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### Study on Correlation between Cavitation and Pressure Fluctuation Signal Using High-Speed Camera System

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#### ABSTRACT

This paper is presenting the correlation between the cavitation and the pressure fluctuation of a propeller. Cavitation images and pressure fluctuation signals were simultaneously acquired by a high-speed camera system connected to pressure sensors for the correlation analysis. The analysis is focusing on the growing and collapsing process of the cavitation and its corresponding patterns of pressure signals. Especially, the relationship between the shape variations of the pressure fluctuation signal and the variations of pressure amplitudes for both the first and second blade frequency components is also studied.

From the analysis on the correlation between cavitation behaviors and pressure fluctuation signals, comprehensive explanations on the fundamental mechanisms of the pressure signal generation and on the moment of the peak creation in the pressure signals are found.

The shape of overall pressure fluctuation signal on hull surface is affected by not only the effect of cavitation from a single blade but also the superposition of the pressure signals from two adjacent blades when the collapsing of the foregoing blade's cavity and the growing of the following blade's cavity are happening at the same time. In this manner, the overlapping phenomena cause the changes of combination of amplitude levels of each blade frequency.

#### INTRODUCTION

It has been widely known that pressure waves which are originated from cavitation and propagating to the hull, pressure fluctuations are related to the cavitation behavior like growing and collapsing of the cavity through a number of empirical and theoretical researches. Nevertheless, the study on the clear mechanism of pressure fluctuation signal variation along the

cavitation behaviors has rarely been conducted, since it is difficult to observe the cavitation behaviors and moreover synchronize cavitation images with pressure signal due to the rapid rotational speed of propellers in model scale even in full scale.

The appearance of high-speed camera made it possible to take a picture of propeller cavitations with special lightings and synchronize the cavitation images with pressure signals. Johannsen[1] and Tukker & Kuiper[2] tried to observe the propeller cavitation with high-speed camera systems. However, the research results about complex phenomena or mechanism of the cavity collapsing process which has important effects on the pressure fluctuation has rarely been presented because of difficulties in theoretical explanation and computational calculation approaches.

Johannsen[3] analyzed the characteristics of the pressure fluctuation signal based on cavitation images, synchronized pressure signal and computational calculation approaches. He showed the results focusing on the peak variation of time-based pressure signals for full and model scales.

In this paper, the fundamental correlation between cavitations and pressure fluctuations and the effects of changes in pressure signal shape affecting the amplitude levels of 1<sup>st</sup> and 2<sup>nd</sup> blade frequencies have been mainly studied.

#### EXPERIMENTAL SETUP

The tests were conducted in SSMB (Samsung Ship Model Basin) large cavitation tunnel. The high-speed camera system for this research is shown in Fig. 1. The manufacturer of this camera system and model name are 'PHOTRON' and 'FASTCAM APX-RS', respectively. As shown in the figure, the camera is able to synchronize images with electric signals through the 'MCDL (Multi Channel Data Link)' and take the

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image up to 10,000 frames per second with the resolution of 640x400. The signal from the encoder was taken together with pressure signal for the calculation of angular position of the key blade.

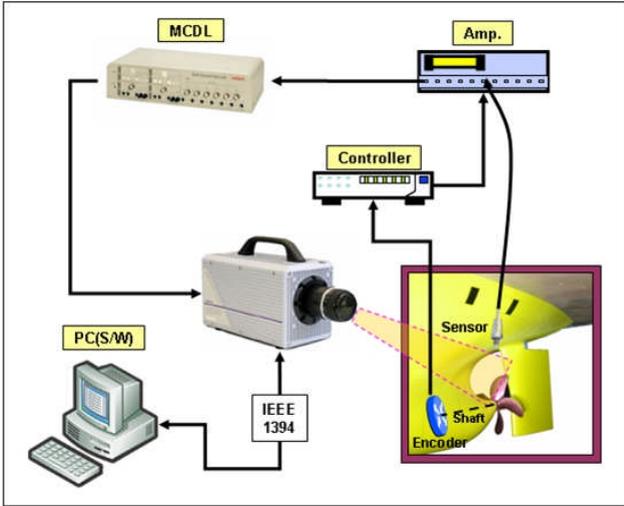


Figure 1: High-speed camera system setup

The synchronization was confirmed by stroboscopic light. The encoder signal from the propeller shaft flows into the controller of the stroboscopic light and the light is emitted when the peak of the pulse is detected in controller. Therefore, if the synchronization is correct, the image captured by the high-speed camera should become bright abruptly by the light emission of stroboscope exactly when the signal from stroboscope controller hit the peak point.

