On the Cavitation Occurring at the Bottom of a Suddenly Accelerated Circular Cylinder*

(Effects of Air Content in Water on Incipient Cavitation)

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A relatively simple device for cavitation testing was developed, with the view to investigating the mechanism of and effects of physical properties of liquids on cavitation. This device is based on the principle that a longitudinal stress wave is generated at one end of the cylindrical rod by an impact given at the other end, causing negative pressures and thus cavitation in the liquid surrounding the lower end of the rod. The results of the investigation can be summarized as follows: (1) By installing a cylinder around the testing rod, it is possible to suppress the generation of the ring cavitation and to realize a nearly one-dimensional pressure field under the bottom face of the testing rod; (2) Decreasing the air content in the liquid can reduce cavitation inception pressures.

Key Words: Cavitation, Bubble, Flow Visualization, Inception, Impulse, Negative Pressure, Air Content

1. Introduction

A large number of experimental and theoretical studies have been done on the cavitation occurring in various types of fluid machinery. Many of these studies have treated cavitation in the flowing water generated by fluid machinery such as pumps and marine propellers. In studying the mechanisms of cavitation inception in flowing water, it is difficult to avoid the effects of gas bubbles and corrosion particles circulating with the flow.

On the other hand, if studies are made using liquids at rest, gas bubbles and solid particles acting as nuclei for cavitation can be removed or controlled, and detailed observation of the cavitation phenomenon can be made by enlarged photography. Since

cavitation is a phenomenon varying quickly over time, it is desirable to observe the whole life of the cavitation bubbles (inception, growth and collapse) in a limited minute range, and to predict the occurrence and collapse of cavitation.

With such in mind, the authors developed a cavitation device in which a low pressure pulse can be generated in still water. The fundamental principle of this cavitation device is that a low pressure can be generated at the bottom of a vertical rod soaked in still water when this rod is suddenly moved upwards. This device is relatively small and mechanically simple and is almost maintenance free. In addition, this device uses a small amount of liquid. Therefore various kinds of liquid can be used for cavitation study. Furthermore, the physical properties of liquid such as air content, surface tension and viscosity can be easily changed. The pressure and temperature of the liquid can also be changed easily as required for the experiments.

In this paper, this cavitation inception device is described and its usefulness for the cavitation experiment is explained. Of the various factors affecting cavitation inception⁽¹⁾⁻⁽⁴⁾, air content in water was

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systematically changed and the experimental results are reported.

2. Nomenclature

- A_1 : Cross-sectional area of testing rod
 A_2 : Cross-sectional area of impact head
 A_3 : Cross-sectional area of impact weight
 c : Speed of elastic stress wave propagation in testing rod
 c_w : Speed of elastic stress wave propagation in water
 E : Modulus of longitudinal elasticity of testing rod
 k : Spring constant
 K_t : Transmissivity of elastic stress wave
 l : Length of testing rod
 Δl : Distance between a pair of photoelectric sensors
 m : Mass of impact weight
 n : Longitudinal vibration of testing rod
 p_0 : Atmospheric pressure
 p_{min} : Minimum pressure in water (under bottom face of testing rod)
 Δp : Pressure at bottom face of testing rod
 Δp_w : Pressure in water
 S : Cross-sectional area ratio $= A_3 / (A_1 + A_2 + A_3)$
 Δt : Time required for rod to pass interval between photoelectric sensors
 ΔT : Duration of increased particle speed range
 v : Particle speed in testing rod
 v_a : Impact speed of impact weight
 v'_a : Measured impact speed
 v_s : Speed of bottom face of testing rod
 x_0 : Initial deflection of spring
 ρ : Density of testing rod
 ρ_w : Density of water

