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An Experimental Study to Investigate Cavitation Noise and Erosion Characteristics, Using Water Jet Test Technique

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ABSTRACT

This paper presents results of a systematic experimental study into the effects of cavitation formation on noise and erosion characteristics, using a water jet (cavitating jet) test rig. Within this respect, the main objective of the study is to enhance the understanding of the cavitation phenomenon by conducting detailed water jet tests and investigate the relation between noise level and cavitation erosion rate. The investigation of the cavitation erosion was carried out using Cu1 (manganese-bronze) propeller material, according to ASTM G-134 standards; while the noise measurements were conducted following ITTC (1978) procedure. The tests were performed for different operating conditions and the effect of cavitation number on noise characteristics and erosion rate were examined. In this matter, the cavitation erosion tests were conducted for different cavitation numbers. Background noise due to main and auxiliary pumps inside the chamber was tried to identify. The cavitation erosion rate, which is a function of mass loss per time, was used as an indicator to evaluate the erosion damage on the material. The surfaces of the tested samples were examined by a 3D optical profilometer instrument and maximum pitting depths on the damaged surfaces over time were obtained. The results of the systematic experiments have shown that the formation of cavitation by water jets were both highly erosive and a dominant source of cavitation noise. Cavitation number was found to have the influence not only on the erosion rate but also on the level of noise. It was detected that the erosion rate become more pronounced with increasing testing duration. Besides, both erosion rate and noise level were more pronounced with decreasing cavitation number. Despite certain limitations, simultaneous investigations of noise and erosion within this study offers a significant insight into the nature of cavitation-dominated noise and cavitation erosion. The ultimate aim of the study is try to explore the similarity of the cavitation erosion and noise level between water jet tests and cavitation tunnel experiments for marine propellers.

Keywords

Water jet rig; cavitation noise; cavitation erosion test; ASTM G-134 standards.

1 INTRODUCTION

Cavitation is a general fluid mechanics phenomenon that can occur whenever a liquid is used in a machine and it usually considered as harmful and undesirable for hydraulic systems (Carlton, 2007).

Cavitation is described by the formation of vapour bubbles, which appear within the flow due to the local pressure dropping below the vapour pressure of the working fluid. These formed bubbles at some point become unstable and collapse within the flow. The instabilities that occur due to bubble formation, oscillation and collapse can result in negative effects such as noise, vibration, performance drop and structural damage (erosion) to any surface that is close to the collapsing bubbles.

Unsteady and violent form of the cavitation bubbles, which collapse in the vicinity of a surface, are considered to be the most aggressive kinds and perhaps the most detrimental result of the cavitation (Peters et al., 2018). Thus, the cavitation erosion is the major problem confronting designers and users of high-speed hydrodynamic systems. It occurs mostly in fluid-flow machinery, for example pumps, water turbines, marine propellers, also in devices in the chemical and petrochemical industries, in diesel engines and pipelines. Many researchers have been investigated this problem to clarify the incipient condition to understand the erosion mechanism or develop a new material which is stronger for resisting to the cavitation erosion (Usta et al., 2018).

Oscillating cavitation bubbles represent a source of intensive pressure waves. As these waves have a random character, they are called cavitation noise. Cavitation noise is carrying information about the oscillating bubbles (Lauterborn and Cramer, 1981).

For ships, quantifying the underwater radiated noise (URN) is not a simple process because ships are installed with many types of machinery, causing different noise and vibration levels (Turkmen et al., 2017). However, when the ship is operating, URN can be contributed and dominated by propeller blades, especially when cavitation occurs (Sasajima et al., 1986). The noise formation process in the water jet (cavitating jet) tests is similar to the ships from this point of view. Because, the noise sources of the water jet system are composed of the machines in the system (high pressure pump, auxiliary pump) and the cavitation noise which can be considered to be underwater radiated noise (URN). With this perspective, URN can be considered as dominating noise of the water jet system. One of the aims of this paper is to investigate whether the noise is a dominant noise component measured by the water jet technique or not.

Cavitation tests on a model-scale are normally carried out in traditional cavitation tunnels or less frequently using depressurised towing tanks according to guidelines and procedures reported by the ITTC (2011). On the other hand, cavitation erosion testing in water jet test rigs is usually conducted by using smaller samples according to ASTM standards. The stipulated tests are ASTM G32, the "Standard test method for cavitation erosion using vibratory apparatus" and ASTM G134 "Standard test method for erosion of solid materials by cavitating liquid jet" (Annual Book of ASTM Standards, 2010). The latter technique is the subject of this study.

