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Measurement of Cavitation Shock around Two-dimensional Elliptic Cylinders.*

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In this paper, the intensity of cavitation shock-noise is measured by using 8 models of elliptical cylinders of various eccentricities for the purpose of knowing the effect of a change of the shape of a body in a cavitating flow.

In a model which has a longer axis, the maximum intensity of shock noise is lower and the cavitation number corresponding to the maximum noise is smaller. When long elliptic bodies are set inclined to the flow, the maximum noise becomes larger as the angle of incidence increases and at the same time the cavitation number corresponding to it becomes larger.

The periods of cavitation shock are also measured. The period for the semi-circular elliptical cylinders shows a tendency of being reduced as the cavitation number becomes small, but for the long elliptical cylinders having the angle of incidence, contrarily the period increases as the cavitation number becomes smaller.

1. Introduction

J.J. Varga(1) has shown through many experimental studies the correlation between the cavity length which is the size of the bubble flow region and the cavitation noise. The relationship between those two parameters and the amount of cavitation erosion over a wide range of cavitation numbers is also examined. From these results he suggests a very useful conclusion that cavitation intensity can be known by measuring the noise of cavitation. We also have investigated the mechanism of cavitation shock by the measurement of the shock vibration and the pressure fluctuation in the wake of a circular cylinder(2).

In the cavitation of a circular cylinder, when the bubble vortices formed on the surface shed into the wake, the direction of flow around a circular cylinder can be observed to violently change as compared with the non-cavitating flow. Then it is supposed that periodical shocks are induced by bubble jets generated with a sudden rise of pressure just after being shed into the wake as a cavity of vortex and the shock gives a strong blow to the channel wall. It is noted that the cavitation noise has been attracting some attention as an index of the cavitation intensity for measuring erosion. On the

other hand, the mechanism of shock generation becomes gradually clear to us. To make it more useful for engineering purposes, an experimental study must be done in depth on the effect of velocity and the influence of model size. As a matter of course we can emphasize that shock intensity is affected by the shape of the model.

This paper covers in great detail the variation of shock intensity that is caused by the effect of the model shape which is systematically changed through a series of elliptical cylinders including a circular cylinder. As the shock intensity is closely related to the cavity length, these models are examined over a wide range of cavitation numbers. Moreover, the frequency of shock vibration caused by cavitating flow is to be considered the main factor of cavitation damage, and the mechanism of shock vibration is also discussed in detail. In this paper, therefore, the shock intensity is measured with a more improved method than in the previous experiment(2) on peak value of shock to establish these programs.

The previous paper deals with the mechanism of the generation of periodical shock through the observation of bubble flow or shedding cavity vortex in cavitating state using a photo-picture technique and an analysis of high speed movie film. In the present studies, we have attached importance to the measurement of the shock intensity in the cavitating flow of many cases.

According to the results of this experimental study, the variations of the shock intensity(i.e. value of acceleration of shock vibration) with the cavitation number make a "Bell shape" curve which resembles Varga's results in the case of a

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circular cylinder (that curve having a peak and a gentle slope following a sharp rise). In a model with a longer axis, the peak of shock intensity is lower, and the location of the peak is shifted to a lower value of cavitation number. In other words, if a long elliptic cylinder is set inclined to the flow, the cavitation state is quite changed, and consequently the shock intensity becomes larger. It can be said that the cavitation of a slender model without the angle of attack is hard to generate; even if the cavitation occurs, the shock intensity is not so strong. On the contrary, if the long elliptic cylinder is set inclined ($\alpha = 12^\circ$) to the flow, the cavitation state is quite changed and the shock intensity becomes larger. This value is also appropriate in the case of a circular cylinder. The data of these experiments are shown by the cavity length. Consequently, we can find that the maximum value of shock intensity against the cavity length (in this experiment) is located at about $\lambda = 2.0$. Concerning the frequency of shock vibration with no angle of attack, it shows a tendency that the frequency decreases with a decreasing cavitation number for a circular cylinder, but if the elliptic model is set inclined to the flow, the frequency of shock (represented by the Strouhal number) is increased with a decreasing cavitation number. Through this experimental study a wide change of cavitation number has a close correlation to the amount of erosion and at the same time the structure of fluid machinery is likely to resonate with a wide variation in the frequency of cavitation shock.

