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Estimation of aggressive intensity of a cavitating jet with multiple experimental methods

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ABSTRACT

An experimental study on the cavitating jet was conducted with emphasis placed on the detection of the energy that is emitted by the collapse of cavitation bubble. Four experimental methods, each respectively utilizing a hydrophone, an acoustic emission (AE) sensor, a laser Doppler vibrometer, and a polyvinylidene fluoride (PVDF) sensor, were compared. Aluminum specimens served as the target that would endure the impact of the cavitating jet. The mass loss was measured and the cumulative erosion rate was calculated. Various upstream pressures were used, and the effect of the cavitation number was considered as well. The results indicated that the cumulative erosion rate becomes maximum with the increase in the erosion time, and it is insensitive to variations in upstream pressure. The time span that is required for the cumulative erosion rate to reach its maximum value becomes shorter for high upstream pressures. An overall increase in the normalized energy is evident as the upstream pressure increases. At any given upstream pressure, the normalized energy varies inversely with the threshold level. The optimum threshold levels were obtained separately for each of the four methods. The correlation between the maximum erosion rate and the normalized energy was established statistically. The PVDF sensor proved to be the most effective instrument in estimating the aggressive intensity of the cavitating jet.

1. Introduction

Cavitation erosion is an explicit manifestation of the cavitation effect, and has been witnessed in several engineering fields, such as in marine and chemical engineering. Of interest is the mechanism of cavitation erosion, which has been explored primarily under laboratory conditions. A useful tool for producing cavitation is the cavitating waterjet [1]. Provided that the operation parameters are properly set, the collapse of cavitation bubbles in the jet stream can enhance the fatigue strength of a material and thereby extends the lifetime of mechanical components [2,3]. The more common situation is cavitation erosion, a pattern of surface damage characterized by erosion pits, cracks, and even exfoliation on the target surface.

The experimental rig plays an important role in cavitating jet experiment. The ASTM G134 standard specifies the procedures and data processing strategies in cavitation erosion test with cavitating jet [4]. The evolution of cavitation is a typical dynamic process, in which intermediate steps last only for a very short time span. Thus tracing those transient phenomena pertinent to cavitation or cavitation erosion necessitates the use of instruments with high sensitivity. The technique of high speed photography enables the capturing of consecutive images of the cavitating jet, thus facilitating the extraction of the shedding frequency from the shrinking and expanding jet stream [5]. In the ambient water surrounding the jet stream, pressure fluctuations excited by the cavitating jet can be detected with sensitive pressure transducers [6]. The focus of these two techniques is usually placed on the cavitating jet itself instead of the cavitation erosion. The polyvinylidene fluoride (PVDF) sensor has been utilized to directly measure the shock impact imposed on the specimen that has been caused by the cavitation bubble collapse [7]. Moreover, acoustic methods have been attempted in cavitation detection [8,9]. Hitherto, the application of acoustic methods in this aspect has been limited to the investigation of ultrasonic cavitation and the cavitation phenomenon arising in mechanical components. Regarding the specimen that has been exposed to cavitation bubble collapse, its surface can be observed using three-dimensional optical microscopy, and a spatial resolution at a scale of micrometers can be accomplished [10]. The conventional mass loss weighing method is straightforward and effective; however, it requires a fairly long erosion time and repeated sampling to attain statistically stable results.

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Nomenclature

d	Nozzle throat diameter [mm]
E_A	Normalized acoustic energy
E_{AE}	Normalized acoustic emission energy
E_L	Normalized vibration energy
E_P	Normalized impact energy
E_R	Cumulative erosion rate [mg/min]
E_{Rmax}	Threshold level of impact force [N]
F_{th}	Threshold level of impact force [N]
P_{th}	Threshold level of acoustic pressure [Pa]
p_d	Downstream pressure [Pa]
p_u	Upstream pressure [Pa]
p_v	Saturated vapor pressure [Pa]
R	Correlation coefficient
s	Standoff distance [mm]
s_{opt}	Optimum standoff distance [mm]
t	Erosion time [min]
V_{th}	Threshold level of voltage [V]
V_{Lth}	Threshold level of vibration velocity [m/s]
Δm	mass loss [mg]
σ	Cavitation number

The majority of previous works on cavitation erosion have placed the emphasis on the material capability of resisting the cavitation erosion [11]. In this aspect, several experiments have been repeatedly conducted to validate and generalize the obtained relationship. Nevertheless, the assessment of the performance of the cavitation-producing system has rarely been reported. Physical quantities, such as the mass loss, erosion pit size, and local heights in the specimen surface, have been overwhelmingly associated with materials [12,13]. Although the adjustment of operation parameters such as jet pressure and standoff distance has been attempted to achieve more favorable cavitation erosion results, the method for predicting the working capability of cavitating jet has not been established yet [14]. The difficulty encountered in devising such a method is appreciable since it is expected to combine the material erosion data with the impact of the cavitation bubble collapse. Essentially, such a method signifies a penetration into the cavitation erosion mechanism.