The effect of cavitation dynamics on noise and erosion are rather complex to understand and investigate. Within this framework, the main aim of the present study is to enhance the understanding of the cavitation noise and erosion by conducting detailed systematic water jet tests to investigate the effect of cavitation number and operating conditions and to scrutinize the relation between cavitation noise and cavitation erosion by water jet technique.

Within the above context, this paper is structured to contain six sections. Following the introduction, section 2 gives some information about the water jet technique – ASTM G134. Section 3 presents the description of the cavitation noise and erosion tests using the water jet rig. Cavitation erosion investigation and noise measurements on Cu1 (Manganese-Bronze) propeller material samples for three different cavitation number conditions are explained in Section 4 and Section 5, respectively. Finally, Section 6 presents the main conclusions obtained from the study.

2 WATER JET TEST TECHNİQUE – ASTM G134

Water jet test technique have been used to investigate the cavitation erosion in a controlled environment and in an accelerated manner (Choi et al., 2012). By conducting the water jet tests, it is aimed to damage (erode) the sample within a required short time period whereas in the real field cavitation erosion is expected to occur after a long duration of exposure.

Cavitation erosion tests should be carried out according to certain standards in order to have scientific validity and to be reproducible. The ASTM established standard methods using specific conditions under the G134 and G32 (ASTM G32, 2010; ASTM G134, 2010; Kim et al., 2014).The ultrasonic technique (ASTM, G32, 2010) and the water jet technique (ASTM G134, 2010) are the two most popular laboratory techniques for testing cavitation erosion characteristics of materials.

The idea of using a water jet for an erosion test was first proposed and implemented by Lichtarowicz (1972). Yamaguchi and Shimizu (1987), Soyama et al., (1988) and Momma (1991) have contributed to involvement of the method's in the literature with their successful studies of testing mechanisms and applications. Later, many researchers have used the water jet technique to study the resistance of various materials to the cavitation erosion (Momma and Lichtarowicz, 1995; Soyama and Asahara, 1999; Soyama and Kumano, 2002; Soyama, 2005; Choi et al, 2012; Franc et al, 2012; Soyama, 2013; Hutli et al, 2016; Li et al. 2017; Hutli et al., 2018; Peng et al., 2018, Kang et al, 2018).

The great advantage of cavitation erosion testing by the use of water jet rig is that the cavitating jet apparatus can simulate different cavitating conditions. Cavitation intensity produced by waters can be varied in a wide range through the adjustment of the jet velocity, nozzle geometry (diameter), the jet angle, the stand-off distance and the ambient pressure in which they are discharged (Kim et al, 2014). This flexibility makes a cavitating jet a useful research and testing tool to study parametrically the effect of these variables on the material behaviour. The cavitation generated by a cavitating jet provides realistic cavitation bubble clouds with distribution of various size micro bubbles, shear flows with vortices, and dense bubble clouds, which collapse on the sample. With the control of the operating pressure (cavitation number), the jet angle and the stand-off distance, the testing time can be adjusted to provide either quick erosion for initial screening or time-accelerated erosion more relevant to the real flows (Choi et al., 2012).

To briefly describe the method, cavitation erosion is formed on the sample by spraying high pressure water from the nozzle to the sample where the nozzle and the sample are placed in a cavitation chamber filled with liquid. Tests are carried out under specified pressure and temperature conditions, using generally tap water.

2.1 General Testing Procedure and Test Rig Properties

The test rig satisfies the following requirements to carry out the cavitation erosion experiments:

• To supply a steady flow of liquid at sufficiently high pressure and flow rate to produce a cavitating jet with a wide range of pressure levels.

• To control and measure both the upstream and the downstream pressures.

• To vary and measure the nozzle characteristics (especially the diameter).

• To control and measure the fluid temperature.

• To vary and measure the stand-off distance from the nozzle to the target surface.

• To control test duration of a cavitating jet even for a few seconds.

• To take the photographs and videos of cavitating jet from a wide range of angles.

3 CAVITATION NOISE AND EROSION TESTS WITH WATER JET TECHNIQUE

To obtain cavitation noise and erosion data, high-pressure water jet (cavitating jet) tests were conducted using the water jet test rig, which has been established in accordance with ASTM G134 standards in Ata Nutku Ship Model Testing Laboratory at Istanbul Technical University.