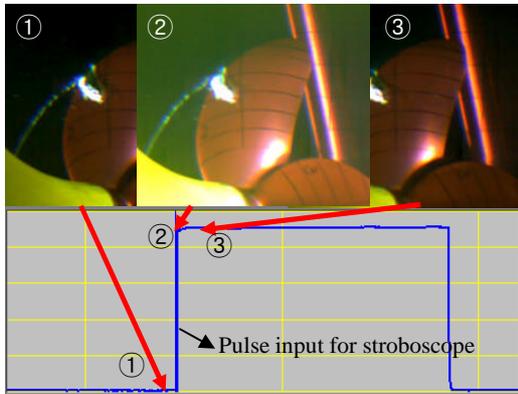


Figure 2: Synchronization between images and signal

Fig. 2 shows the synchronized images and the signal taken by the high-speed camera system with the 10,000 frames/sec speed. As shown in this figure, when the signal abruptly hits the peak point, the image gets brighter than other images because of the illumination of the stroboscope. The illumination time was 30 ~ 40 μs, which was shorter than the 100 μs, the exposure time of the high-speed camera. Through this process, the synchronization was confirmed with the good accordance between signal and image within 1/10,000sec delay. The time

lag specified by the manufacturer of high-speed camera system is less than 10 μs.

The sampling rate of the MCDL is 100,000 Hz when the frame speed is set as 10,000 frames per second.

## BASIC RELATION

First of all, in order to find out the correlation between cavitations and pressure fluctuations, it is very essential to understand the variation of pressure signal shape along the changes of the cavitation behavior.

A 4-bladed propeller with relatively small area ratio for a conventional crude oil tanker was chosen to investigate the relation between the cavitation behavior and the pressure signal clearly. Fig. 3 represents the observation results of this stage and it is easy to comprehend the corresponding pressure signal variation along the changes of the cavitation behavior from this figure.

The principal characteristics are as follows; the pressure signal goes up from the inception point of the cavity on blade, and then after a certain point, the pressure signal goes down in the middle of growing process, finally, the pressure shows the lowest value at fully developed stage of the cavity. After this growing process, the pressure signal hits the peak with the collapsing process. Therefore, it can be concluded that the entire period of the cavitation behavior could be simply divided into the two stages, the growing and the collapsing process.

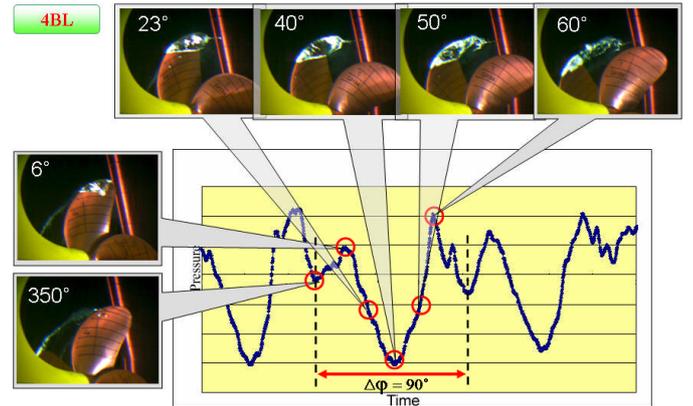


Figure 3: Basic relation between pressure and cavitation

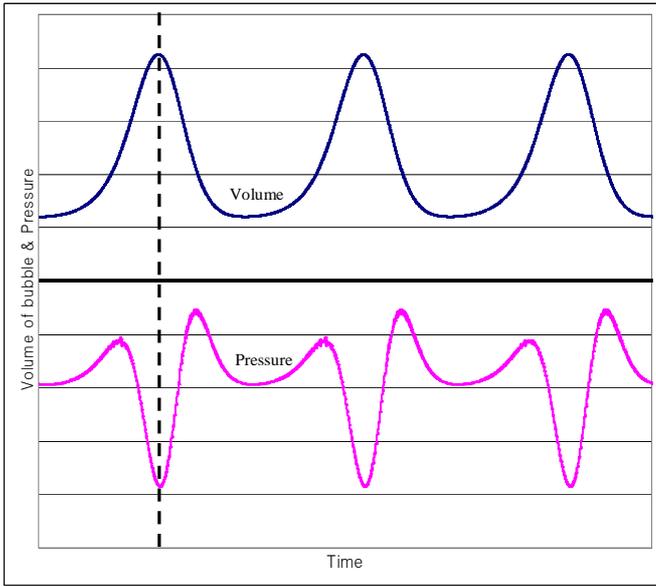
Bubble dynamics of Brennen[4] is introduced to explain the correlation between the cavitation and the pressure signal. Eq. (1) represents the relation between volume change and pressure induced in time domain.

