Journal of Applied Science and Engineering, Vol. 22, No. 1, pp. 83–92 (2019) *DOI: 10.6180/jase.201903_22(1).0009*

Experimental Research on the Waterjet Oscillating Characteristics of Helmholtz Nozzle

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Abstract

Helmholtz nozzle is a typical self-resonating waterjet generator, and has been extensively investigated through target hitting experiment. This paper on jet flow state reveals the essential characteristics of Helmholtz nozzle jet by signal analysis method. The flow pressure pulsation signals were directly acquired in the nozzle's cavity. Spectrum analysis was employed to analyze the oscillating characteristics of self-resonating waterjet generated by a series of Helmholtz nozzles with different structures. The noise level was detected using self-resonating waterjet to hit the target under confining pressure and the cavitation effect was investigated through analyzing the noise power spectrum. The experimental results showed that compared with the organ-pipe and conical nozzles, the self-resonating waterjet generated by Helmholtz nozzle had high-frequency pressure oscillation and strong cavitation effects. The Helmholtz nozzle's upper portion determines the resonance frequency. Meanwhile, The upper structure of the Helmholtz nozzle promotes the cavitation generation, and Helmholtz oscillation cavity enhances the cavitation effect of the self-resonating waterjet.

Key Words: Helmholtz Nozzle, Self-resonating Waterjet, Frequency Characteristics, Cavitation Noise, Signal Analysis

1. Introduction

Self-resonating waterjet is a kind of high-efficiency waterjet which combines the advantages of cavitation and pulsed waterjet. Therefore, we can significantly improve the jet erosion capability under high ambient pressure. Accordingly, a self-resonating waterjet has promising prospects in many fields, such as mining, cutting, drilling, cleaning and surface layer removing [1–6].

Helmholtz nozzle is a typical self-resonating waterjet nozzle that could produce one jet with high-frequency pressure oscillation and large structural vortex bubble rings [7]. The produced jet holds a stronger cavitation capability than a general jet under confining pressure [8]. Thus, Helmholtz nozzle can be used to generate greater destructive power and more desirable erosion effect and dramatically improve the working efficiency [9].

In 1978, Rockwell [10] classified self-resonating oscillations into three basic categories: fluid-dynamic, fluid-resonant, and fluid-elastic oscillations. To increase the erosion efficiency using a self-resonating waterjet, many experiments and numerical analysis have been carried out in the last few decades.

Zhang et al. [11] experimentally investigated the noise of cavitation nozzle by analyzing the noise signals captured by the hydrophones for the cavitation and general nozzles. Fang et al. [12] investigated the flow characteristics of Helmholtz self-excited oscillation pulsed jet by large eddy simulation. The results showed that Helmholtz cavity turned uniform flow into turbulence flow, thereby increasing the scale of verity and intensifying the energy dissipation inside the cavity. Liu et al. [13]

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investigated the turbulent flow past a 120°-impinging edge Helmholtz nozzle. A modified theoretical model was proposed to calculate the range of the oscillation frequency which was also verified by experiment. It was found that the cavitation clouds in the chamber dominated the oscillation frequency under the condition of low pressure and high flowrate. Li et al. [14] experimentally researched the jet-driven Helmholtz nozzle in terms of the axial pressure oscillations of jets against chamber length and standoff distance. It was found that feeding pipe diameter have a great influence on the pressure oscillations.

Organ-pipe and conical nozzles are also usually used as a self-resonating waterjet generator. Wang et al. [15] revealed the vibration and frequency characteristics of self-resonating waterjet produced by an organ-pipe nozzle, for the purpose of increasing the design efficiency of the nozzle and improving the scouring and cleaning efficiency of the jet. Li et al. [16,17] explored the inner surface roughness of organ-pipe nozzle on the waterjet cavitation characteristics. They concluded that surface roughness could greatly affect both the cavitation erosion intensity at the standoff distances around the optimum and the on-erosion efficiency at standoff distances exceeding the optimum. Yang et al. [18] investigated the flow characteristics of cone nozzles. The experimental results showed that the inlet conditions greatly influenced the cavitation energy loss but hardly affected feature ones, and that the nozzle features significantly affected both kinds of energy losses and they tended to be smaller when the inner surface was closer to streamline. The flow field of organ-pipe nozzle was numerically simulated by Fang et al. [19]. Nozzles were tested under different driving pressures in submerged situation. The results showed that the working pressure, cavity length and cavity diameter could influence the characteristics of organ-pipe nozzle.