Water jet method is used in this study in order to study the effects of cavitation on a propeller material, Cu1 in the laboratory by inducing cavitating jets.

The usual test procedure was to expose the sample to cavitation for a selected period of time, interrupt the test, remove the sample and record weight to enable calculation of weight loss as a function of time. In this study, we also measured other characteristics such as surface roughness characteristics and maximum erosion depth by optical profilometer. Besides, took photographs of the evolution of the eroded region.

3.1 Test Rig and Experimental Procedures

Cavitation formation was basically achieved by the maintenance of a high pressure difference in the cavitation chamber (test chamber) which would house a nozzle with a specific diameter and also a sample which would facing the nozzle so as to have the bubbles issuing from the nozzle collapse on it. A liquid must also be present inside the test chamber and could either be allowed to run to waste or by having the liquid recirculated by adding a reservoir and a pump to the set-up.

Water jet test rig scheme is presented in Figure 1.

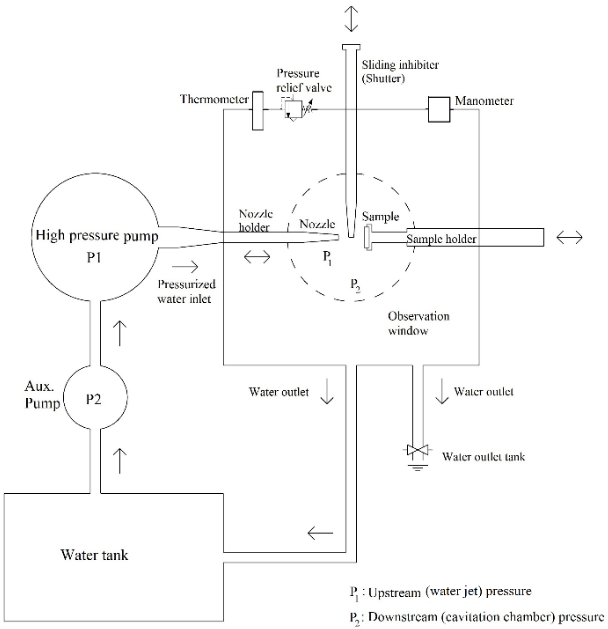


Figure 1 Water jet test rig scheme

A high-pressure plunger pump which can provide 344 bars (5000 psi) pressure with 20 lt/min of water pumping capacity was used to pump the water to the inside of the cavitation chamber. This pump is called as P1. Because the P1 is a one directional pump, an auxiliary pump (P2) that delivers water to the P1 at a flow rate of 20 lt/min was used.

The cavitation chamber in which the tests were carried out is a cylindrical chamber with a diameter of 225 mm and a length of 260 mm covered with two plexi-glass window with thickness of 30 mm. There is a nozzle at which water is sprayed at different speeds, a nozzle holder and the sample holder for holding the sample inside the chamber. The other elements of the water jet tests assembly are the pressure relief valve for adjusting the pressure inside the cavitation chamber, the pressure gauge for monitoring the pressure, the thermometer to control temperature, the shutter functioning as a barrier between the nozzle and the sample named shutter. In addition, the test system consists of a water tank with a capacity of 200 lt.

During the cavitation erosion tests, the upstream pressure (water jet pressure) P_1, and the downstream pressure (the pressure inside the chamber) P_2 were measured and varied by adjusting a valve.

The cavitation chamber and hydrophone location during the tests are presented in Figure 2 and Figure 3, respectively.

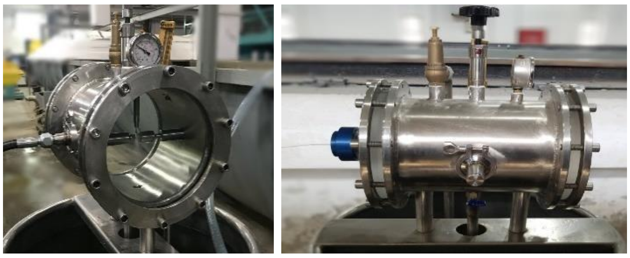


Figure 2 The cavitation chamber

The stand-off distance (S_{off}), is defined as the distance from the inlet edge of the nozzle to the target surface. The position of the high-pressure inlet pipe with a nozzle at its end and the target holder tube were both adjustable along their common axis. This enabled to adjust their locations inside the chamber as well as to change the stand-off distance between the nozzle and the sample surface.