$$\frac{p_a(r/R_M, t/\tau_c)}{P(r)} \frac{r}{R_M} = \frac{\partial^2(v/R_M^3)}{\partial(t/\tau_c)^2} \quad (1)$$

- Where  $p_a$  : pressure induced  
 $r$  : distance from bubble to field point  
 $R_M$  : maximum radius of bubble  
 $t$  : time  
 $\tau_c$  : extinction time  
 $v$  : volume of bubble

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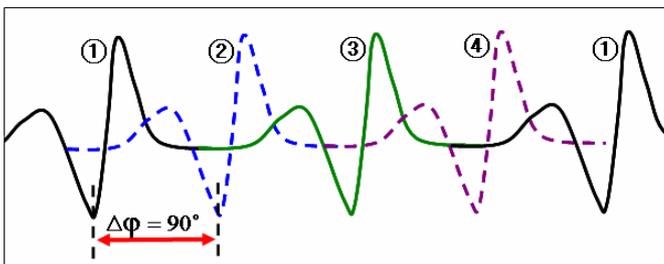
Typical example of the relation between volume change of a bubble and pressure is shown in Fig. 4.



**Figure 4:** Relation between volume change of bubble and pressure induced

According to this figure, in the growing stage of bubble generation, the pressure ascends to the summit and comes down to the minimum levels. The turning point is where the volume variation experiences the inflection point. After this turning point, the level of pressure get down and finally reach to the minimum at the moment the cavity has been fully developed. After this growing stage up to the maximum volume, the bubble experiences the collapsing process where the pressure goes up to the peak point as the volume shrinks.

As mentioned before, the phenomena about the correlation between the bubble volume and the pressure are very similar to the correlation between the cavitation and the pressure variation induced by the propeller as shown in Fig. 3. And it can be found out that the pressure signal induced by cavity has mainly two peaks at the growing and the collapsing process, respectively.



**Figure 5:** Concept of the signal assembly of each blade effect

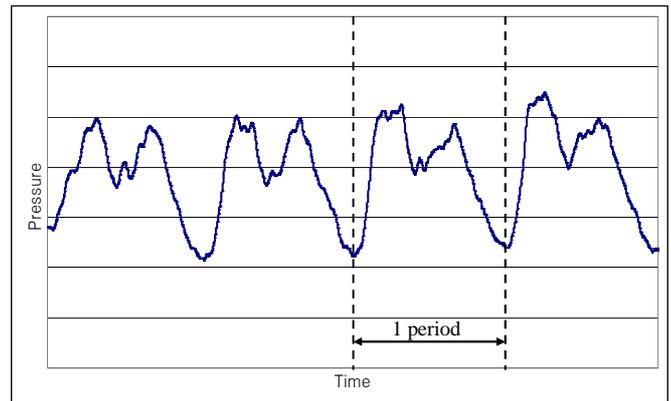
The signal produced by the one blade of the propeller gets weaker as the cavity on this blade disappear and then, the variation of the pressure signal induced by the cavity on the following blade is detected by the pressure sensor with the growing of the cavity on the following blade. In other words,

the pressure signal variation detected by the pressure sensors is the final results of the successive repeat of the cavitation phenomenon from the one blade and the following blade with the rotation of the propeller.

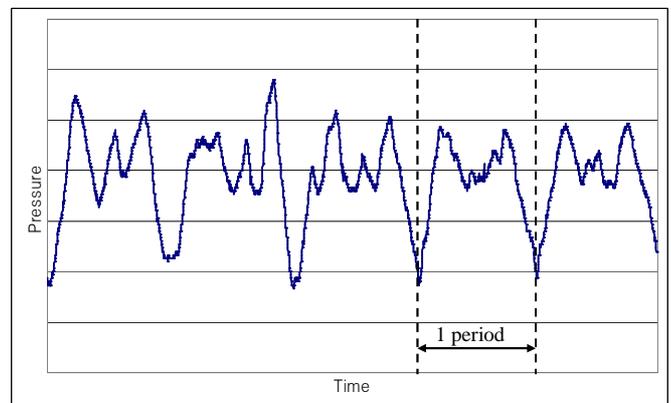
Therefore, geometrical interval among the blades and the variation of the time interval between the growing and collapsing process due to changes of loading based on the total characteristics of the wake distributions and propeller blade geometries can be essential factors to the final shapes of pressure signal. Fig. 5 shows the concept of the superposition of the pressure signals generated by each blade due to the fixed interval between blades for the 4-bladed propeller.

