OBSERVATION OF THE BEHAVIOR OF A SINGLE MICRO-CAPSULE IN AN ACOUSTIC STANDING WAVE

43.25.Yw Acoustic cavitation, vibration of gas bubbles in liquids

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ABSTRACT

The behavior of a single microcapsule in acoustic field is observed by using a high-speed video camera. The vibration modes of microcapsules are observed changing the driving pressure, then it is found that non-spherical vibration modes and the spherical one similar to a free bubble are appeared depending on the initial condition. Regarding to the spherical mode, the experiment results are compared with calculated ones, then the matching between experimental and calculated results are examined and the shell effects expressed as *Sp* are estimated.

INTRODUCTION

In the field of ultrasound diagnosis, ultrasound imaging with contrast agents is a growing method. In this imaging method, high contrast images can be obtained by injecting microcapsules as contrast agents in blood vessels. However, the practical contrast agent, Levovist^{TM}

(Manufactured by Schering AG, Germany), is surrounded by elastic thin shell. Due to the shell effect, the different type vibration modes compared with free bubbles are observed on the microcapsules and this effectiveness is generally expressed as shell parameter, *Sp*.[1] The studies of the shell effect of microcapsules have been focused on its backscatter signal, which is applied to medical imaging systems as a harmonic imaging [2], and there are some reports for determination of *Sp* by its frequency responses. Although these estimations are based on the spherical vibration, it is reported that the microcapsules behave non-spherical vibration in an acoustic field, so that visual observations are necessary to clear on the shell effect. The purpose of this paper is to observe behaviors of a single microcapsule in an acoustic field by using high speed camera. Following the above results, in spherical vibration mode, the shell effect is estimated by comparison with the calculated results by RPNNP equation.

THE CAPSULE MODEL

RPNNP Equation for the Motion of Microcapsule

The well-known equation, RPNNP equation, is applied to only the motion of a free bubble which is always assumed to be spherical. The microcapsules with a thin shell have less nonlinearity on the vibration compared with a free bubble. The modified RPNNP equation including the effect of the shell is expressed as [3]

$$rR\frac{d^2R}{dt^2}+\frac{3}{2}r\left(\frac{dR}{dt}\right)^2=P_g\left(\frac{R_0}{R}\right)^{3\Gamma}+\left(p_v-p_{lo}-\frac{2s}{R}\right)-2S_p\left(\frac{1}{R_0}-\frac{1}{R}\right)-dwrR\frac{dR}{dt}-p_{ac}(t) \qquad (1)$$

where R is the instantaneous radius of bubble, R_0 is the radius of bubble at rest, P_g is the gas pressure inside the bubble, p_{lo} is hydrostatic pressure, d is the damping constant, w is the driving angular velocity, r is the density of liquid, g is the specific heat of inside of bubble, p_v is the steam pressure of inside of bubble, s is the surface tension, and $p_{at}(t)$ is the incident pressure. The damping constant d includes viscous damping, thermal damping, reradiation damping, and internal friction damping. The shell parameter *Sp* is defined as $E.t_w/(1-n)$ where E is the shell elasticity, t_w is the wall thickness, and n is the Poisson ratio.

EXPERIMENTAL PROCEDURE

Principle of Observation with High-speed Camera

The behaviors of the microcapsules are observed by high- speed video camera. The high-speed camera, FASTCAM^{TM} (Manufactured by Photoron, Japan) whose maximum recording rate is 40.5 kHz, is used. The resonance frequency of experimental microcapsules is about 55 kHz, so that if the microcapsule is driven at near the resonance frequency, only one or two frames can be taken in one period for bubble vibration by using the high-speed camera. Therefore, by setting the slight difference between the recording rate and the acoustic driving frequency, the apparent continuously motion can be obtained by the sampling motions. In this report, experiments are carried out with the recording rate of 27 kHz and the driving frequency of 27.075 kHz in order to take 360 frames in one period for bubble vibration.

Experimental Methods

The microcapsules (F-80E, Matsumotoyushi, Japan) whose average radius are 50μm and made of PVC (Polyvinylden chloride–acrylonitrile) are used. The imaging system is shown in Figure 1. A bolt-clamped Langevin transducer is excited with a sinusoidal signal at the frequency of 27075Hz. The light from the Xenon lamp is directed to the observational cell and received by the high-speed video camera. As an acoustic standing wave is generated in the observational cell filled with degassed water, the microcapsule is trapped in the center of the cell. This method is widely applied to the observations of SBSL (Single Bubble Sonoluminescence) of a free bubble. Some microcapsules are attracted to each other due to secondary Bjerknes forces, so that trapping only a single microcapsule is difficult. In our experiments, only a single microcapsule can be infrequently trapped with low concentrated solution of microcapsules and a few data can be obtained.