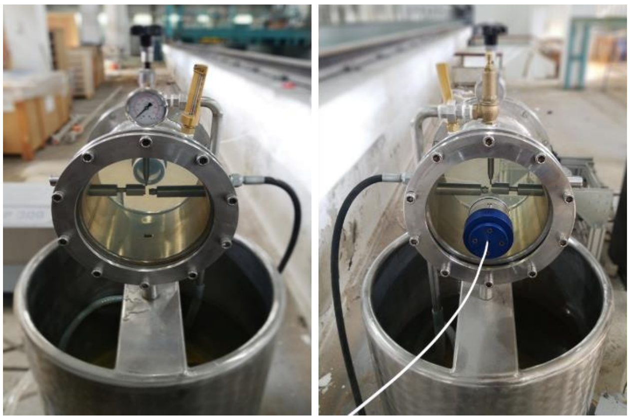


Figure 3 The water jet test rig and hydrophone location during the tests

Time duration of the tests was precisely controlled by a shutter mechanism. Before starting the stopwatch, the shutter was off positioned. When all the conditions were stable, in other words when the water jet pressure and the pressure inside the chamber are stable, the shutter was opened and stopwatch was started. The mass of each sample were measured before and after each erosion test, and mass loss, Δm, was defined as the difference between the two values. The samples were measured on an electronic balance with a precision of ± 0.01 mg.

The samples tested in each test, were stored in a desiccator in a non-humid environment with no moisture. Thus, it was ensured that no condition affected the samples until the surface analysis with the optical profilometer.

3.2 Cavitation Observations

Since the extent, volume, density and dynamics of the cavitation play a major role in contributing to the URN levels, this section summarizes the cavitation observations made from the cavitation chamber through the plexi-glass windows. Cavitation formation observed in the water jet tests for three different cavitation number conditions are shown in Figure 4. The water test conditions are presented in Table 1.

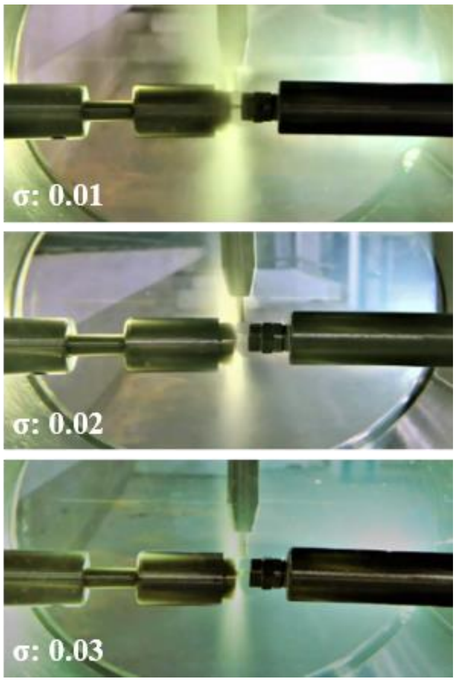


Figure 4 Cavitating jet tests for σ = 0.01, 0.02 and 0.03 (P_1=250 bar)

As seen from the photos that were taken during the cavitating jet tests, cavitation formation is the highest when the cavitation number is the smallest qualitatively. This may lead to that the erosion formation will be greater and the noise will be higher for smaller cavitation number.

4 CAVITATION EROSION INVESTIGATION ON CU1 SAMPLES

4.1 Determination of the Test Conditions

When the studies of the four different research groups (Momma, 1991; Soyama and Asahara, 1999 and 2002; Choi et al, 2012; Hutli et al, 2018) and the ASTM G-134 standards (ASTM, 2010) were reviewed, it was decided that the water jet pressure in the tests should be in the range of 200-300 bar.

In the cavitation erosion tests, the effect of 3 different cavitation numbers on the cavitation erosion rate was investigated. The tests were carried out for 30, 60 and 90 minutes each with a water jet pressure of 250 bar and the chamber pressure of 2.5, 5 and 7.5 bar corresponding to the cavitation number of 0.01, 0.02, 0.03 and 1.4 mm diameter nozzle was used and the water temperature was 27 (±3) °C during the tests (Table 1).