3. Experimental Setup

3.1 Description of cavitation inception device and experimental procedure

The cavitation inception device developed in this study is shown in Fig. 1. Cavitation is generated by the low pressure which is induced by an impulsive motion of a vertical rod soaked in water. Figure 2 is a schematic drawing which shows how the cavitation is generated in this mechanism. A cylindrical rod with its upper part of greater diameter is supported vertically with its lower part submerged in water. When the impact weight is pushed downwards against the coaxial spiral spring and is released suddenly, the impact weight starts to move impulsively upwards and strikes the stepwise widened area of the upper part of the rod. The tensile longitudinal stress caused by the impact propagates downwards and reaches the lower end of the rod in water. This process causes

cavitation at the bottom surface of the rod. The magnitude of the low pressure at the bottom surface of the testing rod can be changed by adjusting the rod speed. The duration of the low pressure period can be changed by adjusting the length of the testing rod.

The testing rod made of aluminum alloy A5052 is 4 mm in diameter and 400 mm in length. The aluminum alloy was selected in view of its corrosion resistance and workability. In order to keep the test surface of the testing rod end as smooth as possible, it

Fig. 1 Cavitation testing device

Fig. 2 Mechanism for producing cavitation

was polished by buffing to achieve the surface roughness of $0.05 \mu\text{m}$ or less.

3.2 Practical test range of the cavitation inception device

The magnitude of the pressure induced at the cross-sectional area of the testing rod can be estimated by the theory of elastic stress wave propagation in a rod as^{(5),(6)}

$$\Delta p = \rho c v \quad (1)$$

where ρ is the density of the testing rod, c is the speed of elastic stress wave propagation in the testing rod (the sound velocity), and v is the particle speed in the testing rod. The magnitude of the pressure induced at the bottom face of the testing rod may be found with the aid of Eq.(1) after noting that the conditions to be satisfied at the impingement face are:

(i) the forces on the impingement face acting from the testing rod, the impact head and impact weight are at all times equal, and

(ii) the particle velocity on the impingement face of the testing rod, the impact head and impact weight are equal.

Thus, the magnitude of the pressure induced at the bottom face of the testing rod is determined by Eq. (1), (i) and (ii) as

$$v = S v_a \quad (2)$$

where $S = [A_3 / (A_1 + A_2 + A_3)]$ is the ratio of cross-sectional areas of the testing rod, the impact head and the impact weight; v_a is the particle velocity of the impact weight (impact speed). Hence,

$$\Delta p = S \rho c v_a \quad (3)$$

At the bottom surface of the rod some part of the elastic stress wave propagates into the water, while the other part reflects and returns into the rod. When the elastic stress wave propagates from the bottom face into the water, the pressure induced underwater is represented by

$$\Delta p_w = K_t S \rho c v_a \quad (4)$$

where the transmissivity is given by

$$K_t = \frac{2 \rho_w c_w}{\rho_w c_w + \rho c} \quad (5)$$

The speed of bottom face of the testing rod can be changed by the impact speed. The impact speed v_a is changed by the spring constant k and the initial deflection of the spring x_0 in such a way as

$$v_a = \sqrt{\frac{k}{m}} x_0 \quad (6)$$

Thus, the magnitude of the pressure reduction underwater induced by the impact is determined by Eqs. (4) and (6) as

$$\Delta p_w = K_t S \rho c v_a = K_t S \rho c \sqrt{\frac{k}{m}} x_0 \quad (7)$$

Table 1 shows the calculated results of the pressure reduction induced underwater at the bottom face

Table 1 Results of calculated pressure

Spring constant (N/m)	Impact speed [m/s] (max.)	Pressure on bottom face [MPa] (max.)	Pressure in water [MPa] (max.)
8.5	1.05	8.48	1.63
25	1.81	14.62	2.81
746	9.87	79.75	15.3
1353	13.3	107.4	20.6

Fig. 3 Experimental apparatus

of the rod using Eq.(7). The pressure drop of 0 - 20.6 MPa is expected to be using 4 types of springs with different spring constants. Therefore the range of experiments from cavitation inception to supercavitation can be conducted using the cavitation inception device developed in this study.

