Direct and indirect measurement techniques of cavitation intensity: a brief review

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Abstract. Cavitation has been one of the critical issues in turbomachinery operation which often causes the reduction of service life of the components. In order to predict the service life, cavitation intensity (CI) needs to be measured accurately. In this paper, several notable developments of techniques to measure CI are reviewed briefly. Those techniques can be classified into two groups, i.e. direct and indirect measurements. For the indirect technique, a method which estimates the impact load of bubble collapse by inverse analysis is particularly elaborated. For the direct technique, a method which utilizes painting technique to quantify the actual CI is specifically presented. The advantages and disadvantages of both direct and indirect techniques are also discussed.

1. Introduction
Cavitation is known as one of the critical issues in turbomachinery operation because it can cause serious damage to the machine component due to cavitation erosion phenomenon which can shorten the service life [1-3]. In other hand, the needs to develop a smaller size of turbomachinery which still possess the same or higher performance are always demanded. A machine in small size yet having high speed could even much increase the risk of damage due to cavitation erosion in the machine components, such as in impeller of pump [4-6]. Because cavitation cannot be removed completely from turbomachinery operation, therefore, a machine should be designed to have a cavitation intensity (CI) level below the allowable criteria. Thus, it could satisfy the designated service life and an unpredictable cost inefficiency can be avoided [7-9]. Furthermore, several surface treatment techniques to protect the machine component from cavitation damage could also be implemented [10-12].

A schematic figure of cavitation bubble formation inside water with low static pressure condition due to high-speed water flow is illustrated in Figure 1. Water near machine components with high-speed rotation, such as impeller, is exposed to low pressure condition. This will cause evaporation at room temperature which then cause the formation of cavity or bubble. Cavitation that occurs in turbomachinery usually reduces the efficiency of the machine [13]. However, a more critical issue of cavitation is when the bubble collapses and then it generates a shock wave that hits a solid surface. This water jet collision, so called cavitation load, with the surface can cause some erosion [1, 2].
In real operation, however, besides cavitation load, other external loads such as centrifugal force and hydraulic pressure do exist. This kind of loads, in fact, also give some influences on the component’s service life while receiving cavitation load. How an external load would affect a cavitation damage as well as the fluid-structure interaction phenomena due to cavitation load have been reported by several literatures [2, 3, 14, 15]. Hibi et al. [2] and Kawamura et al. [3] reported that external loads which generate tensile stress in the impeller could significantly amplify the damage caused by cavitation erosion. Furthermore, Kojima et al. [4] indicated that the damage could be controlled by modifying the surface wettability.

In order to predict the lifespan of turbomachinery due to cavitation erosion problem, CI must be quantified accurately. Prediction of the lifespan is very important to assure the maintenance schedule is arranged properly. It is not only to significantly reduce maintenance cost but also to avoid unexpected losses if the turbomachinery is suddenly broken, such as repairing cost and a loss of potential income. Moreover, for critical components such as a ship propeller for generating a driving force, a broken propeller can endanger the passengers which is a serious safety issue. For this reason, a reliable measurement technique of cavitation intensity is required. In this paper, some significant results of studies that established a technique to measure cavitation intensity are briefly reviewed. The measurement techniques can be classified into two groups, i.e. direct and indirect measurements. For the indirect technique, a method which estimates the impact load of bubble collapse by inverse analysis is particularly elaborated. For the direct technique, a method which utilizes painting technique to quantify the actual CI is specifically presented. Discussion on the advantages and disadvantages of each technique is also provided. Thus, the suitable method should be selected depending on the application.

2. Method
Some important latest journal papers and patents related to the measurement technique of cavitation intensity are collected, studied, and then compared, in order to understand the advantageous and disadvantageous. Specifically, several literatures related to an indirect measurement technique using inverse analysis technique and a direct measurement technique using coating or painting materials are particularly selected to be discussed further in this paper.

3. Result and discussion
3.1. Indirect measurement techniques
Two common techniques known for measuring CI of turbomachinery are by the sound pressure and vibration level [4-7]. Figure 2 shows the typical schematic measurement apparatus. In sound pressure measurement, sensors, such as microphone or hydrophone, are placed in a proper position so that a valid
acoustic data from cavitation can be obtained [16]. In vibration measurement, piezoelectric transducers (accelerometers) are attached in several locations with different angles and directions to acquire vibration amplitudes caused by cavitation impact forces [4]. These two techniques are called as the indirect measurement method, which quantify the level of CI either in sound pressure unit or in vibration amplitude unit. However, these techniques cannot be used to quantify the actual CI value which generates erosion damage on the component’s surface. Moreover, by using this method, the exact location where cavitation load does occur inside the machinery cannot be detected. Therefore, these techniques are usually done together with a numerical simulation by using Computational Fluid Dynamics (CFD) software [6]. Thus, the actual value of CI and the damage location on the component can be predicted.