Table 1 Main conditions of water jet tests

Material	Cu1(Mn-Br)
t (min)	30, 60, 90
P_2 (bar)	2.5, 5, 7.5
P_1 (bar)	250
Cavitation number, σ	0.01, 0.02, 0.03
Flow rate (lt/min)	20
S_{off} distance (mm)	5
D_{nozzle} (mm)	1.4
Water temperature	27 (± 3) ° C

Cavitation number in water jet tests was defined by Lichtarowicz (1979) as follows:

For $P_v << P_1$ and $P_v << P_2$;

$$\sigma = \frac{P_{downstream}}{P_{upstream}} = \frac{P_{chamber}}{P_{water\ jet}} = \frac{P_2}{P_1} \qquad (1)$$

The test samples used in cavitation erosion tests were manufactured of propeller material, Cu1 (manganese-bronze) alloys. They had 20 mm diameter and 10 mm cylinder height (Figure 7). The samples were manufactured and polished, respectively, and finally mechanically polished to mirror like surface before the cavitation erosion tests.

4.2 Cavitation Erosion Rate and Erosion Intensity Prediction Methods

The erosion rate can be used to compare the resistances of different materials to cavitation erosion. The erosion rate is a characteristic value of the resistance of a material to erosion and the erosion rate of each material will be different (Soyama and Kumano, 2002). Momma and Lichtarowicz (1995) defined the erosion rate as;

$$\text{Erosion rate (ER)} = \frac{\text{weight loss (gr)}}{\text{test duration (min)}} = \frac{\Delta m}{\Delta t} \qquad (2)$$

where Δm and Δt are the total (cumulative) mass loss and the total cavitation exposure time, respectively. Therefore using the weight loss method (Momma, 1991; Momma and Lichtarowicz, 1995), the erosion rates were calculated in the study.

The second method to compare different materials with regards to resistance to cavitation erosion is erosion intensity. Mottyll and Skoda (2016) used the highest erosion depth on the tested sample by the time as the erosion intensity, given as below:

$$\text{Erosion intensity (EI)} = \frac{\text{highest erosion depth (}\mu\text{m)}}{\text{test duration (min)}} = \frac{h_{max}}{\Delta t} \qquad (3)$$

In this study, the highest erosion depth on the tested sample surface was determined by the optical profilometer.

As the test duration were 30 minutes in all tests, the highest erosion depths occurred on the surface was taken as the erosion rate in this study.

4.3 Cavitation Erosion Test Results

Cavitation erosion test results of Cu1 samples for three different cavitation number conditions, for 30, 60 and 90 minutes are presented below. Figures 5 and 6 show the erosion rate and erosion intensity values by test durations of 30, 60 and 90 minutes for the Cu1 samples corresponding to 3 different cavitation numbers, respectively. When the results are compared, the erosion rate and intensity are the highest when the cavitation number is the smallest (σ=0.01).

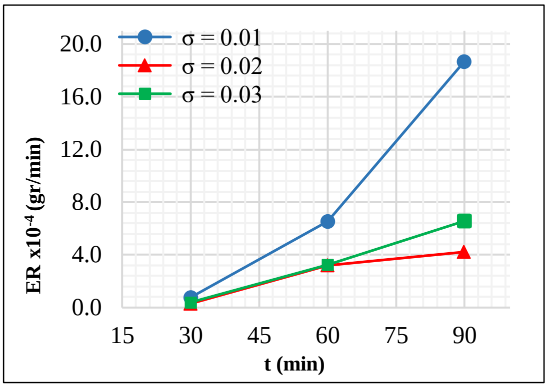


Figure 5 Water jet test results of erosion rate change with time (σ=0.01, 0.02 and 0.03)

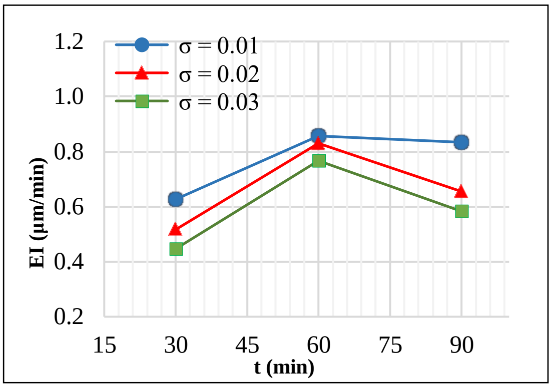


Figure 6 Water jet test results of erosion intensity change with time (σ=0.01, 0.02 and 0.03)

The result deduced from the cavitation erosion tests is that erosion intensity always increases as the cavitation number decreases. As far as the time duration of test is concerned, the erosion rate increases as the time increases. However, it is not the case for the erosion rate at 90 minutes test duration at the all cavitation numbers.