As for now, the superposition of the each blade effect was not importantly treated, but the final shape of pressure fluctuation signal is mainly affected by not only the characteristics of one blade effect but also this superposition phenomenon. This study basically focuses on the importance of this superposition phenomenon, as well as the origin of the pressure signal variation in the time period.

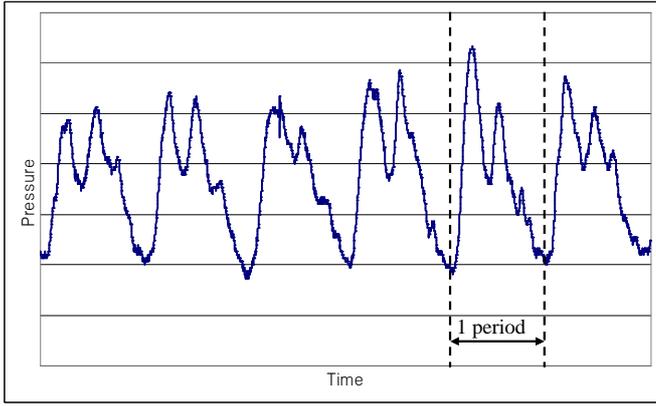
In order to avoid the confusion, the lowest pressure level in the period related to the rotation speed  $\times$  the number of the blades (1<sup>st</sup> blade frequency) is set as the starting and ending point of the basic time period as shown in Figs. 6 ~ 8. Because the lowest pressure in the period is originated just one time when the cavity fully develops as shown in Fig. 3 and it is also easy to recognize with the naked eye.



**Figure 6:** Pressure signal from 4-bladed propeller



**Figure 7:** Pressure signal from 5-bladed propeller



**Figure 8:** Pressure signal from 6-bladed propeller

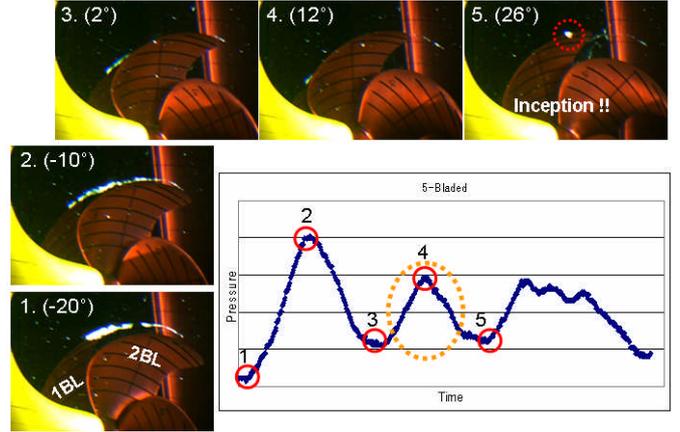
In this study, the characteristics of commercial ships such as the crude oil tankers (C.O.T), LNG carriers (LNGC) and container vessels are treated and the representative cases for each ship kind have been chosen. Figs. 6 ~ 8 show the characteristic shapes of the pressure signals along the change of the number of the blades. Generally, the changes of the number of blades mean the variation of the ship kind. In case of 4-bladed, this means C.O.T. propeller, in case of 5-bladed, it is used for the LNGC, and the 6-bladed is for container vessel. Fig. 6 is from the 115k C.O.T., Fig. 7 is from the 165k LNGC, Fig. 8 is from the 4,500TEU container vessel.

In general, all the signals have two or three obvious peaks between the minimum points for discriminating the period. The cause of the peak occurrence is changes of cavitation behavior such as the growing and collapsing as already explained in previous.

Through comparison of Figs. 6 and 7, we can find out that the shape of the signals are similar in the point of view that the pressure levels go up abruptly and descent to the specific level in the center of the period and then, re-rise and re-drop to the minimum level are continued.

The result from the 6-bladed, container vessels is shown in Fig 8. There are some differences in characteristics of signals in Figs. 6 and 7. The big differences are narrow interval between the peaks compared to the signals of 4 and 5-bladed propellers, and the location of the second peaks that is biased to the first peak. This phenomenon means that the interval between cavity collapsing process on the previous blade and the growing process on the following blade is very close or collapsing and growing process co-exist due to the narrow interval among blades and the high loading. So, it is very difficult to confirm clearly the cause of the origination of the second peak of pressure signal.