The purpose of the present study is to assess the aggressive intensity of the cavitating jet via experimental techniques. Based on a standard cavitating jet experimental rig, four methods were used to detect the energy emitted by the cavitation bubble collapse. Accordingly, four instruments, namely a hydrophone, an acoustic emission sensor, a laser Doppler vibrometer, and a PVDF sensor were used. Signal processing was performed with the introduction of the threshold level. Different types of energy emitted in cavitation erosion were anticipated to be obtained. During the experiment, the upstream pressure was varied and the influence of the erosion time was taken into account. The mass loss was measured and the cumulative erosion rate was calculated. The statistical correlation between the energy and the cumulative erosion rate will be established. This study throws light on experimental methods for evaluating the working capability of the cavitating jet. Moreover, a reliable strategy will be constructed for detecting the energy released in cavitation bubble collapse.

2. Experimental facilities and procedures

The experiments were performed in the Intelligent Sensing of Materials laboratory of Tohoku University. The cavitating jet experimental rig conformed to the ASTM G134 standard and is schematically shown in Fig. 1. The nozzle throat diameter, d, is 0.4 mm. During the experiment, the chamber was filled with water; hence, the specimen was completely submerged in water. The temperature of the medium circulating in the experimental loop was controlled at 25 ± 2 °C through the chiller, which is connected with Tank B, as shown in Fig. 1. The specimens were made of aluminum (JIS A1070) and the diameter of the specimens was 50 mm. There was a remarkable difference among the results of cavitation erosion obtained from different materials under identical operation conditions [15]. However, discussions on material properties are beyond the scope of the present study.

Four instruments, namely a hydrophone, an acoustic emission (AE) sensor, a laser Doppler vibrometer and a PVDF sensor, were utilized separately to detect the energy emitted by the cavitation bubble collapse. In this context, the instruments and the corresponding type of energy to be detected are listed in Table 1. The experimental conditions were maintained identical in each of the four methods.

2.1. Hydrophone

Sound is essentially a pressure wave that is created by a vibrating object. The microphone or hydrophone can capture and visualize sound signals by converting them into electrical signals. More specifically, high sensitivity can be achieved with a hydrophone, which is normally equipped with a piezoelectric transducer. Recently, the hydrophone has been successfully used to detect ultrasonic cavitation [16]. Nevertheless, in terms of detecting cavitating jet, the application of the hydrophone has rarely been reported.

In the present study, the B&K 8013 hydrophone was employed and the measurement system is schematically shown in Fig. 2. As can be seen, the hydrophone is suspended outside the test section to receive the sound wave emitted from the cavitating jet. The position of the hydrophone is set at the same height as that of the axis of the test section window, and the horizontal distance between the sensor and the nearest window side is 100 mm. The window was made of clear acrylic resin and is 15.0 mm in thickness. The voltage sensitivity was 26.4 μV/Pa and the detectable frequencies ranged from 4 to 200 kHz. The acoustic pressure was converted to voltage signals by 0.1 V/Pa via a preamplifier. The entire experimental system was placed in a sound-proof room to avoid interference from environmental noise.

2.2. Acoustic emission sensor

Acoustic emission is a phenomenon of elastic wave propagation within the material, which occurs when the material is subjected to external loads or undergoes irreversible structural change. As the accumulated elastic energy in the material or in the surface is released instantaneously, small surface displacement of the material occurs. In this context, shock waves due to cavitation bubble collapse approach

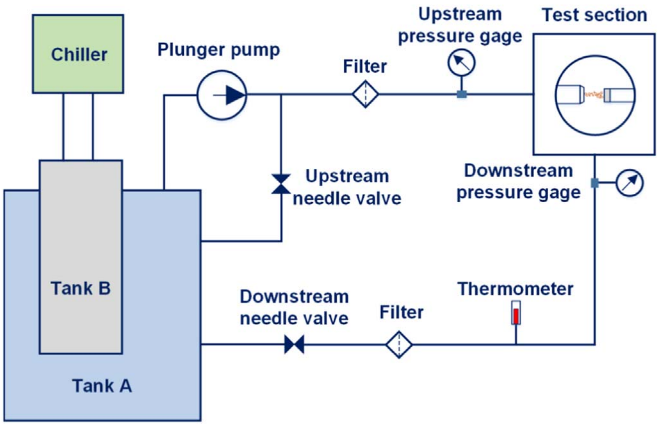

Fig. 1. Schematic of the cavitating jet experimental rig.