Exploration of a Possibility to Assess Erosive Cavitation by Acoustic Emission Technique

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Abstract

In order to complement the conventional model scale cavitation erosion test methods, research is being undertaken to explore the use of an acoustic emission technique to provide a quantified measure of cavitation. The amplitude of AE signals within a structure, such as a propeller shaft, is assumed to change in proportion with the pressure impact loads from the collapse of vapour cavities. Analysis of the power spectrum of the signals should show some meaningful parameters in relation to the cavitation intensity and frequency, which can be used as a quantitative index of the cavitation erosion risk. The main results of a preliminary study are provided with illustration of some results of the experiment using a G-32 type vibratory cavitation apparatus combined with a CFD simulation. It is found that the AE power spectrum indicated two main peak frequencies from the acoustic excitation and the sub-harmonic oscillation of the acoustic cavities as reported in the other relevant literature. However, the acoustic driving frequency component appeared much stronger and the sub-harmonic oscillation frequency appeared as a band rather than a single peak. An investigation on the vibration characteristics of the sonotrode revealed the vibration amplitude could vary in the order of about 15 % of that desired. This might partly explain the reason of the frequency band formation around a central frequency of the sub-harmonic oscillation. Further investigation on the possible causes is underway. It has still a long way to go to establish a new model test methodology, but it appears the AE signal amplitude response has a certain relation with the magnitude of cavitation impact loadings.

Keywords: cavitation erosion; a new model test method; acoustic emission technique; sonotrode; OpenFOAM;

Introduction

For the shipbuilding industry, it is one of the most important task for the ship designers to avoid the risk of material damage from cavitation, and therefore, many efforts have been made to predict the risk of cavitation erosion in the early design stage by means of CFD and model testing. Since computer simulation to predict cavitation erosion requires too much time for practical engineering applications, the final evaluation on a design candidate is made often based on visual observation of the cavitation on a model in the cavitation tunnel and model erosion tests like paint tests ([1]). These model test methods can provide a good qualitative information such as the type of occurring cavitation events and possible location of erosion damages. However, it cannot tell the intensity of cavitation in a consistent way as desired.

Acoustic emission (AE) is the creation of transient stress waves in response to a dynamic event(s) to cause local changes in the strain inside a body ([2, 3]). It has been used for condition monitoring of many industrial structures thanks to its sensitivity to any dynamic changes inside a material ([4-7]). Boorsma and Fitzsimmons [8] reported that the AE signal could be measured inside a ship's engine room and the relevance of its rise of the peaks with the observed cavitation impact events. Since the signal amplitudes increase as the impact loadings, the AE signal amplitude appears to be a good candidate for a reliable indicator to assess severity of cavitation events and potentially the type of cavitation.

To investigate such a possibility of using AE technique for model testing to replace or complement the conventional test methods, a joint research work was started among three industrial bodies. If one can establish an AE amplitude threshold corresponding to the conventional paint tests, just one cavitation observation test while measuring AE signal shall be enough to evaluate the risk of cavitation erosion instead of waiting for another

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erosion tests. Therefore, it is expected to reduce the time and cost to assess the risk of cavitation erosion with more quantitatively consistent criteria by developing this new test method. As part of this wider programme, a G-32 type vibratory cavitation apparatus was used for the study. The cavitation generation by such an apparatus is regarded as reproducible, thus good for testing in the laboratory environment for this type of cavitation research in an accelerated manner ([9]). In this paper, the challenges for the exploration and some experimental results are described.

A new model test method using the AE technique

The new test scheme is in principle based on the energy approach ([10-14]). A simplifying assumption is made that the AE signal amplitude level will respond in proportion with the mechanical impact loads generated from the cavitation bubbles collapse events. Then one can analyse the aggressiveness of any cavitation events by simply analysing the AE signal amplitude and the power spectrum with the knowledge of AE signal amplitude threshold for the cavitation erosion. To do this with a G-32 type vibratory cavitation apparatus as a simpler model than the actual propeller model and the cavitation tunnel environment, it is necessary to know the difference in the power spectrums from the acoustic one and hydrodynamic one in a large cavitation tunnel. From that knowledge, one can determine an appropriate time duration of the tests equivalent to the conventional paint erosion tests in a large cavitation tunnel. For this initial stage of experiment, the equivalent time duration was set to 20 s based on literature review on the sub-harmonic oscillation frequency of the acoustic cavities and an assumption for the frequency of cavitation impact events in a cavitation tunnel that they occur once on each blade per revolution.

