stand-off distance H on the impulsive pressure pattern are evidently clarified. By the same USL type of SPF, the detectable range of pressure is from 0.2 to 0.6 MPa. The intensity of red color shows the intensity of impulsive pressure which induced by the observed cavitation bubble. At the highest intensity, the impulsive area is the largest with a impulsive core is in shape of a red circular. Comparing to the observed cavitation bubble as mentioned above, at H = 1 mm and I = 100 %, the diameter of impulsive area is about 1.7 cm corresponding to the size of attached cavitation in Fig.3a. Comparing to at condition H = 1 mm and I = 30%, although the impact area of the observed cloud cavity is about 2-cm dia. circular, the impulsive area is in the scope of 0.4 cm-dia. circular only. This proved that with a week vibrational intensity, the impulsive pressure mainly caused by the collapses of cloud bubble on the jet flow which pushed by the vibrator as the visualization result.

The similar conclusion is given when accounting to the stand-off distance effect. At H=3 mm, the impulsive pattern is changing from circular shape to the red-spot type with the decreasing of vibrational intensity.

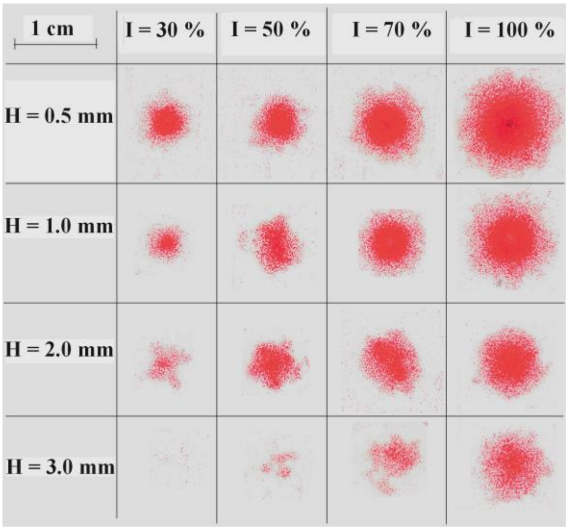
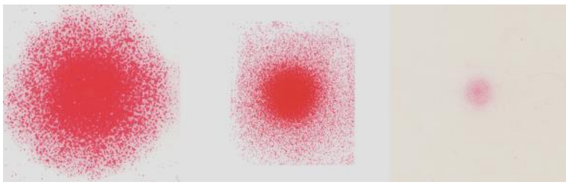


Fig. 5 Relations within stand-off distance H, vibrational intensity I and impulsive pressure pattern (detected by USL film, exposed time 5 s)

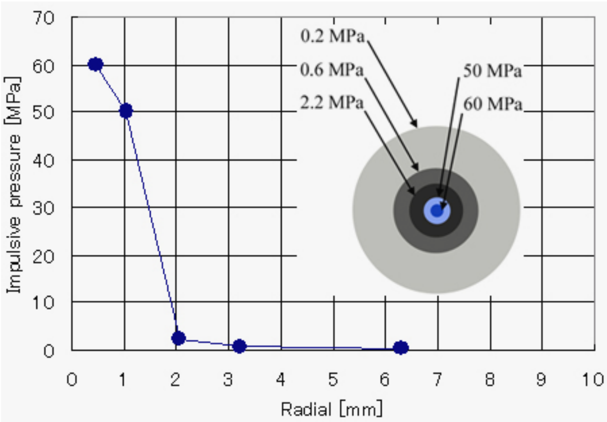
By increasing stand-off distance H, the impulsive area is smaller and also chaging from circular shape to spot type and disappear with H > 3 mm or 1.5×d where the impulsive pressure is smaller 0.2 MPa. Of cause, there is not any impulsive pressure at infinity.



USL film L film H film

(a) Impulsive pressure pattern of vibrational ultrasonic cavitation with different SPFs

(I = 100 %, H = 0.5 mm, exposed time 5 s.)