3.3 Measurements of pressure simultaneous with observation of cavitation

The whole system of the experimental apparatus is shown in Fig. 3. The measurements were done by using the cavitation inception device, impact speed measurement device, a photographing device, pressure transducers and recorders. Photographs were taken by a high-speed camera with 2×10^5 frames per second to record and analyze the behavior of cavitation. Micro-flash (duration of light emission is $200 \mu\text{s}$) was used as a light source. The shutter timing of the camera was controlled by delay device self-made by a personal computer.

The pressure at the cavitation inception region was measured by using a transparent cylinder of acrylic resin which was installed along the testing rod as shown in Fig. 4. The inner diameter of the cylinder was made close to the outer diameter of the testing rod. Two pressure holes of 2 mm in diameter were drilled into the cylinder, one at the bottom face of the

Fig. 4 Measurement of cavitation pressures

rod, and the other 15 mm below it. The pressure sensors were attached through the respective pressure holes (measurement range: 0.07 kPa–700 kPa, precision: 35 Pa, maximum measurement pressure: 7 MPa, natural frequency 500 kHz, and pulse rise time 1 μ s, manufactured by PCB Co.).

3.4 Measurement of impact speed

Since the pressure induced at the bottom surface is proportional to the impact speed as shown in Eq. (7), fluctuation of the impact speed affects the pressure fluctuation of the bottom face pressure. Therefore, the impact speed was monitored by optical-fiber type photoelectronic sensors (response time: 20 μ s) which were set at two different positions (interval Δl), together with a self-made counter circuit to measure the time Δt for the rod to pass the interval. Thus measured impact speed v_a was obtained by dividing the interval of 10 mm ($=\Delta l$) by the time Δt to pass the interval.

3.5 Adjustment of air content in water

As water samples, refined distilled water was used in order to avoid the effects of impurity and contamination. The adjustment of air content ratio (percentage to the saturated air quantity) was conducted by decompressing 1 liter of water in a container using a vacuum pump. The water in the container was stirred by a shaking vessel (frequency 5 Hz). The air content ratio in water was adjusted by this process to values between 0–100% at room temperatures. The time needed for adjustment of water was about 5 minutes.

Fig. 5 Displacement of testing rod

Fig. 6 Velocity of testing rod

The experiments were carried out under room temperature and atmospheric pressure using 1 liter of distilled water treated as described above. The average water temperature during the experiment was about 20°C. The duration of experiments was limited to the extent to which the adjusted air content had not been affected much by air from the atmosphere.

4. Experimental Results and Discussion

4.1 Displacement and velocity of testing rod

In Fig. 5 the displacement of the test surface, i.e. the bottom face of the rod, is shown as a function of time. For approximately the first 80 μ s the test surface stands still, since the elastic wave generated by the impact has not arrived there. With the arrival of the elastic wave (tension in this case), the displacement increases nearly linearly with time until the arrival of compression when the displacement becomes nearly constant. Figure 6 shows the velocity of the test surface obtained by average slope of the displacement. The width of the pulse ΔT can be changed by adjusting the length of the testing rod and its impact head.

The frequency of the first harmonic n of a longitudinal vibration is given by

$$n = \frac{1}{2l} \sqrt{\frac{E}{\rho}} \quad (8)$$

where l is the length between the end face of the impact head and the bottom face of the testing rod, E is the modulus of longitudinal elasticity of the testing rod, and ρ is the density of the testing rod. The width of pulse ΔT is given by

Fig. 7 Cavitation inception and development (without cylinder)