Reproduction of paint tests in the lab environment

A series of experiments were carried out using the G-32 type vibratory cavitation apparatus of a sonotrode according to the alternative ASTM G-32 standard method ([15]) with varying gap distances between the sonotrode horn tip and the test specimen from 30 to 15 mm. A photo of the instrumentation and a summary of the instrument specifications are shown in Figure 1 and Table 1. The objective was to find a test condition begins to remove stencil ink film from the surface of a test specimen similar to that in the conventional paint tests. Tap water was filled in the water bath until the sonotrode horn tip was submerged into water by 10 mm. A small copper alloy block specimen (dimensions: 25 x 25 x 15 mm^3) coated with a stencil ink was placed under the sonotrode horn tip. Each test was carried out with three test samples to confirm repeatability. At a test condition with 15 mm gap distance with 100 % power, the paint removal was started in 20 s and became pronounced in about 5 min. One of the test results are shown in Figure 2. The samples exhibited very good consistency in terms of location of damage and type of the damage pattern as shown in Figure 2(a), but the severity of cavitation felt from the images are fairly varying (cf. Figure 2(b).). This was regarded as to show what one could expect from the conventional paint tests. A later sonotrode vibration characteristics analysis found a possibility that some scatter in the sonotrode vibration amplitude might have contributed to such varying quality of the paint test results.

AE signal amplitude measurement

Another series of similar tests as the above were carried out to measure the AE signal amplitudes with variation of power and gap distances. A piezo-electric type AE sensor was installed just underneath a test specimen to capture the signal with a data acquisition device (National Instrument, NI USB-6251 BNC) capable up to 1.25 MS/s. Three data sets for each test condition were recorded for 5 s with 150 kHz sampling rate in a few seconds after the sonotrode began to move. This was to avoid recording any transient signal. The measured data was analysed using a FFT (Fast Fourier Transform) function implemented in MATLAB (ver. R2017a). The voltage signal from the AE sensor can be expressed in dB with reference to Hsu-Nielsen source by the following relation;

$$S_{AE} = 20 \log \frac{V_{AE}}{1 \times 10^{-6}} \ (dB)$$

The power spectrum of the measured AE signals are illustrated in Figure 3 and Figure 4. In the figures, one can see two peaks that are contributed from the acoustic excitation (19.96 kHz) and presumably from the sub-harmonic oscillation of the acoustic cavitation. The sub-harmonic frequency component barely changed from about 3.7 kHz as the gap distance reduced from 20 mm to 15 mm. The frequency changed to about 1.7 kHz when the gap distance reduced to 0.5 mm while the acoustic excitation frequency stayed the same in all the tested conditions. The experimental results appear to give similar results as the other references ([16-20]). However, the differences were (1) the main pressure driving component was not the sub-harmonic one and (2) the sub-harmonic frequency did not have a single value but rather a band with a central frequency. Finally, (3) the auto-correlation coefficients of the measured AE signals were more like a random process (cf. Figure 5). The last analysis result seems to explain why there appeared numerous frequency components in a wide band. Further investigation needs to be carried out on the possible causes of such departure from those previously reported.

Sonotrode vibration characteristics analysis

The sonotrode vibration characteristics was investigated by analysing the recorded data of the horn tip movement. The vibration movement was measured by a semi-conductor laser displacement sensor (Keyence, LK-G32) at a sampling rate of 50 kHz. Two sonotrode tips were available at the time of measurement. One was a slightly worn tip and used for the AE measurement reported in this paper. The other one was a brand-new one that had not yet tested before. Both tips had the same diameter of 18 mm.