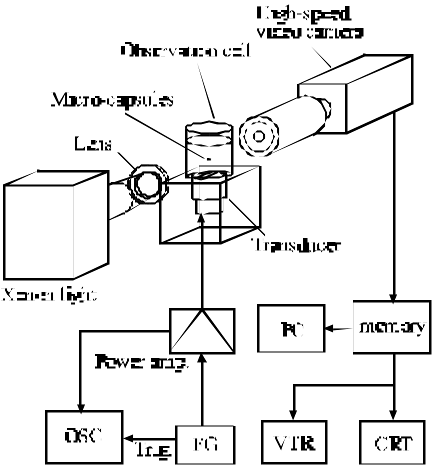

Fig.1 Observation system.

RESULTS

The behaviors of microcapsules are very sensitive to the driving conditions. When raising the driving sound pressure, microcapsules tend to be trapped at the antinode of a standing wave. The vibration of a microcapsule can be distinguished as spherical or non-spherical mode depending on the initial driving conditions. In spherical vibration region, the radius versus time curve (*R-t* curve) is obtained and compared with calculated ones by RPNNP equation.

Non-spherical Vibration Mode

Non-spherical vibration mode is appeared on a microcapsule in low driving pressure region, under 100kPa. Figure 2 shows the motion of the microcapsule driven at the sound pressure of 89.8kPa in an acoustic standing wave. The microcapsule exposed to ultrasound expands and contracts in synchronization with the incident pressure. In Figure 2, the microcapsule shows non-spherical vibration between the maximum of radius on the picture (a) and the minimum of radius on the picture (f); the most remarkable deformation is appeared on the picture (e).

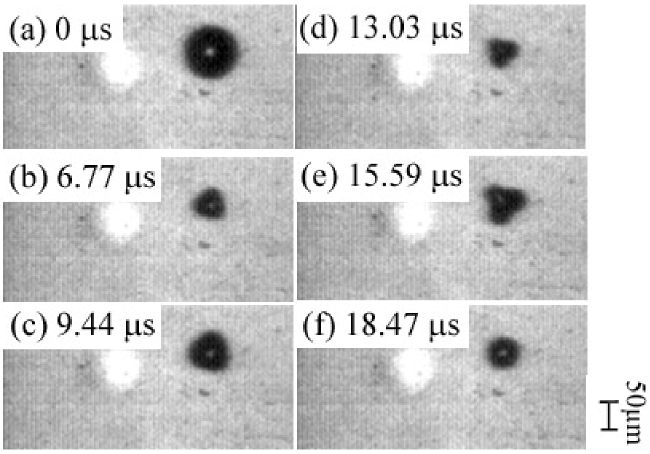

Fig.2 Motions of an observed microcapsule over half a period. (f=27075[Hz], P=89.8[kPa])

Spherical Vibration Mode

In the case of higher pressure, a microcapsule changes its vibration mode to spherical and shows rebounds similar to a free bubble motion appeared on SBSL. Figure 3 shows the pictures of the microcapsule driven at the sound pressure of 184.6kPa.

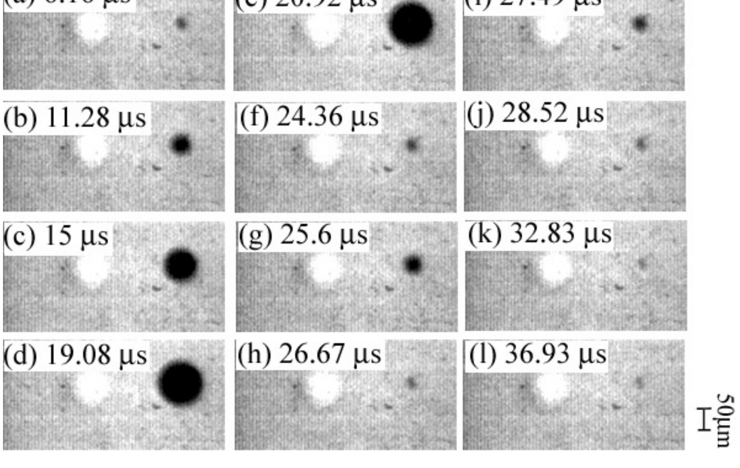

Fig.3 Motion of an observed microcapsule with rebounds. (f=27075[Hz], P=184.6[kPa])

In spherical vibration region, *R-t* curve can be obtained from imaging processing and compared with the one for a free bubble simulated by RPNNP equation. (Figure 4) In the same initial condition, smaller expansion and bigger rebounds on the microcapsule compared with calculated ones are appeared due to the shell effect. Some matching on *R-t* curves between the experimental result and calculated ones are tested with changing the driving pressure. As a results, the maximum of radius is matched with a free bubble's ones at the pressure of 132 kPa. On the other hand, the collapsing time is matched with a free bubble's one at the pressure of 172 kPa. It is considered that these results are depended on the effect of the shell stiffness and elasticity. Furthermore, the value of *Sp* is estimated by the comparison with calculated results including the shell effect expressed eq.(1). Figure 5 shows the calculated *R-t* curve at several *Sp*. By focusing on the maximum of radius and the collapsing time, the value of *Sp* is estimated at 0.19 and 0.05 respectively.

