Experimental and theoretical analysis on chamber pressure of a self-resonating cavitation waterjet

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\textbf{A B S T R A C T}

Self-resonating cavitation waterjets (SRCW) offer the advantages of both cavitation jets and pulsed jets, and thus have been used in a broad array of practical and industrial applications. Pressure oscillations in the SRCW chamber are closely related to the resonating mechanism and the cavitation inception, and experiments focusing on the chamber pressure were conducted under various pressure drops and inspiratory methods. Hilbert-Huang transform (HHT) combined with empirical mode decomposition (EMD) were able to filter the undesired signals and provide a better frequency definition. Based on the experimental results, the bubble cluster accounts for the energy fluctuation and should be considered in frequency prediction. A modified model was proposed based on the combination of fluidic networks and the Gas-Spring Theory and in accordance with the frequency variation under various pressure drops. When air was introduced, the frequency characteristics is attributed to the unsteady motion of the mixture flow, in which the water and the bubble cluster appeared alternately.

1. Introduction

Waterjet technology, known as a non-thermal and environmentally-friendly machining method, has been applied in a wide range of industries including cutting (Hsu et al., 2013), conveying (Xiao et al., 2015; Long et al., 2016), mining (Liu et al., 2016), surface treatment (Soyama, 2007) and etc. With the booming ocean industry and the prevalence of large-scale exploitation platforms, waterjet technology has also been introduced in both the deep sea and offshore exploration. For instance, Kohan et al. (2015) investigated a jetting system to move the self-elevating mobile jack-ups units, which is employed for offshore exploration and development purposes. However, the erosion effect of waterjet reduces drastically due to the high confining pressure and shock excitation underwater. As a result, advanced waterjet technologies such as pulsed waterjets and cavitation waterjets are introduced to improve the jet performance. Self-resonating cavitation waterjets (SRCW) are an integration of pulsed waterjets and cavitation waterjets. SRCW not only combine the advantages of both cavitation waterjets and pulsed waterjets, but also possesses two unique merits: (1) they can produce effective pulsed waterjet without using any moving parts in the supply system; (2) they can significantly increase the cavitation inception number (Chahine and Johnson, 1985). These two merits guarantee the durability and reliability of SRCW in harsh working environments (like deep-sea mining and clay cleaning). As a result, SRCW have been the subject of relatively intense studies.

Several SRCW nozzle design concepts were developed (Johnson et al., 1982 a,b and c); “ORGAN-PIPE”, “PULSER” and “PULSER-FED”. The Organ-pipe nozzle was the simplest one and used for the deep-hole rock cutting, and demonstrated its ability to substantially outperform conventional nozzle. (Chahine et al., 1983, Chahine and Courbiere 1986, 1995; Li et al., 2005, 2009). Further study focusing on the effects of area discontinuity and inner surface on SRCW was achieved by Li (2016a,b). Stronger jet modulations were achieved in “PULSER” and “PULSER-FED”, which were consisted of the Organ-pipe and the Helmholtz resonator. However, the “PULSER” was strictly limited by its structural parameters, and the “PULSER-FED” suffers from the excessive energy loss...
These pioneering studies have paved a way for the research on the Helmholtz resonator. Liao and Tang (1987) optimized the shape of impinging edge based on equations of disturbance wave and two-dimension vortex and found that the conical impinging edge with an angle of \(120^\circ\) (Fig. 1) outperformed other nozzles. Based on the acoustically tuned mechanism, Li et al. (2000) analogized the SRCW nozzle to the electric circuit and calculated the oscillation frequency, which was in accordance with some experimental results in the high pressure-low flowrate (HPLF) condition. In addition to the acoustic modulation, Liao and Tang (1989) also concluded that the vapor around the bulk flow acts as an accumulator due to its compressibility. This theory, termed the Gas-Spring Theory, contributes to the low-frequency oscillation in the low pressure-high flowrate (LPHF) condition. The inspiratory SRCW was proposed and developed by Gao et al. (2012) based on the negative pressure zone in the chamber. In their field experiments (Liu, 2015), the inspiratory SRCW was adopted in clay cleaning in the underwater condition, and achieved preferably results. The effects of compressible gas on the oscillation frequency were investigated by Hu et al. (2014) and Liu et al. (2017).

In spite of such rewarding developments, there is still a relevant degree of uncertainty in the design stage arising from the lack of reliable methods for predicting the eigen frequency, especially for the LPHF nozzle and inspiratory nozzle. Due to the synergism of jet instabilities and the Helmholtz resonance, the oscillation amplitudes of SRCW are typically nonlinear (Rockwell and Naudascher, 1978). The cavitation also has effects on the modulating mechanism (Johnson et al., 1981), as well as entrained air. As a result, the oscillation signals are non-linear and non-stationary. Moreover, there are several electronic signals which act as noises should be filtered in the experimental situations. To the best of our knowledge, there is rather limited study which mentioned the signals filtering in order to select the real signals caused by the oscillation. It is reasonable to filter and transform properly these nonstationary and nonlinear characteristics with a new method.

In the present work, to have a better understanding of oscillation mechanism of \(120^\circ\)-LPHF nozzle, experiments with three air inspiratory methods were conducted: no-inspiratory air, self-inspiratory air (driven by negative pressure in the chamber) and forced-inspiratory air (powered by air compressor). Moreover, the various pressure drops (10 bar, 20 bar and 25 bar) were also considered. Hilbert-Huang transform (HHT) combined with empirical mode decomposition (EMD) were used in filtering and analyzing the pressure signals in the chamber for they are capable of transforming non-stationary and non-linear signals. Based on the filtered and transformed results, the energy fluctuation was
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