(b) Impulsive pressure distribution by isobarics

Fig. 6 Impulsive pressure distribution pattern

The above analysis is the result from measurement by USL film so that the distribution of impulsive pressure is still unclear, especially on the red-core area. So that we make several measurement with other film types, such as L- and H-film. The result is shown in Fig.6a. Noted that L-film has a detectable range of 2.5 - 10 MPa, while the H-film has a detectable range of 50 - 130 MPa. The measurement for the case of H = 0.5 mm and intensity by 100%, the maximum impulsive pressure is at the central core of the red-circular. Based on the color calibration, the spatial distribution of impulsive pressure on the impulsive area is shown in Fig.6b. The isobaric lines roughly are axisymmetric. The maximum measured pressure is in order of 60 MPa at the 0.2×d diameter circular. The effective area of impulsive pressure is limited in a scope of 1 mm radius. With the range of a stand-off distance H > 0.5 mm, the impulsive pressure is smaller 50 MPa as there is not any impulsive trace appeared when using H-film for detecting. Additionally, at a far stand-off distance, the spatial ditribution is not a circular but spot type.

Using the optic sensor, so called densitometer of FujiFilm with accuracies is 5%, we can measure an averaged impulsive pressure on the impulsive area. The spatial distribution of impulsive pressure in the stand-off direction is shown in Fig.7. The curve relation between maximum averaged impulsive pressure (MAIP) in the detectable scope is alike power function. At the stand-off H = 0, there is no motion of vibrator so the MAIP is expected by 0. This result is an evidence to prove that the cavitation bubble collapse gives a highest impulsive pressure in the order of 30-35 Mpa at a closed-area around the tip of the probe. The erosive strength of cavitation can be controlled well by driving stance-off distance belong with the vibrational intensity.

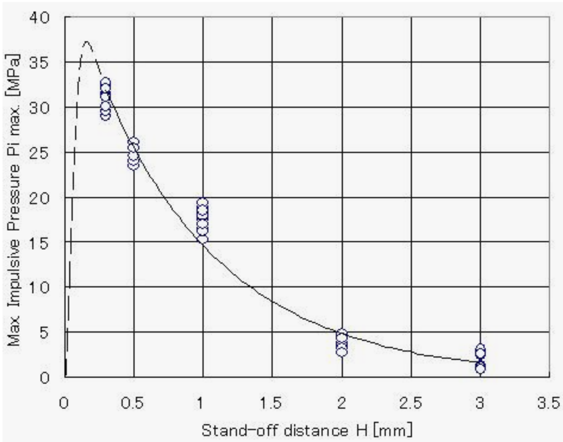
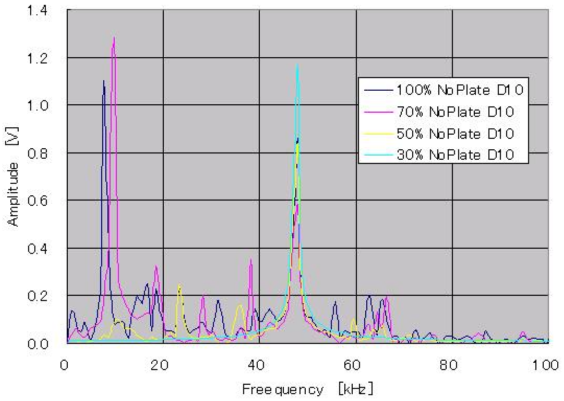


Fig. 7 The dependence of maximum averaged inpulsive pressure (MAIP) on stand-off distance H (detected by Fujifilm densitometer)