The existing self-resonating waterjet researches that investigated the oscillating and cavitation characteristics were mainly carried out through target hitting experiments to explore the jet striking effect. However, no internal relation has been explicitly revealed between the flow state of jet and oscillating characteristics as far as we know. Furthermore, three kinds of nozzles are usually used in previous research as self-resonating waterjet generators, i.e. Helmholtz nozzle, organ-pipe nozzle, and conical nozzle. Helmholtz nozzle is considered as the most readily adaptable to a pulsed jet, followed by organ-pipe nozzle. However, the other researchers believe that the cavitation effect of organ-pipe nozzle is much better than that of the other two nozzles [20]. This discrepancy primarily results from the lack of unified evaluation criteria.

Therefore, this paper adopted the sensing technology to obtain the flow pressure pulsation signals directly in nozzle's cavity and the cavitation noise signals under submerged condition. Using signal analysis method, we investigated the frequency and cavitation characteristics of Helmholtz nozzle jets. We also revealed the internal relationship among jet flow state, frequency characteristic and cavitation characteristics. The characteristics of self-resonating waterjet generated by Helmholtz nozzle were analyzed by comparing the properties of the three types of nozzle jets.

2. Working Principle of Helmholtz Nozzle

The structural parameters of Helmholtz nozzle determine the characteristics of the self-resonating waterjet generated by the nozzle. Helmholtz nozzle is mainly composed of two parts: the upper portion of a conical nozzle, and the lower portion of a Helmholtz oscillation cavity. To comparatively analyze the difference between two kinds of self-resonating nozzles, this paper cites the research achievements of Li [21] to improve the Helmholtz nozzle structure. The upper portion of conical nozzle was replaced by an organ-pipe structure, and the lower portion retained the Helmholtz oscillation cavity (Figure 1c). To make the structural parameters adjustable, the nozzle structure was designed as two detachable portions (Figure 1a and Figure 1b) and the two portions could therefore formulate the Helmholtz nozzle with different structural parameters.

For comparison, the organ-pipe nozzle structure in Figure 1a and the conical nozzle structure in Figure 1d can also be used to investigate the characteristics of the self-resonating waterjet generated by organ-pipe nozzle and conical nozzle, respectively.

As shown in Figure 1, D_s is the inlet diameter of the Helmholtz nozzle, D_1, L_1, and d_1 are the diameter, chamber length, and outlet diameter of the upper portion of the

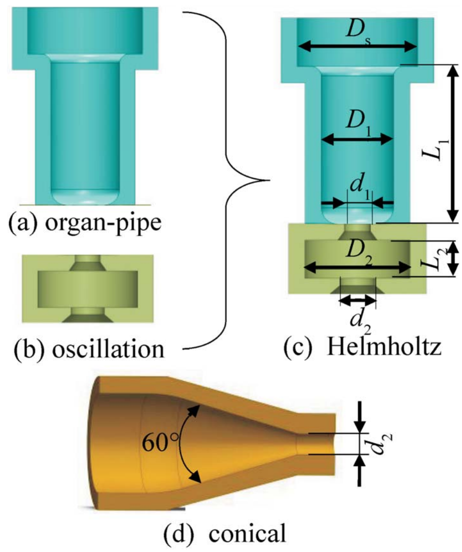


Figure 1. Experimental structures of organ-pipe, Helmholtz and conical nozzles.

organ-pipe nozzle, respectively. D_2 and L_2 are the diameter and chamber length of Helmholtz oscillation cavity structure, respectively, and d_2 is the outlet diameter. The conical nozzle structure is shown in Figure 1d, where the nozzle cone angle is 60°, and the outlet diameter is also d_2.