2. Apparatus and test procedure

2.1 Significance of shock measurement

Varga showed that the amount of cavitation damage could be determined by the measurement of the cavitation noise. The noise was expressed as the acceleration of vibration caused by cavitation shock that was detected by an accelerometer head attached on the outside of test channel wall. The present authors also used in the past the same method to investigate the shock intensity of cavitation. In the first place we discuss the method of shock measurement.

In the conclusion of the previous paper, it is made clear that a collapsing bubble jet blows against the wall when the pressure is suddenly raised by the shedding cavity vortex and the structure of the test channel is vibrated; this overall vibration can be detected by an accelerometer. It can be confirmed by an observation of the output signal of a transducer or a frequency spectrum analysis.

A typical example of the output signals of the pressure (upper trace) and accelerometer (lower trace) transducer is shown in Figure 1 in the case of a circular cylinder model. It can be observed that a sharp pulse in each periodical

pressure fluctuation is coincident in time with the shock vibration of the channel as shown in Figure 1. Figure 2 shows the typical result of the frequency analysis

Fig.1 Each signal is one in which periodical pressure shock(upper)and its shock(lower) was taken by accelerometer;time= 10msec/div,the pressure transducer was located at a point 135° behind the circular cylinder. Cavitation number $\sigma = 2.10$, Strouhal number $S = 0.268$.

Fig.2 Frequency analysis of acceleration of a circular cylinder 20 mm in diameter. Upper curve: periodical shocks of 500 Hz, lower curve: non-cavitating period.

of the shock vibration caused by a cavitating flow around a circular cylinder. The upper curve shows the case of a maximum shock intensity having a very steep peak at around 500Hz and others being in a higher frequency zone. In the lower curve, a non-cavitating case is shown. Here, we can see some peaks over the entire frequency range but none which are significantly high. These results are sufficient to understand that the peak at 500 Hz is considered to be related to the frequency of a physical shock vibration just mentioned above which is induced by the collapsing bubble jet blow and it corresponds to the number of shocks per unit time. This peak frequency is closely related to the shedding cavity vortex from both sides of a circular cylinder; therefore, in the lower curve it does not appear. The acceleration in the high fre-

quency zone must be related to the vibrations of various parts of the whole structure that forms the test channel and several peaks in the curve might be related to the period of natural frequencies of the structure that constitutes the channel. In the lower curve also, we may see several peaks in the high frequency zone which are due to the vibration of the structure as induced by other sources.

From these considerations, we may say that the measurement of shock vibration is done to detect the frequency and the intensity of cavitation shock due to the vibration of the structure caused by the collapsing bubble jet in the test channel. The intensity will not differ, even with a little change in position of the shock. A shock test is conducted with a dropping ball in order to confirm the above results. The procedure of this test was also used in the cavitating flow experiment. The shock is caused by a falling steel ball from a known height instead of the cavitation shock. The value of shock intensity is measured on the opposite side of the channel plate by an accelerometer. Figure 3 shows the variations of shock intensity caused when the dropping height and the thickness of the plate are changed. In the case of a circular cylinder, the diameter is 20mm and the flow velocity is $V_{\infty} = 18.78\text{m/s}$, the maximum value of intensity being $G = 6.18 \times 10^5 \text{gal}$. The value is the peak-to-peak average in the case of cavitating flow, while the value of the dropping shock is counted every time. Comparison between two values shows distinctly, as described later, that both of them have a close relation to the peak value of shock.