The particular point is three peaks are observed in Fig. 7, on the other hand, two major peaks are detected in Fig. 3. In Fig. 9 which shows another period of the 5-bladed propeller test results, it is confirmed that the center peak is not produced by the cavity growing process on following blade ('2BL'). Therefore, it is inferred that the center peak between the one from the collapsing process and the other from growing process is produced by the rebounding effects at the collapsing process.



**Figure 9:** Pressure signal from 5-bladed propeller

In this manner, the correlation between cavitation and pressure signal is explained with the introductions of bubble dynamics focusing on the cause of the generation of pressure peaks, and the behaviors of the cavitations and pressure signal shows a good accordance with the behaviors of the bubble and the radiated pressure. And the cause of the peaks' generation could be explained for from 4 to 6-bladed case.

## ANALYSIS

The intervals, amplitudes, locations and so on of these peaks generated by the cavity behavior make the characteristics of analyzed pressure fluctuations in frequency domain. Therefore, it is very important to find out the relation between the shapes of pressure signal and the resultant pressure fluctuations to understand causes of the origination of pressure fluctuation components for each blade frequency.

Fourier transform was used to analyze the components of the pressure fluctuations in the frequency domain as follows;

$$p(t) = \frac{a_0}{2} + \sum_{n=1}^{\infty} (a_n \cos 2\pi n f_1 t + b_n \sin 2\pi n f_1 t) \quad (2)$$

$$\text{Where, } f_1 = \frac{1}{T_p}$$

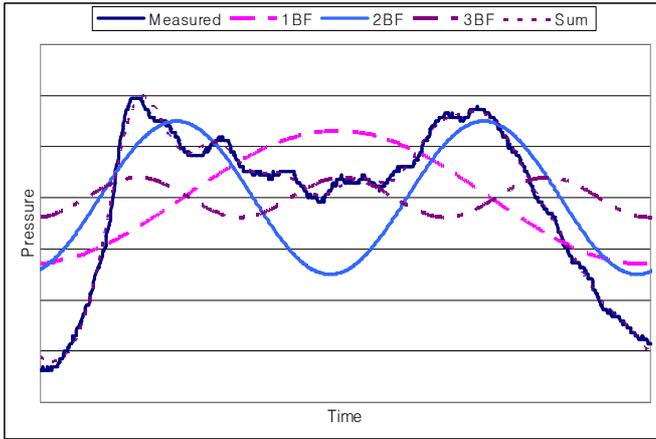
$$a_n = \frac{2}{T_p} \int_0^{T_p} p(t) \cos 2\pi n f_1 t dt \quad n = 1, 2, \dots$$

$$b_n = \frac{2}{T_p} \int_0^{T_p} p(t) \sin 2\pi n f_1 t dt \quad n = 1, 2, \dots$$

Fig. 10 shows the measured and analyzed signal based on Eq. (2) for the 4-bladed propeller test results. It can be easily conceived that the 1<sup>st</sup> and 2<sup>nd</sup> blade frequency signals have the main effects on the signal shape and the peaks of the 2BF (blade frequency) component nearly accord with the peaks of the measured signal. It implies that the 2BF component is related to the shape of interval between two peaks occurring during the growing and collapsing process and the combination of the 1BF and 2BF amplitudes can be changed by the shape of this interval.

In case that the interval of two peaks gets big enough to match to the peaks of 3<sup>rd</sup> blade frequency component, the shape variation of the interval can affect the combination of the 1 ~

3BF amplitudes. But the probability of the occurrence like this case is low except for the extremely low loading condition.