The jet structuring frequency f_j is expressed as:

$$f_j = \frac{S_d U}{d_1} \tag{1}$$

where S_d is the Strouhal number, commonly being 0.3; d_1 is the outlet diameter of Helmholtz nozzle; U is the waterjet speed.

Acoustic resonance was achieved in the nozzle feedtube assembly when a standing wave formed in the organ-pipe section. This section was created by the upstream contraction, $(D_s/D_1)^2$ and the nozzle contraction $(D_1/d_1)^2$.

The fundamental frequency f_0 can be defined as [22]:

$$f_0 = K_N \frac{a}{L} \tag{2}$$

$$K_N = \frac{2N-1}{4}, \quad N = 1,2,3\ldots \tag{3}$$

where K_N is the mode parameter of oscillation; N is mode number; a is the local sound speed; L_1 is the length of nozzle inlet.

Peak resonance would occur when the fundamental frequency was close to the jet structuring frequency.

3. Experimental Apparatus and Parameters

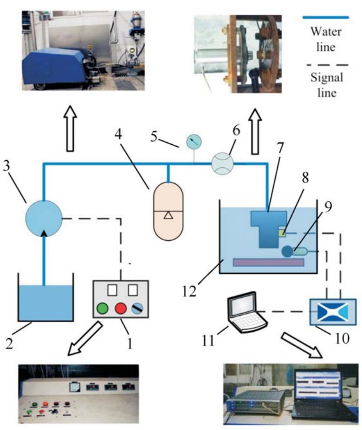
3.1 Experimental System

To obtain the flow pressure pulsation signals in the nozzle's cavity and the cavitation noise signals of jet under the submerged condition, the experimental system was constructed, as illustrated in Figure 2. The system consisted of control table, water tank, pump, accumulator, electromagnetic flowmeter, jet apparatus, submerge tank, transducer, and data acquisition unit.

The methods to detect fluid pulsation signal in the nozzle cavity, to select pressure transducer, and to arrange measuring points can be found in previous research [23, 24]. Similar to the previous research, one pressure transducer was installed on the nozzle's side wall to obtain the flow pressure pulsation signals in the nozzle's cavity. A hydrophone was arranged near the target plate to obtain the jet's cavitation noise signal. Using fast Fourier transform, the flow pressure pulsation signals were analyzed to explore the amplitude-frequency characteristics and the jet's oscillating characteristics [25]. The power spectrum was used to analyze the cavitation noise and explore the cavitation effect of self-resonating waterjet.

3.2 Experimental Variables

The nozzles with different structural parameters are



1–control table; 2–water tank; 3–plunger pump; 4–accumulator; 5–pressure gauge; 6–flowmeter; 7–jet apparatus; 8–pressure transducer; 9–hydrophone; 10–data acquisition unit; 11–laptop; 12–submerge tank

Figure 2. Experimental system.

shown in Table 1. Five groups were formulated, and the flow velocities were the same in all cases.

4. Experimental Results

4.1 The Oscillating Characteristics of Self-resonating Waterjet

The oscillating characteristics of self-resonating waterjet are related to the coming flow parameters and mainly determined by the structural parameters of the waterjet generator.

4.1.1 The Waterjet Oscillating Characteristics of Helmholtz Nozzle

Section 2 shows that Helmholtz nozzle is composed of organ-pipe nozzle and oscillation cavity. For this reason, investigation was performed on the relation between the structural parameters of the two parts and Helmholtz jet's oscillating characteristics.

(1) Helmholtz jet's oscillating characteristics with different oscillation cavity parameters

Firstly, the structural parameters D_1, d_1, L_1, D_2 and d_2 were kept constant. The influence of oscillation cavity length on the Helmholtz jet's oscillating characteristics was investigated by changing the value of L_2. The experimental condition is shown in the first group of Table 1. The frequency spectrum obtained by Group 1 is shown in Figure 3.