2.2 Apparatus and procedures

The experimental studies are conducted in a high speed cavitation tunnel of closed loop type as mentioned in the previous paper(2), and the test section mea-

Fig.3 Chart for shock intensity of falling ball for four steel plate thicknesses.

sures $15\text{mm} \times 100\text{mm} \times 400\text{mm}$. The flow velocity in the test section can be regulated from 10m/s to 25m/s and the cavitation number is varied by the entrance static pressure with the velocity kept constant. Temperature of the working water was maintained constant at about 15°C by the feeding pump during this experiment and the amount of air content could not be measured. The system pressure in the tunnel is set higher than the atmospheric pressure, so that the water can be kept from mixing with the external air and the ratio of air content can be held constant.

The test models consisted of 8 different elliptic cylinders including a circular cylinder. Their shapes are shown in Figure 4. The minor axis of each model is kept at 20mm. Special model #8 has the shortest major axis ($a = 14.5\text{mm}$). Each of these models is fixed to a circular disk plate in the test section and the angle of attack of the model in the flow direction is given by rotating the disk up to 12° in steps of 2° (Figure 5).

The shock vibration is detected by the mini-accelerometer transducer with as high as possible sensitivity response ($2\text{Hz} \sim 20\text{kHz}$) to amplify the output signal of the transducer. The range of frequencies of shock vibration is 100Hz to 10kHz and the holding time of the shock is short. The value of other range is small. In the previous paper(2), the value of shock vibration was represented by the average of these two values, but in this experiment the results are shown with the peak value of the sharp shock vibration. The period of shock is around 1/100 sec., therefore, it may safely be said that the

Fig.4 Shape of models and numbering.

Fig.5 Front view of the test section and the location of transducers.

shock intensity is the average value of the peaks of each shock. Then, we took the mean of the value as the cavitation shock intensity and all of them were normalized by the maximum shock intensity $G_{c_{max}}$ of the circular cylinder cavitation.

3. Results and discussion of shock intensity

3.1 Shock intensity(without attack angle)

The cavitation shock intensity (G) vs. cavitation number (σ) for each elliptic cylinder, which has no angle of attack is shown in Figure #6. Figure 7

Fig.6 Relationship between normalized cavitation shock intensity and cavitation number for each elliptic cylinder, without an attack angle.

Fig.7 Effect of axis ratio on incipient cavitation number and minimum pressure coefficients.

shows the variation of minimum pressure coefficient, both experimental $|C_{pmin}|$ and calculated $|C_{pmin}|$ and cavitation number of just before (●) and after (○) at incipient cavitation for the various models (model #2 to #7). The right side, the axis of abscissa, corresponds to a circular cylinder model and toward the left the axis-ratio increases and the model becomes more slender and elliptical. Model #7 is shown with a lower value of incipient cavitation number in this study. In Figure 6 the incipient cavitation of a circular cylinder(model #1) takes place around $\sigma=2.30$. After that point, the value of G increases with a decreasing cavitation number and it forms bell shape curves as described by Varga. The characteristics of shock intensity on the semi-circular cylinder(model #2) is represented in almost the same manner as model #1 and the range of G for cavitation number shows on great difference from a circular cylinder case. In model #3, the value of G gradually increases and suddenly decreases after the peak. This curve has no bell shape. Of course, the shock intensity becomes smaller and the range of cavitating flows also shifts to the lower cavitation number. Therefore, when the model has a longer major axis, the cavitation is difficult to take place and even though the cavitation is generated on the surface of the model the shock intensity becomes smaller and then this value of G decreases at a lower cavitation number. In other words, we can say that the cavitation state in this case is immediately translated to the super cavitating flow with a little change of σ . Contrarily, in the model #8 which has the shortest major axis set as perpendicular to the flow the intensity of shock is increased to about 2 times those of the other models(#1 and #2) and the range of cavitating flows also

Fig.8 Relationship between cavity length and cavitation number for each elliptic cylinder.

shifts toward the high value side of σ as can be expected. From these results, it appears that the shock intensity of cavitating flow is affected by the shape of the model. Especially, when the model has a longer major axis, the range of cavitating state against σ becomes more narrow.