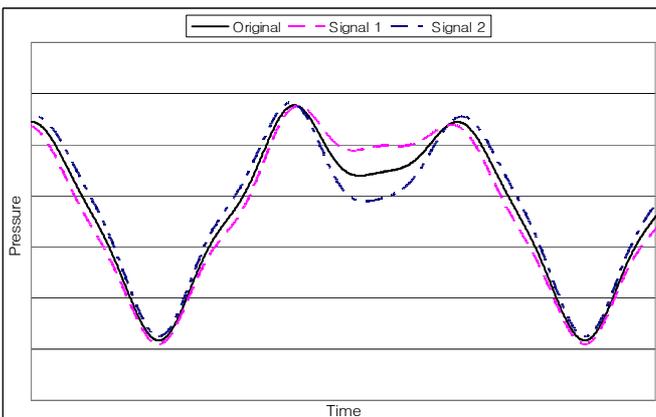


**Figure 10:** Analyzed pressure signal from 4-bladed propeller

In order to investigate effects of the shape of the interval between two peaks for 4-bladed, an attempt to investigate the pressure signal variations along the changes of the 1BF and 2BF amplitudes has been made. The original signal and changed signals are shown in Fig. 11. In this figure, the solid line means the original signal made from the superposition of each blade frequency component from 1<sup>st</sup> to 5<sup>th</sup> for the result of 4-bladed case, and ‘Signal 1’ and ‘Signal 2’ mean the signals which have the only change in 1BF and 2BF amplitude as specified in Table 1. In this table, the values mean the amplitude ratio compared on the value of the original signal. Signal 1 has the amplified 1BF amplitude by 120% and reduced 2BF amplitude by 80% and Signal 2 has the reduced 1BF amplitude by 80% and amplified 2BF amplitude by 120% compared to the original signal.

**Table 1:** Amplitude levels of 1 & 2BF for pressure signal1, 2

	Signal 1	Signal 2
1BF	120 %	80 %
2BF	80 %	120 %

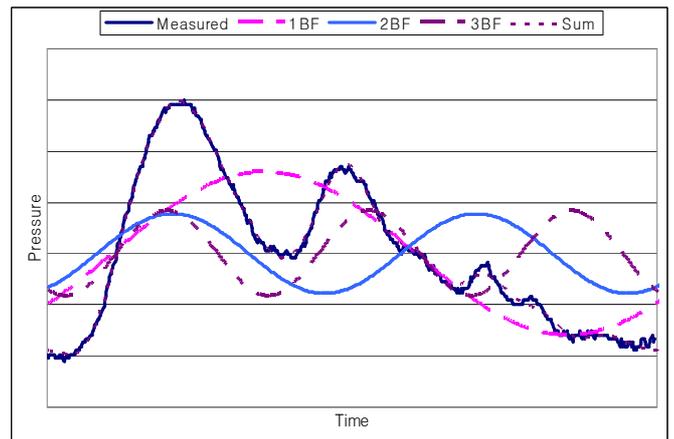


**Figure 11:** Pressure signal variation along the change of 1BF & 2BF amplitudes for 4-bladed propeller

As shown in Fig. 11, it can be confirmed that the signals have the only change in the shape of the interval between two peaks without the variation in height from minimum to maximum point of two peaks only by changes in 1BF and 2BF amplitudes. Therefore, from this figure, we can understand the importance of the signal shapes between two peaks for the combination of the 1BF and 2BF. Especially, 2BF/1BF gets higher as the depth of the valley gets bigger within the fix of the total height from minimum to maximum point. The probability of the smooth variation of the signal in the interval between two peaks is generated by quick coupling of collapsing and growing process.

However, these points explained just in previous are only applicable to the 4 and 5-bladed cases that have the signal forms like in Figs. 6 and 7 because the peak of 2<sup>nd</sup> blade frequency component has to accord with the peaks of original measured signal.

The measured and analyzed signals based on Eq. (2) for the 6-bladed propeller results are described in Fig. 12. As shown in this figure, the peaks of 2<sup>nd</sup> blade frequency component do not match well to the peaks of the measured signal except for the first peak of measured signal. In case of second peak of measured signal, the peak of 3<sup>rd</sup> blade frequency component accord with this peak in the middle of the period. Therefore, the shape variation of the interval between two peaks of the measured signal does not solely affect the 1BF and 2BF component. Namely, the shape variation of the interval between two peaks of 6-bladed case affects the combination of not only 1BF and 2BF amplitudes but also 3BF amplitude. The another point that we should pay attention to is the high-order components should be also needed to express the inclined shape compared to the 4 or 5-bladed propeller signal. In other words, since the signal shape for 6-bladed is asymmetric on the basis of center line between two minimum levels, higher order components should be needed to express the signal shape, even though the second pulse is faint.