Figure 7 shows the results of the erosion test for the Cu1 samples in three different cavitation numbers and three different test periods, respectively. The first line represents the results for test durations of 30 minutes, the second line represents the results of 60 minutes and the third line represents the results of 90 minutes. The first column represents σ=0.01, the second column represents σ=0.02, and the third column represents the results of the σ=0.03.

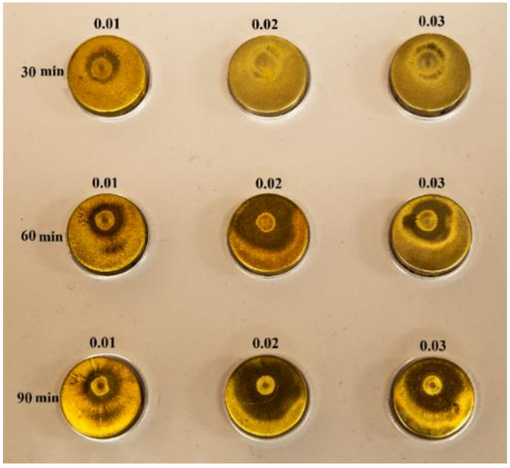


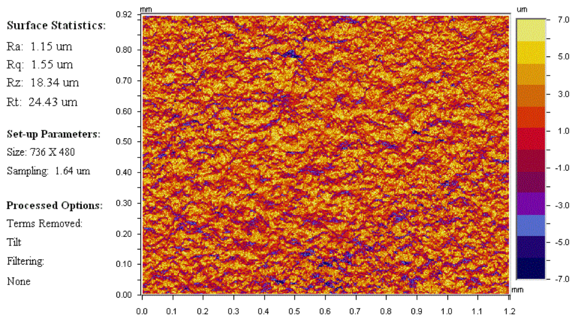
Figure 7 Photos of the samples tested in different conditions

The samples used in the tests are in gold colour. The black regions show the eroded parts of the tested samples. When the photos are investigated, it is seen that the eroded area increases if the test duration increases.

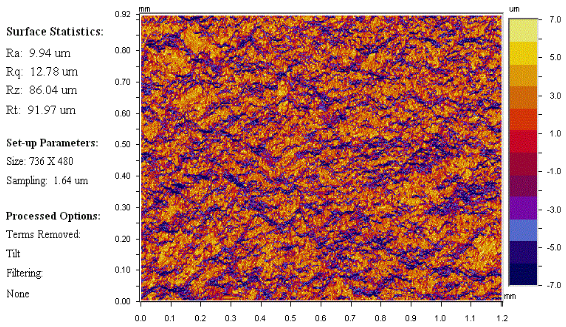
The erosion rate and the erosion intensity results are obtained the highest, when the cavitation number is the smallest (σ=0.01). However, it is not the case at σ=0.01, hence the area of the eroded region is not the largest for σ=0.01. As a result, smaller cavitation number does not always generate larger eroded area. In other perspective, higher erosion rate or higher erosion intensity does not always mean larger eroded region area in these tested samples (material).

After each test, the surfaces of the tested samples were examined by a 3D optical profilometer. Roughness characteristics (Ra, Rq, Rz and Rt) and maximum pitting depths on the damaged surfaces were obtained.

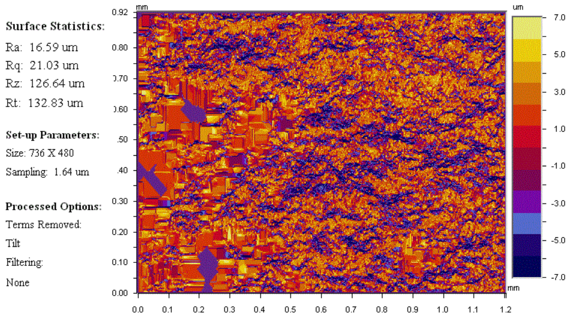
Optical profilometer analysis of the Cu1 samples for 30, 60 and 90 minutes test durations under σ = 0.02 condition are presented in Figure 8. Where, Ra represents the arithmetic average roughness, Rq represents the root mean square roughness, Rz is the average peak-to-valley height and Rt is the distance between the highest asperity (peak or summit) and the lowest valley. The legend scale was arranged to be ±7 μm for the analysis. The straw yellow colour represents +7 μm, while the black colour represents -7 μm in Figure 8.