The linearity of vibration amplitude response to the power control was evaluated by the least square method. The results are shown in Figure 6. Both tips did not show any significant difference in the residual squared of $R^2 = 0.8531$ (new tip) and 0.8799 (worn tip). However, there were significant variations of the average amplitudes between individual recording sessions outside the power band of 70 ~ 80 %. Therefore, a possibility was there to get a lower or similar amplitude with a higher power setting than a lower one. From this regard, the variance of the paint test results shown in Figure 2 might have been influenced from this variance of vibration amplitudes and it is recommended to perform the paint tests again by varying only the gap distance with a fixed power setting in 70 ~ 80 % power band. With this setup, the expected variance of the amplitude was ±13 μm assuming it follows Gaussian normal distribution. This still appears a large deviation compared with the mean amplitude of 78.6 μm at 80 % power setting. The influence of such variation needs to be evaluated using CFD simulation later.

A numerical approach to investigate the phenomenon

A study of the numerical simulation for the acoustic cavitation phenomenon has been carried out by the authors in order to understand better the relevant physics ([21, 22]). A HEM (Homogeneous Equilibrium Mixture) based compressible multiphase flow solver ‘cavitatingFOAM’ in an open source software, OpenFOAM (ver. 3.0.1) package was used. The description on the latest numerical model and the solver as used can be found in the reference ([22]). A test case with a 3.2 mm horn tip diameter was chosen from the experimental work of Žnidarčič, *et al.* [16]. Wallis barotropic compressibility model was used to simulate the compressibility effect and the time step size was set to 1×10^{-8} s (corresponding acoustic CFL number is 1.45). To prevent the solution from diverging at an early time stage, the minimum mixture density value had to be limited to a high value as 300 kg/m^3. The simulated time duration was up to 4.03 ms and the results are shown in Figure 7. The predicted pressure peaks appeared similar as the published experimental results, but the sub-harmonic frequency was predicted to be about twice the published results. The source of such deviation is yet to be further investigated.

Figures & Tables:

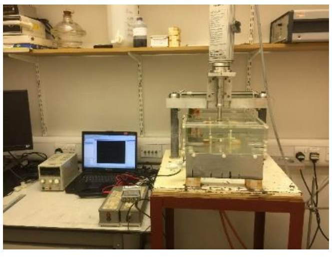

Figure 1. Instrumentation of the sonotrode to reproduce paint test results on a test specimen.

Sonotrode	Make/model: Hilscher UIP-1000HD Nominal max power output: 1000 W (adjustable range: 50 ~ 100 %) Operating frequency: 20000 ± 500 Hz Vibration amplitude (peak-to-peak): 43 (at 50 %) ~96 (at 100 %) µm Titanium horn tip diameter: 18 mm
AE sensor	Make/model: McWade, NS3303 Type: PZT. Data sampling frequency: 150 kHz. Output voltage: ± 10 V.
Water bath	Material: transparent polycarbonate acryl Dimensions: 305 x 400 x 115 mm^3

Table 1. Summary of the specifications of the instrument.

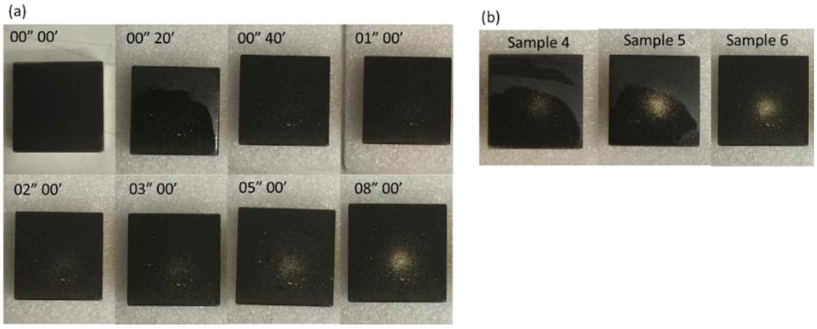

Figure 2. Damage patterns observed on the test specimens (Test condition: output power 100 %, gap distance 15 mm, exposure time: 8 min.). (a) time history of paint removal with sample 6, (b) test results showing different severity.