Table 1. The nozzles with different structural parameters

Group	Nozzletype	Nozzle marks	Nozzle parameters (mm)		
			d_1	d_2	L_2
1	Helmholtz	1	2.5	3	2
	Helmholtz	2	2.5	3	10
	Helmholtz	3	2.5	3	26
2	Helmholtz	4-17	2.5	3	0-26
3	Helmholtz	18	2	2.4	12
	Helmholtz	19	2.5	3	12
	Helmholtz	20	3	3.6	12
4	Helmholtz	21	2	2.5	12
	Organ-pipe	22	2	/	/
	Conical	23	/	2	/
5	Helmholtz	24	2.5	3	12
	Organ-pipe	25	2.5	/	/
	Conical	26	/	2.5	/
6	Helmholtz	19	2.5	3	12
	Organ-pipe	22	3	/	/
	Conical	25	/	3	/

As shown in Figure 3, when L_2/d_1 exhibited a large value, the resonance peak amplitudes significantly differed while the resonance frequency of self-resonating waterjet was almost the same. In Figure 3, the resonance peak value was 1.50×10^5 Pa when $L_2/d_1 = 0.8$. The resonance peak value was 3.14×10^5 Pa when $L_2/d_1 = 4$. Furthermore, the resonance peak value was 1.76×10^5 Pa when $L_2/d_1 = 10.4$. However, all the resonance frequencies fluctuated around 340 Hz, indicating that the oscillation cavity length significantly affected the oscillation amplitude of the self-resonating waterjet but hardly influenced the resonance frequency.

To further analyze the relation among oscillation cavity length, oscillation frequency and amplitude of self-resonating waterjet, the second group of experiment was performed using the conditions shown in the second group of Table 1. The experiment adopted 14 nozzles by keeping the parameters of D_1, d_1, L_1, D_2, and d_2/d_1 constant. The difference of the cavity length of adjacent-number nozzle was 2 mm. Firstly, the spectrum of self-resonating waterjet produced by each nozzle was obtained through

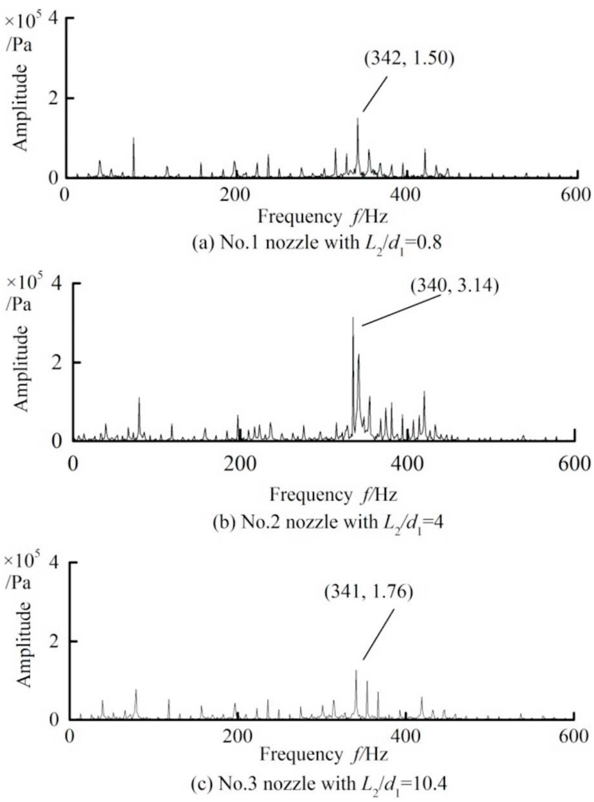


Figure 3. Helmholtz nozzle jet's spectrum with different oscillation cavities (d_1 = 2.5 mm).

experiment to acquire the resonance frequency and amplitude of the self-resonating waterjet. Figure 4 shows the relationship among cavity length, resonance frequency, and amplitude of the self-resonating waterjet of 14-nozzle experiments. As can be seen from Figure 4, with L_2/d_1 increasing, the resonance frequency did not change significantly, all fluctuating around 340 Hz; the resonance peak amplitude rose dramatically and decreased after reaching the maximum value. The minimum peak value was 1.5×10^5 Pa, for $L_2/d_1 = 0.8$; the maximum peak value was 3.4×10^5 Pa, for $L_2/d_1 = 4.8$, which was 2.3 times of the minimum.