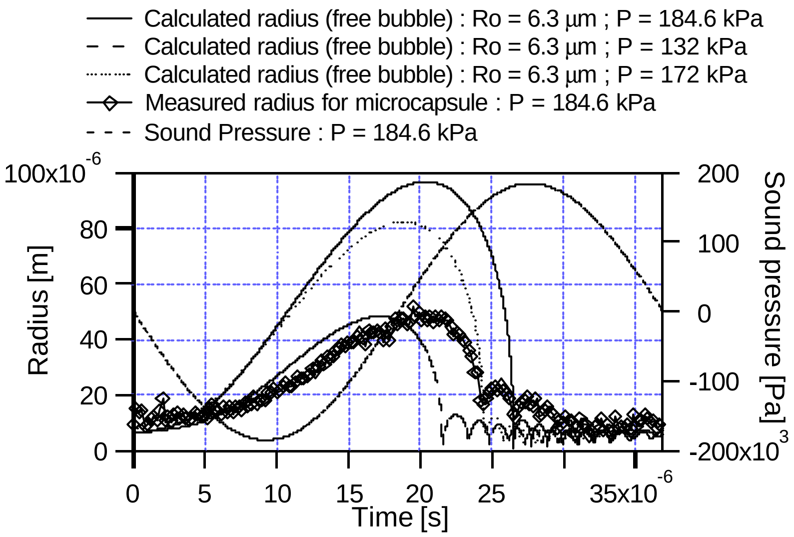

Fig.4 Radius versus time curve for a microcapsule compared with the calculated radius of a free bubble.

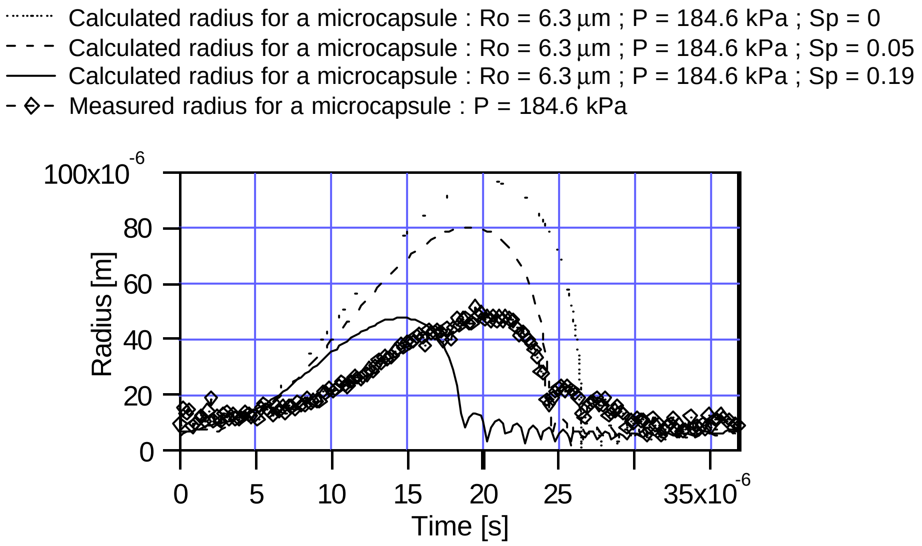

Fig.5 Radius versus time curve for a microcapsule compared with the calculated radius of a microcapsule.

CONCLUSION

The vibration fundamental properties of microcapsules were discussed. The behaviors of a single microcapsule were observed by using a high-speed video camera. A single microcapsule could be trapped at the antinode of a standing wave with experimental set up used for SBSL. The vibration mode of a microcapsule could be distinguished by initial driving conditions. In low pressure region, non-spherical vibration modes were appeared in the microcapsule, then with raising the driving pressure, spherical vibration mode and rebounds similar to a free bubble was observed in high pressure region. From comparison between the experimental results and calculated ones by RPNNP, it is thought that smaller expansion, bigger rebounds and longer collapsing time in experimental results show the effects of the shell.

BIBLIOGRAPHICAL REFERENCES

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