(a)



(b)



(c)

Figure 8 Optical profilometer analysis of the tested sample surfaces at σ = 0.02 condition. (a) t = 30 mins., (b) t = 60 mins. and (c) t = 90 mins.

Based on the surface measurement results, one may conclude that as the test duration increases, the eroded region (darker colour parts on the figures) increases, as expected. It is valid for all the examined surface roughness parameters (Ra, Rq, Rz and Rt). The roughness analysis for the cavitation numbers of σ=0.01 and σ=0.03 using optical profilometer were also conducted. Roughness characteristics are found similar trend with the σ=0.02. As the test duration increases, surface roughness parameters also increase for σ=0.01 and σ=0.03.

5 CAVITATION NOISE TESTS

During the noise measurements the nozzle pressure (P_1) was kept constant and different cavitation numbers were obtained by varying the chamber pressure (P_2), given in Table 1. The noise sources of the water jet test rig system is composed of the noise of high-pressure pump (P1), auxiliary pump (P2) and the cavitation noise inside the chamber. The auxiliary pump (P2) supplied constant flow rate of 20 lt/min during the noise measurements, whilst the pressure level of the main pump (P1) was fixed to 250 bars as same as the cavitation erosion experiments. In this study noise of the pumps were considered as the background noise.

Acoustic measurements are expressed using the unit of “decibel”, which is a description of a logarithmic ratio of an actual measurement and a predefined reference value (Hildebrand, 2009). The use of the decibel unit simplifies the understanding of the large variations experienced in the measurements.

The measurements were recorded using a Bruel and Kjaer type 8103 miniature hydrophone mounted in a water filled, thick walled, plexiglass cylinder placed on a 15 mm thick plexiglass window at a horizontal distance of 0.150 m from the centerline of the experimental setup (Figure 3). The signals from the hydrophone were collected by further Bruel and Kjaer equipment, in this case a PC based ‘Pulse’ digital acquisition and analysis system up to a frequency of 20 kHz.

In order to reduce the measured values of Sound Pressure Levels (SPL) in each one-third octave band to an equivalent 1 Hz bandwidth a correction formula recommended by ITTC (1978) was implemented, as follows.

$$SPL_1 = SPL_m - 10\log\Delta f$$

where SPL_1 is the reduced sound pressure level to 1 Hz band width in dB; re 1 μPa, SPL_m is the measured sound pressure level at each centre frequency in dB; re1 μPa and Δf is the band width for each one-third octave band filter in Hz (Korkut and Atlar, 2012). The ITTC also required that the sound pressure levels be corrected to a standard measuring distance of 1 m using the following relationship.

$$SPL = SPL_1 + 20\log(r)$$

where SPL is the equivalent 1 Hz at 1 m distance sound pressure level (in dB; re 1 μPa) and r is the vertical reference distance for which the noise level was measured (r=0.150 m).

5.2 Cavitation Noise Test Results

Total and background noise levels are presented in Figure 9 for σ= 0.01, 0.02 and 0.03.

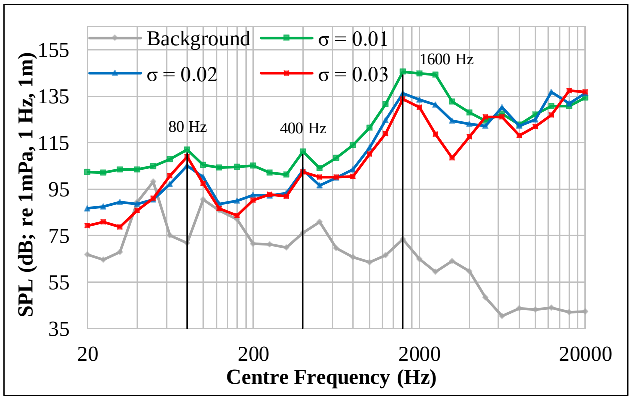


Figure 9 Total and background noise levels of tested sample at σ = 0.01, 0.02 and 0.03

The results of the experiments proves that the noise level of the system directly related with cavitation number by considering the general characteristics and the peak values of the measurements. It is interesting to figure out that under cavitation conditions there are some peak frequencies (harmonics) are observed at 80 Hz, 400 Hz and 1600 Hz. However it is not the case for the background noise spectrum, which requires further more detailed investigation.