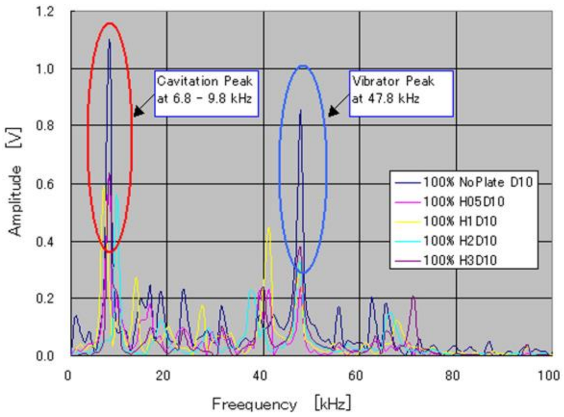
3.3 Acoustic emission (AE) detection of vibrational ultrasonic cavitation

For understanding more about the cavitation control, the AE measurement is also carried out to detecting acoustic signal emitted from cavitation bubble collapses. The AE sensor is placed at under side of the target plate.

The result of measurement for a very far distance of stand-off H is shown in Fig.8a. Intensity effect on the cavitation collapse is clarified. For the all intensity range, every case gives a same high peak at 47.8 kHz where is the frequency of the forced vibrational motion.



(a) AE spectrum of cavitation at a different intensity (without target plate)



(b) AE spectrum of cavitation at a different stand-off H with intensity I = 100%

Fig. 8 Spectrum of ultrasonic cavitation

Specially, at a high intensity range (I = 70% and 100%), there are only two very high peaks corresponding to each case. The peak at 9.8 kHz in 70% I case and the peak at 7.8 kHz in I =100% case. Those peaks must belong to the frequency of a private bubble collapse with the highest amplitude, so called cavitation collapse frequency. Additionally, there are several other frequency where expected belong to cavitation collapse at an amplitude in the order of 0.2 - 0.3 V but all of them is at very low freequency under 70 kHz. The Fig.8b shows the effect of stand-off distance H at I = 100%. It is different to the case above. In the range of H ≤ 3 mm, the cavitation peak always appears with the frequency in the range of 6.8 - 9.8 kHz. The interesting feature from comparison between the data of H = 0.5 mm and H ≥ 3 mm is that although the stand-off condition quite different but the cavitation collapse frequency is in the same order. One case is measured in the condition of a very small H and the other is of a very far stand-off distance H.

Generally, the frequency of the high-energy cavitation peak at a high vibrational intensity suggests that the collapse of attached cavitation is stronger than of cloud cavity on the induced jet flow. The main collapse cycle of present ultrasonic cavitation is roughly by 1/5 to 1/7 the frequency of the vibrational source.

IV. CONCLUSIONS

The ultrasonic cavitation phenomenon produced by the vibrator has been investigated effectively by means of visualization, SPF and AE measurements. Some remarkable conclusions are given below:

1. The ultrasonic cavitation of the vibrator can be controlled well by the parameters, such as, vibration intensity I and stand-off distance H.

2. The spatial impulsive pressure of cavitation bubble collapse is clarified. The maximum impulsive pressure can reach 30 - 60 MPa. Every material can be destroyed at this pressure pulse. With a wide range of controllable impulsive pressure and the ability in minimizing dimensional scale, the vibrational probe has a good potential to be applied as a knifeless "micro-bubble" cutter in surgical technology and kidney stone therapy.

3. There are 3 main types of cavitation in vibrational cavitation, such as, (i) attached cavitation on the probe's surface; (ii) peripheral vortex cavitation and (iii) jet flow cavitation. The most effective impulsive pressure is produced from the type (i). The highest intensity of impulsive pressure is located at the central area of the jet flow and limited in a scope of about d/2 radius.

4. The strongest collapse of present ultrasonic cavitation comes from attached cavitaton near the probe's tip suface. The main bubble collapse frequency is roughly by 1/5 to 1/7 the frequency of the vibrational source.

ACKNOWLEDGEMENT

The authors would like to thank to the supports from Institute of Fluid Science of Tohoku University, Japan, especially to an enthusiam technician, Mr. Higuchi in Complex Flow Systems Laboratory.

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