Fig. 9 Cavitation inception and development (with cylinder)

$$\Delta T = \frac{1}{n} = 2l \sqrt{\frac{\rho}{E}} \quad (9)$$

It is evident that ΔT is proportional to l when the testing rod is made of a homogeneous material. In this experiment ΔT was set at about 200 μ s. The pulse height shown in Fig. 6 was assumed as the speed of the bottom face of the testing rod v_s in this study. Since the speeds of the bottom face of the testing rod v_s were found to be correlated with the impact speeds of the impact weight v_a by

$$v_s \approx 2v_a, \quad (10)$$

the magnitude of the low pressure in underwater was calculated by

$$\Delta p_w = K_t \rho c (2v_a) \quad (11)$$

4.2 Cavitation phenomenon when tested without cylinder

First, experiments were carried out with the testing rod alone installed in the test vessel. Figure 7 shows a typical example of the cavitation patterns around the bottom face of the testing rod. Right after the testing rod starts upwards, bubbles are generated underwater and then they are distributed uniformly on the bottom face with further increase in displacement. The bubbles tend to take a ring shape and grow with time^{(7),(8)}. This phenomenon is similar to that observed by Hooper⁽⁹⁾ who investigated the initiation of cavitation behind a circular disk dropped into water. Such a ring shape is considered to be due to formation of a vortex ring at the sharp edge of the bottom face.

4.3 The behavior of the cavitation when tested with cylinder

In studying cavitation inception mechanisms, it is

Fig. 8 Location of cavities (Side view)

desirable to conduct experiments under a pressure field uniformly reduced through out the water sample. As an attempt to realize this, experiments were conducted by installing a transparent cylinder along the testing rod near the bottom end. The cylinder was made of acrylic resin with a diameter close to that of the testing rod. It was expected from this cylinder that the pressure wave in the testing rod would propagate into the water and yield an almost one-dimensional pressure field. Further, pressure sensors can be mounted on it to monitor the pressures as related to the cavitation observed. With this configuration it became possible to produce cavitation on and below the bottom face of the testing rod without radial effects and to control the pressure more easily for the detailed observation of cavitation. Referring to Fig. 8, the cavity occurred at various positions such as the bottom face of the testing rod, on the wall of the transparent cylinder, or in the water. The cavitation patterns after the impact are shown in Fig. 9. The

Table 2 Rate of cavitation inception

Air content	Impact speed [m/s]	Rate of cavitation inception [%]	On bottom face [%]	On wall [%]	In water [%]
26%	1.5	18	15	3	6
	3.0	76	76	0	7
	5.0	100	100	0	75
100%	1.5	61	52	0	16
	3.0	87	68	34	15
	5.0	100	72	45	26

cavity began to disappear when the speed of the bottom face became close to zero (cf. Fig. 6).

From this result it is concluded that it is possible to generate the one-dimensional cavitation with installation of the cylinder. It is also possible to generate hemispherical and spherical cavities as long as the upward velocity of the test surface is maintained (between $100\ \mu\text{s}$ and $300\ \mu\text{s}$ after impact)⁽¹⁰⁾.

4.4 Rate of occurrence and location of cavitation

Numbers of experiments were repeated according to the method described in section 4.3, varying air content in water and speed of the testing rod. As a result it was found that cavitation was not initiated every time and the location of the initial bubbles changed with experiments. Therefore the number of cavitation occurrences were divided by the number of experiments and shown in Table 2 as the rate of cavitation inception. The rate of cavitation inception increases as the speed of the testing rod increases. This tendency is in accordance with the negative pressure under the bottom face given by Eq. (11), and increases in proportion to the speed of the bottom face, similar to the water hammer phenomenon^{(11)–(13)}. Of the locations of cavitation, the bottom face is most frequently observed, followed by the inner wall of the pipe, and lastly in the water. In other words the cavitation is most likely to occur at a solid surface, which also means a liquid-and-solid interface.