Recently, Ishii et al. [17] developed an indirect measurement technique which quantifies how large the impact force of bubble collapse on a solid boundary. Figure 3a describes the measurement system. Here, to clarify the micro-to-milli-scale impact phenomena of bubble collapse near to a solid boundary (surface), and to evaluate the damage of the solid boundary, impact loads from spark-generated bubble were estimated by inverse analysis. The experiments were conducted with polycarbonate cylinder, cast iron block, and pure aluminum plate, and impact loads and loading locations were inversely estimated with AE (Acoustic Emission) sensors. As a result of observing the phenomenon by a high-speed camera, impact loads were confirmed when shock waves hit the boundary, and it was found that a pressure of around 110 MPa was generated by a 10 mm diameter bubble. Figure 3b shows the sequence of bubbles generation until collapse captured by a high-speed camera [17].

3.2. Direct measurement techniques

To be able to quantify the actual value of CI, the impact force of collapsing cavitation bubbles can be measured using piezoelectric sensor as introduced by Soyama [18]. Meanwhile, Udo et al. [19] proposed a different approach which utilizes the erosion rate of a soft metal plate attached on the component’s surface that directly attack by the cavitation load. However, both techniques are difficult to be done especially for application in the field. The piezoelectric sensor is difficult to be used in the field because measurement of the impact forces from cavitation bubbles has to be done while the sensor is soaked inside the fluid. For this reason, modifications on the turbomachinery structure to insert the sensor as well as complicated sealing technique for cables installation must be considered carefully. Measurement of CI utilizing cavitation erosion characteristics of soft metal could be less difficult. However, the exact location of cavitation is usually unclear, thus deciding where to attach the soft metal plate would need some time. Moreover, this technique also requires relatively longer time to generate erosion on the soft metal. In addition, it might also need a 3D scanner to measure the volume loss of the soft metal plate due to cavitation erosion which makes it quite complicated for implementation in site.

![Figure 2. Schematic figure of cavitation intensity measurement by using sound.](image-url)
Figure 3. Schematic figure of measurement system of impact force of bubble collapse for inverse analysis (a) and observation result by high-speed camera of single bubble generation and collapsing process near solid boundary (b). The figures were adopted from Ishii et al. [17].

Figure 4. Measurement procedure of cavitation intensity using paint-erosion test technique [20].

A newly proposed technique to directly measure CI of turbomachinery is introduced by Triawan and Maeda [20]. Figure 4 shows the flow chart of CI measurement for application in pump. Instead of using piezoelectric sensor or soft metal plate as described previously, it utilizes the cavitation erosion behavior of coating/paint materials to quantify the level of impact force from cavitation bubble collapse. By this technique, the exact locations of severe CI on the impeller surface can be determined quickly and easily.
because the paint materials are made of polymer or non-metal material that is easy to get eroded. Thus, the actual value of cavitation intensity also can be quantified directly. Triawan et al. [13] reported that the paint erosion test could give a measurement deviation of below 30% compared to the reference data obtained from sound pressure measurement. However, the accuracy of this technique is strongly influenced by the combination of paint/coating materials. Moreover, a big database of relationship between erosion rate of materials and CI is necessary to use this technique. The database making should be done carefully by conducting cavitation tests of those explained in ASTM G32 and ASTM G134.

Summary of the advantageous and disadvantageous of each technique presented in this paper is provided in Table 1. For obtaining an accurate and correct value of CI, a combination of direct and indirect measurement techniques could be necessary.

### Table 1. Comparison of indirect and direct measurement techniques of cavitation intensity.

| Measurement Techniques          | Method         | Advantageous            | Disadvantageous                      |
|--------------------------------|----------------|-------------------------|--------------------------------------|
| Sound pressure                 | Indirect       | Practical in the field  | Less accurate                        |
| Cavitation length              | Indirect       | Practical in the field  | Less accurate                        |
| Vibration accelerations (       | Indirect       | Practical in the field  | Less accurate                        |
| including inverse analysis     |                |                         |                                      |
| Soft metal plate attached on   | Direct         | Accurate                | 3D scanner needed                    |
| surface                        |                |                         | Need longer time for erosion         |
| Piezoelectric (PVDF) sensor    | Direct         | Accurate                | Complicated cable installation       |
| Coating/Paint erosion          | Direct         | Accurate                | Could be disconnected or detached    |
|                                |                |                         | during measurement                   |
|                                |                |                         | Need extensive materials’ erosion    |
|                                |                |                         | rate database.                       |
|                                |                |                         | Depend on materials combination      |

### 4. Conclusion
In order to predict the lifetime of turbomachinery, cavitation intensity (CI) needs to be measured accurately and precisely. Various methods by direct and indirect techniques have been developed to measure cavitation intensity. Both methods have unique characteristics, in terms of its measurement procedures or the obtained results. A combination of these techniques should be considered carefully to obtain an accurate and correct CI value in a turbomachinery.

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