The experimental results in Figure 3 and Figure 4 show that the oscillation cavity length generally did not affect the resonance frequency but significantly influenced the resonance peak amplitude. The optimal value of oscillation cavity length was 12 mm.

The parameters of the Helmholtz nozzle's upper portion determine the generation and the frequency spectrum structure of the self-resonating waterjet. The Helmholtz oscillation cavity exerts a selective amplification function on the spectrum amplitude of the self-resonating waterjet. Furthermore, an optimal value exists but almost holds no effect on the spectrum structure of the self-resonating waterjet. In other words, the Helmholtz nozzle's upper portion (i.e. organ-pipe structure) determines the resonance frequency. The Helmholtz oscillation cavity structure's chamber length L_2 will not change the resonance frequency of the self-resonating waterjet.

The parameters of the upper portion of Helmholtz nozzle determine the frequency spectrum of the self-resonating waterjet. The Helmholtz oscillation cavity could

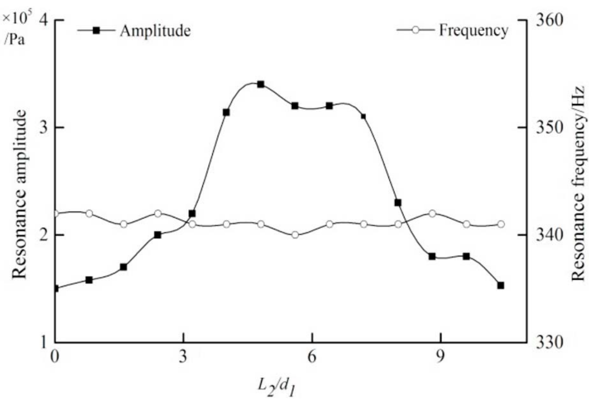


Figure 4. Relationship among cavity length, resonance frequency and amplitude.

selectively amplify the spectrum amplitude. Furthermore, an optimal value existed but almost held no effect on the spectrum structure of the self-resonating waterjet. In other words, the upper portion of Helmholtz nozzle determines the resonance frequency while the cavity length L_2 will not change the resonance frequency of the self-resonating waterjet.

(2) Helmholtz jet's oscillating characteristics with different upper-portion parameters

The Helmholtz nozzle's upper portion holds various structural forms and numerous parameters. For convenience, the upper portion was considered as the organ-pipe. The oscillation cavity parameters remained constant during the experiment, with the cavity length $L_2 = 12$ mm. The influence of outlet diameteron the oscillating characteristics was researched by changing d_1. The experimental conditions are shown in the third group of Table 1, and the results are shown in Figure 5.

The oscillation cavity parameters remained the same as those in the previous experiment, whereas the upper-portion structural parameter d_1 was changed. As seen

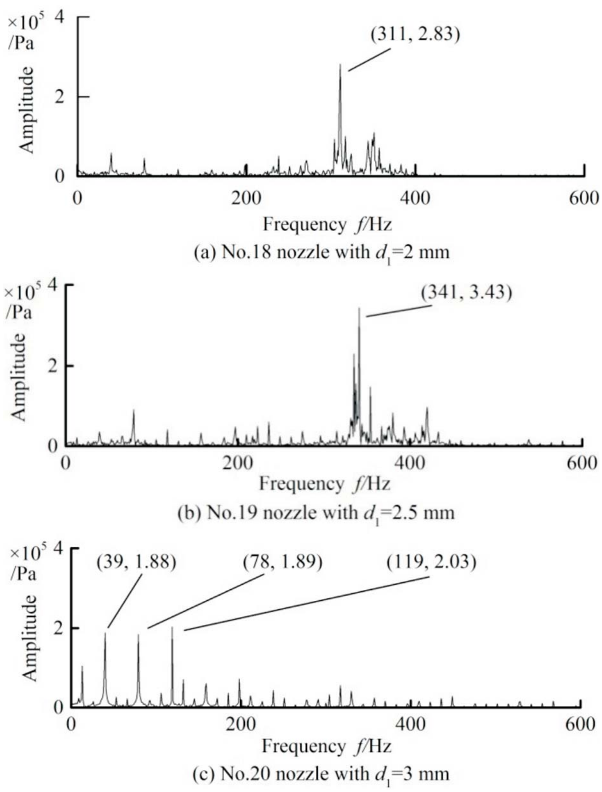


Figure 5. Helmholtz nozzle jet's spectrum with different upper portion parameters.