4.5 Pressure fluctuations under the bottom face as contrasted with cavitation pictures

Figure 10 compares photographs of cavitation with the pressure fluctuations under the bottom face. The experiments were conducted with a bottom face speed of $3.0\ \text{m/s}$ and an air content ratio of 26%. To facilitate analysis of locations and shapes of the cavities, sketches made from the photographs are given below. The photographs were taken at intervals of $5\ \mu\text{s}$, and some of their numbers are shown in the pressure diagram as a function of the elapsed time after impact. The elastic stress wave generated by the impact propagates through the testing rod,

Fig. 10 Photograph, sketch and measured pressure

reaches the bottom face about $80\ \mu\text{s}$ after the impact, and goes through to the water. Therefore, there is no variation in pressure right after the impact, as explained in section 4.1.

The cavitation inception pressure was determined based on figures like those in Fig. 10. In this case a cavity was first detected, as shown in sketch ④, at $95\ \mu\text{s}$ after impact. The pressure at this point was defined as cavitation inception pressure. The pressure fluctuations, as shown in the time range after ⑧ in Fig. 10, were seen many times. As the number of bubbles increased, higher frequency components became dominant in the pressure fluctuations. Perhaps this was due to the scattering of the pressure waves at the vapor-liquid interface⁽¹⁴⁾.

4.6 Effects of air content

After adjusting the air content in the water sample and changing the speed of the bottom face, observation of cavitation inception and measurement of

Fig. 11 Effects of air content on rate of cavitation inception

Fig. 12 Minimum pressures at bottom face

pressure was performed. Referring to Table 2 and Fig. 11, the rate of cavitation inception increases as the air content increases. As stated before, the rate of cavitation inception increases as the speed of the bottom face of the testing rod increases. With the experimental results obtained so far, effects of the pressure change under the bottom face are more pronounced than those of the air content. In this context, the measured minimum pressures are plotted against the bottom face speed as shown in Fig. 12. As the speed of the bottom face increases, the minimum pressure tends to decrease. Letting p_0 be the atmospheric pressure, the minimum pressure at the bottom face can be expressed as:

$$p_{min} = p_0 - K_t \rho c v_s \quad (12)$$

and this calculated p_{min} is also plotted in Fig. 12. When air is saturated in water (air content ratio 100%) the minimum pressures are nearly zero absolute. For other air contents the minimum pressures go down to negative values, but not further beyond 6 m/s. The reason why the pressures at air content ratio of 100% differ from others may be due to the presence of cavitation which prevented pressures in water from reaching their possible minimum. The reason for the difference between the calculated and measured p_{min} 's

Fig. 13 Effects of air content on cavitation inception

cannot be explained yet. The authors are examining the applicability of a simple one-dimensional stress wave theory and measurement techniques.

Next, cavitation inception pressures were plotted against air content in Fig. 13. The data obtained at the saturated vapor pressure at a water temperature of 20°C are shown in the upper part of Fig. 13. A clear correlation can be seen between the cavitation inception pressure and the air content. The cavitation inception pressure tends to decrease as the air content decreases. Cavitation was known to occur when the ambient pressure reaches the saturated vapor pressure, but this experiment shows that cavitation can occur at absolute pressures below zero. That is to say, when the air content is less than the saturated value, it is necessary to decompress the liquid to below the saturated vapor pressure for inception of cavitation.

It should be noted, however, that the duration of pressure decrease was extremely short in this experiment. Some studies maintain that liquids can withstand tension for a short length of time. Therefore it is necessary to investigate the relation between the magnitude of the negative pressures and their duration in more detail.

5. Conclusions

Based on an idea that cavitation can be initiated at the bottom of a cylinder when impulsively accelerated in an axial direction, a simple cavitation inception device was developed. With this, the behavior of the cavitation was photographed and the pressures in its vicinity were measured. To summarize the results of the investigations, the following conclusions were obtained.

(1) A relatively small and simple cavitation inception device was developed, and its usefulness was

recognized for observation of inception, growth and collapse of cavitation.

(2) When the testing rod alone is soaked in a liquid and impulsively moved upwards, two different types of cavitation can occur at the end surface of the rod, i.e. bubble cavitation and ring shape cavitation.