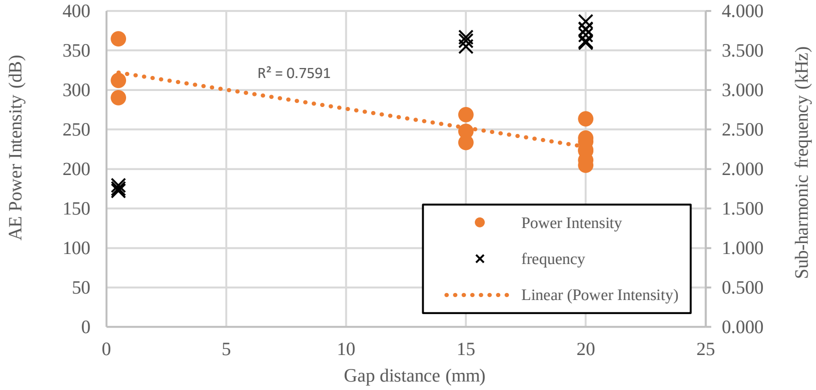

Figure 3. Measured AE power amplitude and sub-harmonic frequency vs gap distance.

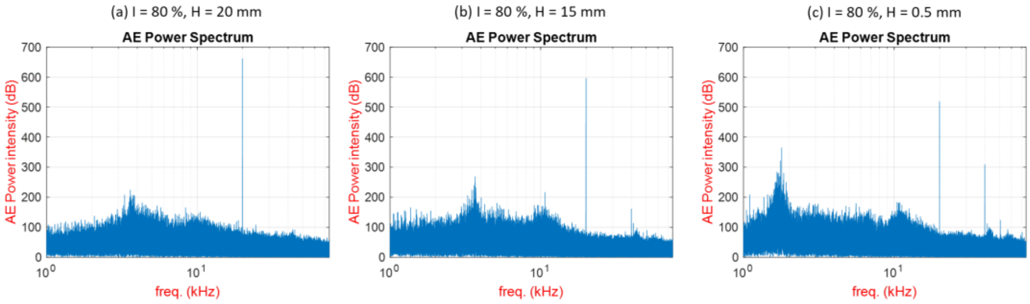

Figure 4. Power spectrum of the measured AE signals at different gap distances.

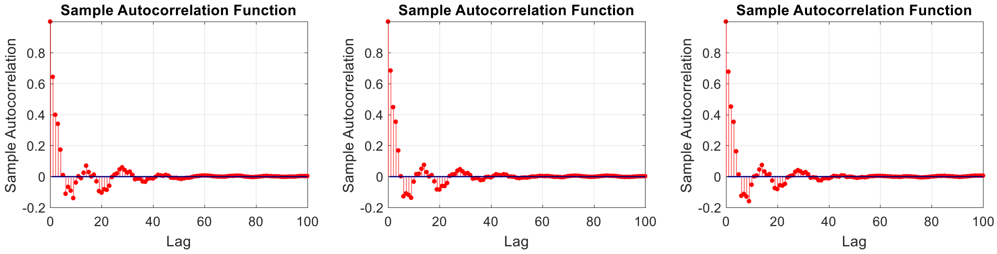

Figure 5. Auto-correlation coefficients of a set of the measured AE signals (80 % power, 15 mm gap distance).

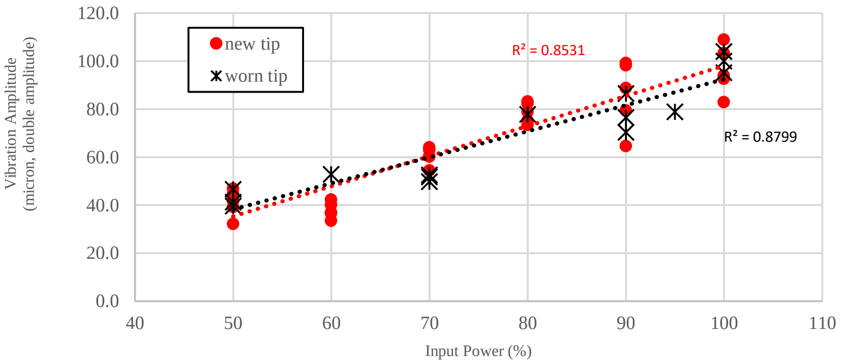

Figure 6. Mean amplitude data measured from the two sonotrod tips.