from Figure 5, both the resonance frequency and amplitude of the self-resonating waterjet produced by the Helmholtz nozzle also varied. The resonance frequency and amplitude were 311 Hz and 2.83×10^5 Pa, respectively, for $d_1 = 2$ mm; they were 341 Hz and 3.43×10^5 Pa, respectively, for $d_1 = 2.5$ mm. However, when $d_1 = 3$ mm, the self-resonating waterjet did not exhibit the phenomenon of frequency resonance, and the oscillation frequency was the integer times of the disturbance frequency. The results showed that the parameters of the Helmholtz nozzle's upper portion significantly influenced the generation, frequency spectrum structure, and resonance frequency of the self-resonating waterjet.

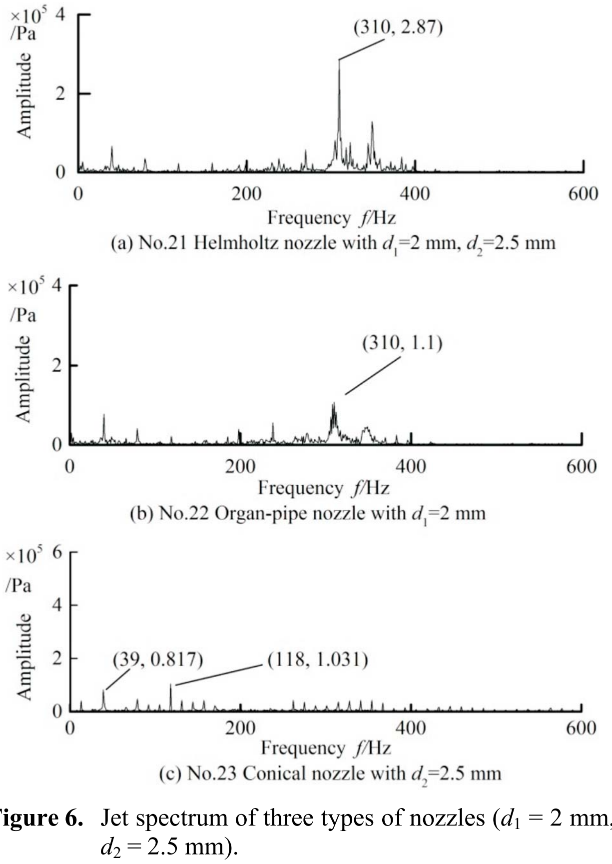
4.1.2 The Waterjet Oscillating Characteristics of Different-structure Nozzles

In addition to Helmholtz nozzle, organ-pipe nozzle and conical nozzle are also used as self-resonating waterjet generator independently, but the three nozzles have considerably different structures. To explore the relationship between nozzle structure and jet oscillating characteristics, the experiments were performed with the Groups 4 and 5 of Table 1.

In experiments, for the convenience of analysis and comparison, the organ-pipe nozzle structure was the same as the upper portion of the Helmholtz nozzle, and the outlet diameter of the conical nozzle was the same as that of the Helmholtz nozzle. However, the experimental conditions of the two groups were different, namely, the outlet diameter of the nozzles d_1 and d_2 varied as shown in Groups 4 and 5 of Table 1. The experimental results are shown in Figure 6 and Figure 7.

As indicated by Figure 6, when $d_1 = 2$ mm, the resonance peak of the organ-pipe nozzle jet was 1.1×10^5 Pa, and that of the Helmholtz nozzle jet was 2.87×10^5 Pa, which was 2.6 times of the former. However, the resonance frequency remained at 310 Hz for the two nozzles. As shown in Figure 7, when $d_1 = 2.5$ mm, the resonance peak of the organ-pipe nozzle jet was 2.37×10^5 Pa, and that of the Helmholtz nozzle jet was 2.87×10^5 Pa, which was 1.4 times of the former. However, the resonance frequency was both 341 Hz for the two nozzles. The organ-pipe nozzle structure was the same as the upper portion structure of the Helmholtz nozzle. Hence, the jet oscillation, a high-frequency oscillation generated by the Helmholtz nozzle with the oscillation cavity, was stronger than that of the organ-pipe nozzle. The structural parameters of the Helmholtz nozzle's upper portion determined the resonance frequency of the self-resonating waterjet. Meanwhile, the oscillation cavity could amplify the resonance peak but basically did not affect the resonance frequency.