In the present study, the correlation between the peak levels of noise, cavitation erosion intensity and cavitation erosion rate at different cavitation numbers were investigated. The Figure 10 shows cavitation erosion rate and total noise variations for different cavitation numbers and Figure 11 shows cavitation erosion intensity and total noise variation for different cavitation numbers.

As a result of the measurements, the trends of the peak level of noise and cavitation erosion intensity (EI) were compatible for all cases (Figure 11), whilst the trends of cavitation erosion rate (ER) differed for the peak level of noise and cavitation intensity (Figure 10). As far as noise increase due to cavitation development is concerned, the noise increase between the smallest cavitation number ($\sigma = 0.01$) and the medium cavitation number ($\sigma = 0.02$) is greater than that of between the highest ($\sigma = 0.03$) and the medium one. This dramatic increase in the noise levels may be related to well developed cavitation.

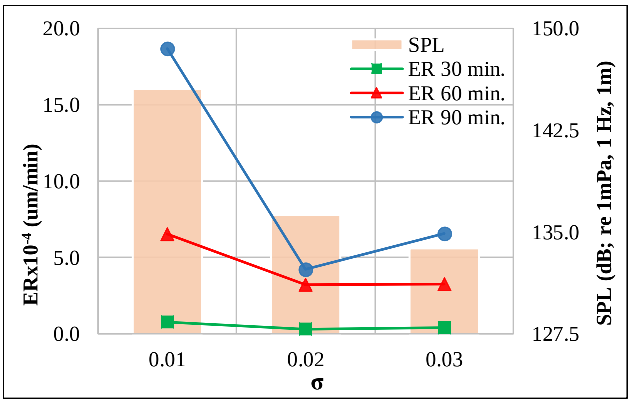


Figure 10 Cavitation erosion rate and total noise variation with cavitation number

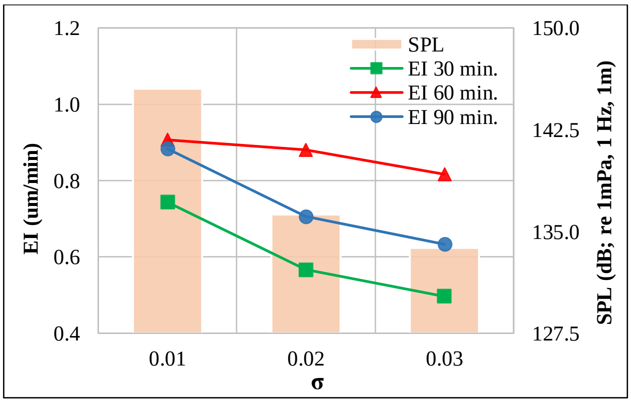


Figure 11 Cavitation erosion intensity and total noise variation with cavitation number

6 CONCLUSIONS

A comparative study was performed to investigate the effect of different cavitating flow conditions, i.e. different cavitation numbers on noise and erosion by water jet technique. The results of the systematic tests have shown that the formation of cavitation by water jets were both highly erosive and a dominant source of cavitation noise.

The general conclusions below are drawn from the study:

- Water jet (cavitating jet) test technique is a convenient way to investigate the effect of cavitating flow conditions.
- The visualizations of the cavitation formation show that the cavitation number has a strong influence on the cavitation intensity (aggressiveness) and on the distribution and strength of the bubbles in the cavitation chamber.
- Cavitation number was found to have an influence not only on the erosion rate and erosion intensity, but also on the level of noise. As the cavitation number decreases erosion intensity and noise level also increase. However, erosion rate may not increase.
- As the test duration increases, erosion rate also increases. However, this correlation is not valid for the test duration and erosion intensity. The erosion intensity increases until a certain test period, and then it decreases.
- As the test duration increases, eroded area on the sample also increases. However, no correlation obtained, between the eroded area on the tested sample and cavitation number.
- Performing water jet test is a rather simple and cheap way to investigate the cavitation erosion resistance of different materials comparing the cavitation tunnel tests.
- Despite certain limitations, simultaneous investigations of noise and erosion within this study offers a significant insight into the nature of cavitation-dominated noise and cavitation erosion.
- In further research of the authors, the ultimate aim of the study is to explore the similarity of the cavitation erosion and noise level between water jet tests and cavitation tunnel experiments for marine propellers.

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