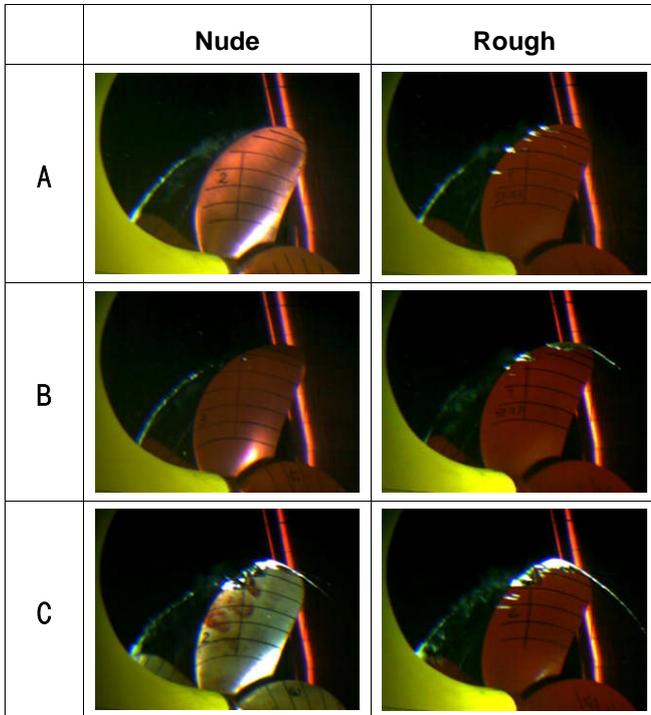
**Figure 12:** Analyzed pressure signal from 6-bladed propeller

## DISCUSSION

To sum up, the 1BF and 2BF amplitude levels of pressure fluctuations for 4 and 5-bladed propellers are highly related to the signal shape of interval between two peaks and this shape is mainly affected by how the superposition of the signals from

the collapsing process on foregoing blade and growing process on following blade occurs. Finally, the ratio of 2BF/1BF gets smaller as the winding located between two peaks gets gentler due to the faster coupling of the collapsing and growing process.

The tests for verification of correlation between cavitation and pressure fluctuations explained previously were conducted through the roughness control of the blade surface. The roughness effect of propeller blade promotes the cavitation occurrence, so it is effective way to change the signal shape of the interval between two peaks. C.O.T. (4-bladed) and LNGC (5-bladed) were selected for this experiment. The roughness of the propeller blades was controlled by whether the application of the special paint or not. In this paper, ‘Nude’ means the propeller without application of roughness paint and ‘Rough’ means the propeller with application of that paint. When the roughness is applied, the roughness of the blade is approximately 15 $\mu$ m and Nude case is about 5 $\mu$ m.



**Figure 13:** Cavity image for 4-bladed propeller at  $\theta = 350^\circ$  (Comparison of Nude & Rough)

Fig. 13 shows the images of cavitation test for the same ship with three different 4-bladed propellers at the blade angle of  $\theta = 350^\circ$  which is considered to be the best angular position to compare the development degree of the cavitations. All propellers have same geometry except for the rake distribution. In this figure, it is confirmed that the angular position of the cavitation inception on roughness controlled blade surface is promoted for all propellers.

Table 2 shows amplitudes of pressure fluctuations for 1BF and 2BF normalized by the 1BF amplitude of the nude case for each propeller. From this table and Fig. 13, it is verified that 2BF/1BF ratio for all cases decreased with the promotion of the cavitation inception from the blade angular point of view due to

the blade roughness. This point matches well with the relation between ratio of 2BF/1BF and the signal shape of interval between two peaks in Fig. 11.

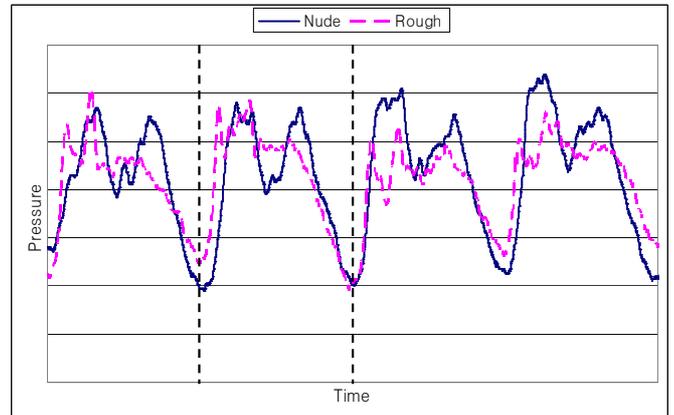
**Table 2:** Comparison of amplitude levels of 1 & 2BF for propellers A, B and C (Nude & Rough)

Propeller	A		B		C	
Roughness	Nude	Rough	Nude	Rough	Nude	Rough
1BF	1.00	0.99	1.00	1.49	1.00	0.98
2BF	0.84	0.64	0.91	1.11	0.49	0.41
2BF/1BF	0.84	0.65	0.91	0.74	0.49	0.42

Fig. 14 presents the comparison of time signals for Nude and Rough cases of propeller A. The locations of the minimum point for both cases according to the fully developed cavitation are very similar and the difference is less than  $3^\circ$  based on the angular position. It means that both starting positions of the cavity collapsing process are very similar, even if the different blade roughness, therefore we can conclude that the collapsing process is mainly depends on the wake distributions.