3.2 Cavity length and shock intensity

We have examined the cavity length around elliptic cylinder models to discuss the relationship between the shock intensity and the extent of cavitation bubble flow. The cavity length in this experiment is defined as the visible length of bubble flow region along the flow direction. The actual length ℓ is measured from the initial attached point of cavity on the model surface to the rear end of its cavity. This is done from the photographs of cavity flow that were taken by a 35mm still camera using an exposure time of 1/30 second. The cavity length ℓ was normalized with the length of major axis

Fig.9 Variations of normalized cavitation shock intensity with cavity length of each model.

Fig.10 Effect of attack angle on cavitation shock intensity of elliptic cylinder #5.

$2a$, then λ was used for ℓ . The experimental results are shown in Figure 8. Varga also used the cavity length to find out the relation between the noise intensity and the cavitation state in the case of a circular cylinder. The dotted lines in Figure 8 represent the calculated values for various half angles of wedge γ on the theory developed by Tulin and published in the literature of Cohen and Gilbert (3).

Figure 9 shows the variation of cavitation shock intensity with cavity length of each model. As can be expected, the peak value of shock intensity for each model is extended over a wide range of cavitation numbers but as shown in Figure 9 the maximum shock intensity for each model is attained at almost the same value of λ . It is apparent that the peak value of model #8 is concentrated around $\lambda \approx 2.0$. The peaks of other models are slightly shifted towards smaller λ with a decreasing value of axis ratio $a (= a/b)$. In the most slender elliptic cylinder model #7 in this experiment, the peaks of shock intensity are located for the cavity length around $\lambda = 0.8$. The results show that the varia-

Fig.11 Effect of attack angle on cavitation shock intensity of elliptic cylinder #7 having long major axis.

Fig.12 Influence of attack angles in cavity length and cavitation number in model #7.

tion of shock intensity of the elliptic cylinder for the cavity length λ forms a peak with its maximum value at approximately $\lambda=2.0$ in most models.

3.3 Shock intensity(with angle of attack)

When the shape of the model becomes slender, the cavitation is difficult to cause and the shock is weak. If a slender elliptic cylinder is set inclined to the flow the cavitation condition in the generation is quite changed and of course the shock intensity is also varied since the cavitating flow pattern is different from that of non-inclined case.

In Figure 10, the shock intensity for the model #5 is shown for various angles of attack from $\alpha=0^\circ$ to 12° . When the angle of attack was set $\alpha=12^\circ$, the incipient cavitation number shifted from 1.4 to 2.0 and the value of maximum shock intensity increased approximately 30%. Through these experiments it can be seen that the shock intensity of an elliptic model having an angle of attack becomes larger with a more slender ellipse.

Figure 11 shows the effect of attack angle on the shock intensity of model #7 having a long major axis when the axis ratio is around 1:4. The peaks of curves become large as the angle of attack is increased, consequently the values of maximum shock intensity also become large and at the same time σ shifts toward a higher value. The peak value of shock intensity for $\sigma=12^\circ$ is reached at 5.0×10^5 gal. This value is proportionate to a circular cylinder case. This trend of an increasing shock intensity is more apparent when the major axis becomes longer.

The experiment was repeated to investigate the relation between G and λ with attack angle. For this purpose the data of λ for σ with angle of attack are needed. The results are shown in Figure 12 for the case of model #7 with the attack angle increment of 2° up to 12° .

Figure 13 shows the effect of attack angle on the relation between G and λ in models #2, #5 and #7. The angle was changed from 6° to 12° . It can be seen that the peak value in model #2 is not af-

ected very much by a changing angle of attack. On the other hand, a noticeable shape change with the value of the peak is observed in model #7, but the peak for λ does not shift with a changing angle, therefore the peak appears approximately at $\lambda=2.0$. It may be suggested that the bubble flow in the cavitation has almost the same flow pattern at the maximum intensity of shock for the cavity length.