(3) By installing a cylinder around the testing rod, it is possible to suppress the generation of the ring cavitation and to realize a nearly one-dimensional pressure field under the bottom face of the testing rod. The pressures at the onset of the cavitation can be measured by mounting pressure sensors on the cylinder.

(4) Decreasing the air content in the liquid can reduce cavitation inception pressures.

(5) The cavities appear most frequently at the interface of the liquid and the cylinder, but they can appear also on the bottom face of the cylinder and in the liquid in its vicinity.

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References

- (1) Yamazaki, T., Cavitation Engineering, (in Japanese), (1983), p. 90, Nikkan-Kogyo Publishing Company.
- (2) Numachi, H. and Shiina, T., A Contribution on the Cavitation Inception Mechanism (The First Report), Trans. Jpn. Soc. Mech. Eng., (in Japanese), Vol. 3, No. 11, (1935), p. 177-181.
- (3) Numachi, H., A Contribution on the Cavitation Inception Mechanism (The Second Report), Trans. Jpn. Soc. Mech. Eng., (in Japanese), Vol. 3, No. 11, (1935), p. 182-185.
- (4) Oba, R., Kim, K. T. and Uranishi, K., The Unique Behavior on the Cavitation in Unsaturated Water, Trans. Jpn. Soc. Mech. Eng., (in Japanese), Vol. 48, No. 430, B (1982), p. 1025-1031.
- (5) Yanagihara, N., A Method of Numerical Analysis Based on the Theory of One-dimensional Elastic Stress Wave for Multi-body Impact Problems, Proc. of Jpn. Soc. Mech. Eng., (in Japanese), No. 920-55, A (1992), p. 133-136.
- (6) Johnson, W., Impact Strength of Materials, (1972), p. 35-40, Edward Arnold.
- (7) Tanibayashi, H., Ogura, K. and Matsuura, Y., On the Cavitation Occurring at the Bottom of an Accelerated Circular Cylinder, Proc. of 3rd International Symposium on Cavitation, Grenoble, France, Vol. 1 (1998), p. 161-166.
- (8) Matsuura, Y., Study on Impulse Cavitation (Effects of Air Content in Water on Incipient Cavitation), (in Japanese), Proc. of 9th Symposium on Cavitation, Sendai, Japan, (1997), p. 111-114.
- (9) Hooper, L. J., Experimental Investigation of Initiation of Cavitation Behind an Accelerated Circular Disk, Proc. IAHR Symp., Sendai, Japan, (1962), p. 125-141.
- (10) Matsuura, Y., Tanibayashi, H. and Ogura, K., On the Cavitation in Impulse Testing Device, (in Japanese), Proc. of 8th Symposium on Cavitation, Kyoto, Japan, (1995), p. 85-88.
- (11) Lee, I. Y., Cavitation Inception Caused by Transient Flow in an Oil Hydraulic Pipeline (Effects of Solid Particles and Gas in Liquid), Trans. Jpn. Soc. Mech. Eng., (in Japanese), Vol. 52, No. 476, B (1986), p. 1581-1588.
- (12) Lee, I. Y., Kitagawa, A. and Takenaka, T., On the Transient Behavior of Oil Flow under Negative Pressure, Trans. Jpn. Soc. Mech. Eng., (in Japanese), Vol. 50, No. 458, B (1984), p. 2655-2662.
- (13) Sanada, K., Kitagawa, A. and Takenaka, T., A Study on Analytical Methods by Classification of Column Separations in a Water Pipeline, Trans. Jpn. Soc. Mech. Eng., (in Japanese), Vol. 56, No. 523, B (1990), p. 585-593.
- (14) Takagawa, S., A Study on the Measurement Method of Underwater Bubble Distribution by Acoustic Attenuation, (in Japanese), University of Tokyo Doctoral Thesis.