As shown in this Fig. 14, the winding of the signal located in the middle of two peaks for Nude case is more obvious and severe than Rough case because of occurrence of the clear second peak. So, the ratio of 2BF/1BF for Nude case is rightly larger than Rough case.

In case of propeller C, the difference between Nude and Rough case is relatively small compared to other results, because the cavitation of Nude case has already developed at  $\theta = 350^\circ$ . In the comparison among propellers at same blade surface condition, C has the smallest value of 2BF/1BF and the reason is same as explained ahead.

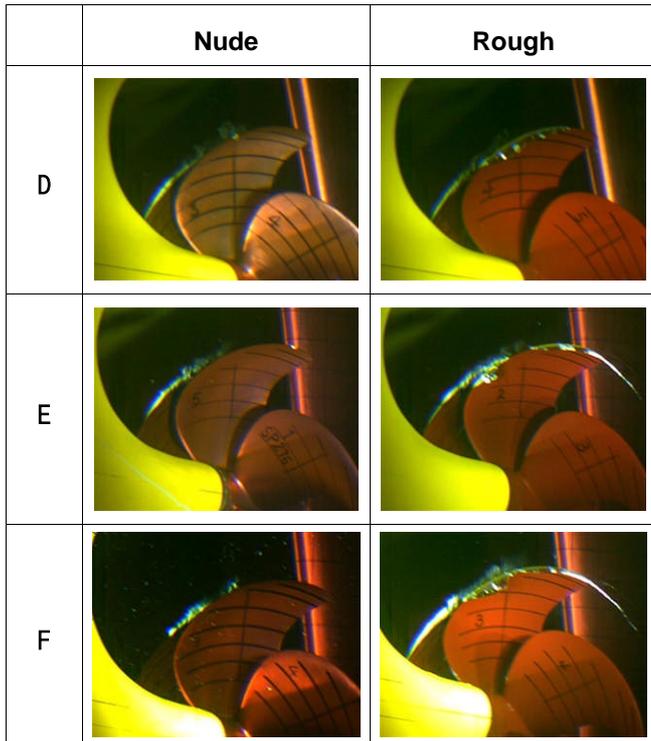


**Figure 14:** Time signal comparison between Nude and Rough for propeller A

Fig. 15 shows the images from the cavitation tests for the different capacities LNGC, and all propellers have also different geometry. Propeller D is from 145k, E is from 155k and F is from 165k LNGC. This figure shows the differences between Nude and Rough for each test result like the Fig. 13. Table 3 presents amplitudes of pressure fluctuations for 1BF

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and 2BF normalized by the 1BF amplitude of the nude case for each test.



**Figure 15:** Cavity image for 5-bladed propellers at  $\theta = 0^\circ$  (Comparison of Nude & Rough)

**Table 3:** Comparison of amplitude levels of 1 & 2BF for propellers D, E and F (Nude & Rough)

Propeller	D		E		F	
	Nude	Rough	Nude	Rough	Nude	Rough
1BF	1.00	1.04	1.00	2.21	1.00	2.45
2BF	0.70	0.50	0.82	0.68	1.37	1.03
2BF/1BF	0.70	0.48	0.82	0.31	1.37	0.42

In LNGC results, it is confirmed again that the roughness treatment makes the ratio of 2BF/1BF decrease and the amount of variation is greater than the C.O.T. case.

## CONCLUSION

In this research, the variation of pressure fluctuation signal along the changes of cavitation behavior has been investigated through cavitation behavior and synchronized pressure signals which is obtained from the model test for the 4-bladed propeller, and it is confirmed that the correlation of these two matches well with the relation between the bubble volume and the pressure in bubble dynamics. After these fundamental studies, it is possible to conclude the causes of the pressure variation along the changes of cavitation behavior.

What this research have found out is that the time interval of collapsing and growing of cavitations on adjacent blades

have an important effect on the overall shape of pressure fluctuation signals and this effect concludes the combination of amplitude levels for each blade frequency.

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