From this experiment, the characteristic of the shock intensity of the elliptic cylinder for a wide range of cavitation numbers which is affected by difference in model shape and the influence of the angle of attack can be made clear.

4. Measurement of periodical shock frequency

In the foregoing chapter, only the values of shock intensity were measured to know the effect of changing both the shape of the model and the angle of attack. In this chapter the experimental results of the frequency of shock vibration are discussed. The significance of the frequency measurement can be explained as follows: First, if we want to find out the correlation between the intensity of shock and the amount of cavitating damage, it will be necessary to measure the number of shock experienced on the surface. Second, the pressure fluctuations and the period of shock vibration are important parameters to know the mechanism of periodical cavitation shock, because the shock vibration is induced by a collapsing bubble jet which causes a sudden pressure rise at the same time as the shedding cavity vortex even in the case of an elliptic cylinder.

In this experimental study the measurement of shock frequency was conducted with a pressure transducer, the frequency was calculated from the pickup traces of the output signal. The specification of the transducer is given in Table 1. Pictures of the transducer output signals were taken by a still camera from oscilloscope traces also showing the accelerometer signals. The pressure transducer was so mounted as to have its active surface in contact with cavitating flow. The location of the transducer was inside the trailing edge of the elliptic cylinder, as shown in Figure 5.

Fig.13 Shock intensity variation of attack angles from 6° to 12° in #2, #5 and #7 models.

Item	Accelerometer	Pressure transducer
Sensitivity	3.2 mV/G	14.3 mV/(kg/cm ²)
Range of frequencies	2 Hz ~ 20 kHz	2 Hz ~ 400 kHz
Rise time	-	2.0 μ sec
Element	Ceramic	Quartz

Table 1. Specification of the measuring transducers.

4.1 Frequency of periodical shock (without angle of attack)

The relation between Strouhal number (S) and cavitation number for each model without attack angle is shown in Figure 14. It can be divided into two groups, one similar in shape to a circular cylinder (model #1, #2 and #8) and the other an elliptic cylinder with a long major axis (model #5, #6 and #7). The change of Strouhal number (S) in the first group extends over a range of $\sigma=2.3$ to 1.3; when σ exceeds the value of 2.0, the decreasing of S becomes rapid for the decreasing σ . But the second group is very sensitive to a change in σ as shown in Figure 14. In this case, it should be noted that the shedding starts from a higher value of S .

Figure 15 shows the typical output signals of model #2 without attack angle. The extent of cavitation increases toward the right side of the picture. The picture (c) of Figure 15 shows very clear signals in periodicity and regularity in these cycles, and the shock intensity has a maximum value. It can be seen that the cavity vortex is shed into the wake from both sides of the elliptic cylinder, therefore, the frequency of shock vibration is two times the oscillation of pressure. When the cavitation number decreased from $\sigma=2.14$ to 1.53(d), the period

of pressure fluctuations and the regularity of shock frequency both become random and weak. This decreasing of S is a noticeable feature of the change in the periodicity as a function of cavitation number.

Figure 16 shows the typical output signals of model #7 without attack angle. In this case also the value of σ decreases from (a) to (d), the traces of output signals being quite different from model #2 (Figure 15). The periodical pressure fluctu-

Fig.14 Variation of Strouhal number with cavitation number in each elliptic cylinder without attack angle.

Fig.15 Variation of output pressure transducer(upper) and accelerometer(lower) under different cavitating conditions in a #2 elliptic cylinder: time is 5 msec/div.

Fig.16 Variation of output pressure transducer(upper) and accelerometer(lower) under different cavitating conditions in a #7 elliptic cylinder without angle of attack: time is 5 msec/div.

tuation in this case can be observed only in (b) of Figure 16.

