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Effects of area discontinuity at nozzle inlet on the characteristics of high speed self-excited oscillation pulsed waterjets

Deng Li [a,b,c], Yong Kang [a,b,*], Xiaolong Ding [a,b], Xiaochuan Wang [a,b], Zhenlong Fang [a,b]

[a] School of Power and Mechanical Engineering, Wuhan University, Wuhan 430072, Hubei Province, China
[b] Hubei Key Laboratory of Waterjet Theory and New Technology, Wuhan University, Wuhan 430072, Hubei Province, China
[c] Department of Mechanical Science and Engineering, University of Illinois at Urbana-Champaign, 1206 West Green Street, Urbana, IL 61801, United States

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ABSTRACT

High speed self-excited oscillation pulsed waterjet (SEOPW) offers many advantages over continuous jets or external-excited pulsed jets and has a large number of practical and industrial applications. In order to take better advantage of SEOPWs, effects of area discontinuity at nozzle inlet were analyzed based on the previous related research and then experimentally investigated with respect to the axial pressure oscillations. A jet-driven Helmholtz oscillator, which is capable of producing effective SEOPWs, was employed in the experiment. It was found that area discontinuity has a capacity of enhancing the peak, which largely depends on the inlet pressure and standoff distance. The enhancement decreases with increasing inlet pressure and only happens within small standoff distances. Compared with the continuous case, area enlargement enhances the peak by 25%, 21%, and 16%, corresponding to inlet pressures of 10, 15, and 20 MPa, respectively; while area contraction turns to be a better one by improving the peak by 8% at inlet pressure of 25 MPa. However, at inlet pressure of 30 MPa, both enlargement and contraction decrease the peak. Moreover, area discontinuity cannot influence the optimum standoff distance where the maximum peak appears. For the pressure oscillation amplitude, even both area discontinuities have the ability of increasing the amplitude regardless of inlet pressure and standoff distance, contraction enhances the amplitude much more than enlargement does at all the testing inlet pressures. In addition, area discontinuity has nearly no influence on the oscillating frequency and causes perturbations that may only affect the intensity of self-excitation by amplitude.

1. Introduction

High-speed waterjet technology has achieved obvious progress during the last few decades, stimulated by the demand of a wide range of industries that have recognized the incomparable advantages of waterjet [1–3]. It is the only existing cold working method, especially suitable for machining thermo-sensitive materials [4]. In more specific terms, high-speed waterjet is a non-conventional machining method that can be used to clean surface, remove surface layers, excavate and break rocks and cutting almost all kinds of materials in fields of machine, mining, transportation and even military [5–7]. In order to make better use of high speed waterjet technology, different kinds of waterjets have been invented like, cavitating waterjet, abrasive waterjet, pulsed waterjet, rotating waterjet and so on. Among them, pulsed waterjet, which can cause serious damage to the surface and interior of the target material by generating water-hammer effect, has been the subject of numerous studies [8–10]. For producing high speed pulsed waterjets, mechanical methods including rotating, reciprocating and wobbling have been successfully applied. However, the devices using these methods require high levels of mechanical maintenance and their durability and reliability in harsh working environments (like well drilling, rock cutting or tank cleaning) are very limited. Even Vijay et al. [11] and Foldyna et al. [12] have introduced a kind of high frequency pulsed waterjet with the use of an ultrasonic upstream of the nozzle, the jet's energy is pretty low, which has prevented its wide applications. Under these conditions and driven by a desire to achieve more powerful waterjets while at the same time keep the pump pressure relatively low, SEOPW is getting considerably high attentions in research. The most attractive point of this technology is that by taking full advantage of the jet instability of organizing into large-scale structures, it can produce effective pulsed waterjets without using any moving parts in the supply system. Simultaneously, it also has all the advantages of a pulsed jet,

* Corresponding author at: School of Power and Mechanical Engineering, Wuhan University, Wuhan 430072, Hubei Province, China.
E-mail address: kangyong@whu.edu.cn (Y. Kang).