Power output setting		50 %	60 %	70 %	80 %	90 %	100 %
Worn tip	Average	42.5	-	51.4	-	77.8	99.7
	Standard deviation	3.6	-	1.5	-	8.1	4.4
New tip	Average	41.0	37.9	60.4	78.6	86.0	96.3
	Standard deviation	5.7	3.4	3.7	4.3	14.4	10.1

Table 2. Summary of the measured vibration amplitude data.

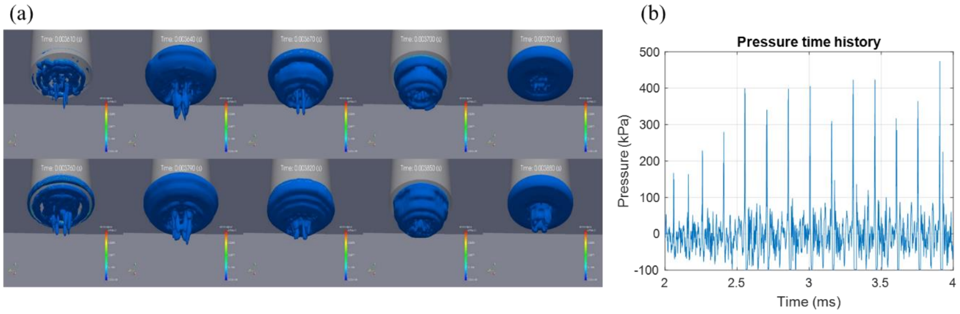

Figure 7. Predicted (a) acoustic cavity oscillation for two cycles (time interval between the frames: 30 μs, acoustic excitation period: 50 μs) and (b) time history of the pressure peaks calculated at a location laterally 7 mm apart from the horn tip end.

Conclusion

Based on the energy approach, a new model test method is being explored to utilise the acoustic emission (AE) technique to assess the risk of cavitation erosion during the early design stage of marine propellers. The key assumption is that the AE signal will respond with a certain correlation with the intensity of the cavitation events. Therefore, by measuring and analysing the power spectrum of the signals with the knowledge of the AE signal amplitude threshold for cavitation erosion, one may be able to assess the risk of cavitation erosion with more consistency without necessity of doing additional separate paint erosion tests compared with the existing model test methods.

A G-32 type vibratory cavitation apparatus was used to investigate an AE signal amplitude threshold equivalent to the conventional paint erosion tests. From the experiment, a limitation of the current paint erosion tests was seen in terms of the evaluation of severity of the involved cavitation events although a further investigation necessary to exclude the influence of variance of the vibration amplitude of the cavitation apparatus itself. Also it appears the AE signal amplitude increases as the intensity of the cavitation events become higher with a certain predictable relation. To confirm this relation, necessary several more experiments for the other gap distances between the tested points.

The power spectrum analysis results of the AE signals measured for 5 s revealed some deviation from the recent study results by other researchers. The first deviating fact was that the sub-harmonic frequency component formed a kind of band rather than a single frequency. The second fact was that the dominance of the acoustic excitation frequency component in the signal. The vibration characteristics of the cavitation apparatus was investigated to find any relevant source of such departure. It revealed a potential problem in repeatability of the acoustic excitation especially in the power range outside 70 ~ 80 % output power. Further investigation is necessary to address to main cause of such deviation in the power spectrum analysis results.

References

[1] ITTC (2005). *The specialist committee on cavitation erosion on propellers and appendages on high powered/high speed ships - proceedings of the 24th international towing tank conference.* International Towing Tank Conference. 2.

[2] Eitzen, D.G. and Wadley, H.N.G. (1984). *Acoustic-emission - establishing the fundamentals.* Journal of Research of the National Bureau of Standards. 89(1).