4.2 Frequency of shock(with angle of attack)

Figure 17 shows the effect of attack angles on Strouhal number(S_h) which was defined in terms of the projected height (h) of model to direction of flow and the free-stream velocity (see upper corner in Figure 17). The parameter of each curve is the attack angle(α) of the model. The Strouhal numbers are gradually increased as the cavitation number is decreased. This characteristic in frequency is quite different from the previous results shown in Figure 14. The significant difference in these results can be described as follow. In the case of a symmetrical shape model for flow, in general, the frequency of shock vibration or pressure fluctuation in the wake of a cavitating flow decreases with a decreasing cavitation number. Contrarily, when the long major axis elliptic cylinder is set inclined to the flow, at the beginning of the shedding cavity state

(high value of cavitation number) the Strouhal number S_h is lower than that in the case of the non-cavitating flow(4) and

Fig.17 Effect of attack angle on modified Strouhal number with project height in #7 elliptic cylinder.

(a) $\sigma=2.42$, $S_h=0.08$

(b) $\sigma=2.00$, $S_h=0.104$

(c) $\sigma=1.70$, $S_h=0.147$

(d) $\sigma=1.38$, $S_h=0.214$

Fig.18 Variation of output signals with pressure transducer and accelerometer. Each corresponding cavity length is shown above for model #7, angle of attack-10°; time-5 msec/div.

it increases up to a maximum value, as the cavitation number decreases. But after the peak, S_h , with a small change of σ , rapidly decreases owing to a supercavitating flow state.

Figure 18 shows the output signals of model #7 with attack angle, $\alpha=10^\circ$ case. These pictures are corresponding with the extent of cavitation shown above. The period of pressure fluctuations and that of shock vibration gradually become short; in other words, the frequency of cavities gradually rises with a decreasing σ . In the early stage of cavitation(a), a lower pressure takes place intermittently in a long cycle. The bubble appears on the upper surface of the model, although the region of cavity is very small and disappears in a short time. In this case, the period of shock vibration is relatively long, but it becomes short with an increasing cavity length.

The mechanism of a cavitating bubble flow around the elliptic cylinder should be discussed separately from this subject.

Figure 19 shows the effect of attack angle on the frequency of cavitation shock in model #7. It can be seen that the data are scattered when plotted in Figure of σ - f . The shock intensity as presented in the previous chapter is the peak value of the

Fig.19 Effect of attack angles on frequency of cavitation shock in #7 elliptic cylinder.

Fig.20 Characteristic curves of cavitation shock intensity (G), cavity length (λ) and shock frequency (f) against body shape with and without attack angle.

shock vibration. In measuring the amount of the cavitation erosion we must take into account the number of shocks to estimate the extent of damage. On the other hand, the results presented here may provide useful information concerning the resonance of a blade in the fluid machinery which is exposed to a cavitating flow.

5. Summary and conclusions

In this paper we have presented the results of measurements of the intensity (G), cavity length (λ) and frequency of shock (f) of a cavitating flow around various elliptic cylinders. The effect of model shape and the influence of attack angle have been compared with those three significant parameters as functions of cavitation number. Finally, in two cases, the characteristic curves of the parameters, such as G , λ and S , plotted as a function of σ are shown in Figure 20. Figure 20(a) is the larger axis ratio case, in which the model shape resembles almost a circular cylinder and (b) is a slender elliptic cylinder having an angle of attack. In this experiment, when the angle of attack is zero and also the shape of the model becomes more slender, the values of both G and σ were smaller. But the three parameters G , f and λ for σ showed almost the same feature in the characteristic curve. On the contrary, if the slender model has an angle of attack, not only the shape of λ - σ curve violently changes but also f becomes quite different from a circular cylinder case. We can get information to solve the problems of cavitation erosion and prevention of structure vibration caused by resonance. But, the intensive variations λ and f with a decreasing cavitation number shows us a presence of a large difference in the fluid dynamical mechanism of a cavitating bubble flow around a body which is between a circular cylinder and an elliptic cylinder having an angle of attack.

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