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Nomenclature

A	section area of the jet	P_{max}	axial pressure oscillation peak
A_0	cross section of Helmholtz resonator inlet	P_{min}	minimum of axial pressure oscillation
a	local sound speed	ΔP	axial pressure oscillation amplitude
d_0	inlet diameter of Helmholtz resonator	S	standoff distance
d_1	outlet diameter of upstream nozzle	S_L	a set of discrete numbers
d_2	diameter of downstream nozzle	S_o	optimum standoff distance
d_f	diameter of feeding pipe	S_t	Strouhal number
d_i	inlet diameter of upstream nozzle	t	time
D_c	diameter of the oscillation chamber	u	velocity of the jet
f_n	natural frequency of Helmholtz resonator	u_c	convective velocity
f_s	frequency of acoustic wave	V	volume of Helmholtz resonator
f_v	structuring frequency of the jet	V_l	volume of liquid
f_0	oscillating frequency of SEOPW	V_g	volume of gas
g	acceleration of gravity	x	position
h_i	local pressure loss	Z	water head
h_l	linear pressure loss	ρ_m	mean density of liquid-gas mixture
K_l	bulk modulus of elasticity of liquid	ρ_g	density of gas
K_g	bulk modulus of elasticity of gas	p_l	density of liquid
L_c	length of oscillation chamber	α	volume fraction of gas in the mixture
l_0	length of Helmholtz resonator inlet	θ	convergent angle of upstream nozzle
N	model number	β	taper angle of the impinge edge
p	pressure	λ	wavelength
P_a	axial pressure of SEOPW	δ	frequency correction factor of 0.6
P_i	inlet pressure	ξ	velocity loss coefficient

such as larger impact stresses, larger outflow velocities, cycling of loading, and so on [13].

Actually, self-excited oscillation generated by fluids passing through a Helmholtz resonator has already been recognized many years ago, even not directly. Early in the year of 1961, in order to understand the amplified sound resulting from the action of a jet emerging from a slit orifice and impinging upon a fixed cylinder, Powell [14] theoretically analyzed the feedback mechanism of hydroacoustic waves. They found that the acoustic field is primarily due to the dipole associated with the fluctuating fluid force on the edge, and jet instability characteristics depend acutely on the Reynolds and Strouhal number, as well as the orifice-edge distance. Years later, a model of Helmholtz nozzle was established by Wilson et al. [15] to investigate the fluid mechanics of whistling. The results showed that the essential mechanism for exciting the nozzle to generate pulsation depends on the instability of a jet to form vortex rings and the interaction of the rings with a rigid boundary in the flow. Then, for the purpose of figuring out the mechanism of large-scale orderly pattern coupling with the acoustic field of a jet, Crow and Champagne [16] performed systematical experiment to visualize the flow of round subsonic jets with advancing Reynolds number under periodic surging of controllable frequency and amplitude. They concluded with the conjecture that Strouhal number of 0.30 is the most dispersive wave on a jet column in some sense, and under this condition the wave is the most capable of reaching the largest amplitude before saturating. In addition, Howe [17] proposed a theory for the excitation of a Helmholtz resonator by external disturbances involving the derivation of the Green function of the resonator. He claimed that the generated large-scale structure in the shear layer of a jet may be caused by a Kelvin-Helmholtz type of instability. Moreover, Rockwell and Naudascher [18] detailed studied the self-sustained oscillation mechanism of impinging free shear layers from aspects of feedback mechanism, frequency of oscillation, amplitude of oscillation, and resonance effects. These investigations pose as the theoretical foundation for the SEOPWs discharging from Helmholtz oscillators. Then based on these studies, Morel [19] experimental studied the pressure characteristics of jets passing through a Helmholtz nozzle of variable configure under different velocities. He confirmed that at certain jet velocities, very powerful pressure fluctuations, whose amplitude can reach 5.6 times the value of jet dynamic pressure, may occur as a result of the jet instability coupling with the Helmholtz resonance.

Eventually, Chahine et al. [20] put an explicit explanation on the mechanism of SEOPW and proposed the concept of a Helmholtz nozzle ("Pulser") producing such jets. This has paved a way for the research conducted by Liao and Tang [21], who experimentally studied the effects of nozzle configurations on the pulsation and frequency characteristics.

In recent years, the interest on the characteristics of Helmholtz nozzle keeps growing. To be more specific, Ma et al. [22] experimentally and theoretically investigated a flow-excited Helmholtz resonator and proposed a model for predicting pressure fluctuations based on the thickness of the approach boundary layer. In addition, Cora et al. [23] have already provided a new methodology to design the Helmholtz resonators and determine the acoustic performance theoretically. By entraining and mixing air into the cavity of a Helmholtz oscillator, Hu et al. [24] proposed a new way of generating pulsed air-water jet. Also, Tang et al. [25] conducted a study to further investigate the frequency behaviors of a Helmholtz oscillator and found there was an optimum cavity length corresponding to the jet dynamic pressure. Most recently, Li et al. [1,26] performed experimental investigations on the characteristics of SEOPWs influenced by nozzle surface roughness and feeding pipe diameter.

Although a considerable amount of research have been carried out on SEOPWs, to the best of our knowledge, there is so far little literature on how area discontinuity at nozzle inlet influences the performance of the jets. However, when the diameter of feeding pipe is not equal to that of the nozzle inlet, area discontinuity will be formed, which could cause perturbations in the flow before it enters into the nozzle. Since perturbations can have a great influence on the generation and feedback of hydroacoustic waves yielded in the chamber of a Helmholtz oscillator, area discontinuity