[3] Wadley, H.N. (1986). *Acoustic emission: Nature's ultrasound.* Review of progress in quantitative nondestructive evaluation.

[4] Rogers, L. and Carlton, J. (2010). *The acoustic emission technique: Application to marine structures and machinery.* Proceedings Lloyd's Register Technology Days.

[5] Zain, M., Jamaludin, N., Sajuri, Z., Yusof, M. and Hanafi, Z. (2010). *Acoustic emission study of fatigue crack growth in rail track material.* National Conference in Mechanical Engineering Research and Postgraduate Studies.

[6] Faisal, N., Ahmed, R. and Reuben, R. (2011). *Indentation testing and its acoustic emission response: Applications and emerging trends.* International Materials Reviews. 56(2).

[7] Ukpai, J.I., Barker, R., Hu, X. and Neville, A. (2013). *Exploring the erosive wear of x65 carbon steel by acoustic emission method.* Wear. 301(1).

[8] Boorsma, A. and Fitzsimmons, P. (2009). *Quantification of cavitation impacts with acoustic emissions techniques.* 7th International Symposium on Cavitation. (Paper No. 13).

[9] Chahine, G.L., Franc, J.-P. and Karimi, A. (2014). *Laboratory testing methods of cavitation erosion.* Advanced experimental and numerical techniques for cavitation erosion prediction. 106.

[10] Pereira, F., Avellan, F. and Dupont, P. (1998). *Prediction of cavitation erosion: An energy approach.* J Fluid Eng-T Asme. 120(4).

[11] Karimi, A. and Leo, W.R. (1987). *Phenomenological model for cavitation erosion rate computation.* Mater Sci Eng. 95.

[12] Fortes-Patella, R. and Reboud, J.L. (1998). *A new approach to evaluate the cavitation erosion power.* J Fluid Eng-T Asme. 120(2).

[13] Fortes-Patella, R., Challier, G., Reboud, J.L. and Archer, A. (2013). *Energy balance in cavitation erosion: From bubble collapse to indentation of material surface.* Journal of Fluids Engineering. 135(1).

[14] Fortes-Patella, R., Choffat, T., Reboud, J.L. and Archer, A. (2013). *Mass loss simulation in cavitation erosion: Fatigue criterion approach.* Wear. 300(1-2).

[15] International, A. (2011). *Standard test method for cavitation erosion using vibratory apparatus.*

[16] Žnidarčič, A., Mettin, R., Cairós, C. and Dular, M. (2014). *Attached cavitation at a small diameter ultrasonic horn tip.* Physics of Fluids. 26(2).

[17] Žnidarčič, A., Mettin, R. and Dular, M. (2015). *Modeling cavitation in a rapidly changing pressure field - application to a small ultrasonic horn.* Ultrason Sonochem. 22.

[18] Mottyll, S. and Skoda, R. (2016). *Numerical 3d flow simulation of ultrasonic horns with attached cavitation structures and assessment of flow aggressiveness and cavitation erosion sensitive wall zones.* Ultrasonics sonochemistry. 31.

[19] Truong, V.A. (2009). *A study of impulsive pressure distribution of cavitation generated by a high frequency vibrational probe.* J. Sci. Technol.(Technical Universities Pub. Hanoi, Vietnam). 73.

[20] Mottyll, S., Müller, S., Niederhofer, P., Hussong, J., Huth, S. and Skoda, R. (2014). *Analysis of the cavitating flow induced by an ultrasonic horn–numerical 3d simulation for the analysis of vapour structures and the assessment of erosion-sensitive areas.* EPJ Web of Conferences. 67.

[21] Kim, B.G., Wilson, P.A. and Turnock, S.R. (2016). *Numerical simulation of an ultrasonic vibratory cavitation device.* 19th Numerical Towing Tank Symposium.

[22] Kim, B.G., Wilson, P.A. and Turnock, S.R. (2017). *Simulation of acoustic stream with a sonotrode.* 20th Numerical Towing Tank Symposium.