The conical nozzle did not exhibit an obvious high-frequency oscillation when the outlet diameter d_2 was 2.5 mm or 3 mm, as indicated by Figure 6c and Figure 7c, and the oscillation frequencies were mainly concentrated at 39 Hz and 118 Hz. The 39 Hz was the flow disturbance frequency caused by pump, and the maximum peak value was close to the flow disturbance amplitude. Thus, it was determined that the jet pressure fluctuations of conical nozzle were mainly caused by inflow interference, without generating obvious self-oscillation. As seen from Figure 7a and Figure 7c, when the outlet diameter of the Helmholtz nozzle d_1 was 2.5 mm, the waterjet resonance frequency was 341 Hz, and the resonance peak was 2.37 $\times 10^5$ Pa, which was three times of the conical nozzle's.



(a) No.21 Helmholtz nozzle with d_1=2 mm, d_2=2.5 mm

(b) No.22 Organ-pipe nozzle with d_1=2 mm

(c) No.23 Conical nozzle with d_2=2.5 mm

Figure 6. Jet spectrum of three types of nozzles (d_1 = 2 mm, d_2 = 2.5 mm).

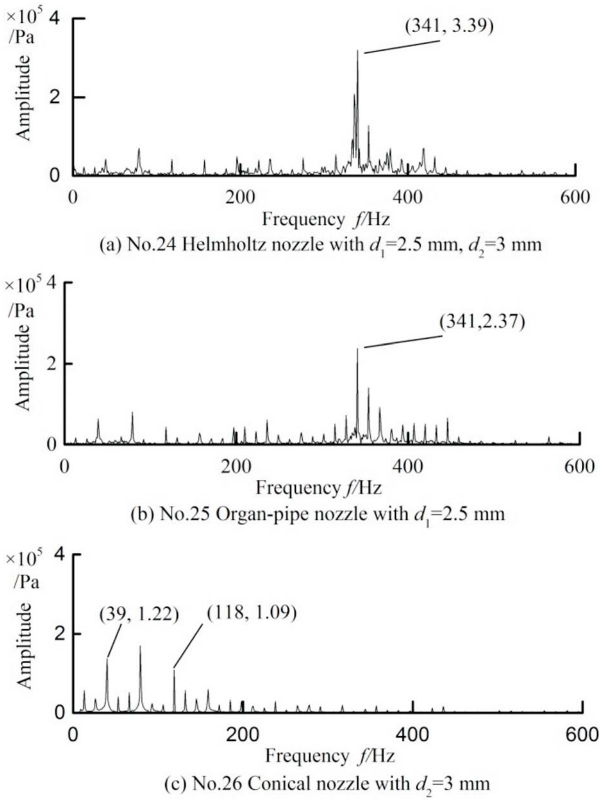


Figure 7. Jet spectrum of three types of nozzles (d_1 = 2.5 mm, d_2 = 3 mm).

This result indicated that, compared with the conical nozzle, the Helmholtz nozzle could produce high-frequency self-oscillation effect and enhance the oscillating characteristics.

In summary, the oscillating characteristics of the self-oscillating waterjet were closely related to the structural parameters of the nozzle. Under the same conditions, the Helmholtz nozzle exhibited the best oscillating characteristics, followed by the organ-pipe nozzle, and then the common nozzle. In addition, by analyzing the spectrum characteristics of the jet flow regime, the oscillating characteristics of the waterjet were well evaluated.

4.2 Cavitation of Self-resonating Waterjet

A self-resonating waterjet also generated cavitation phenomenon when producing high-frequency oscillation. When an object is struck by the jet entraining the cavities at high speed under submerged conditions, a bubble collapse will occur. Simultaneously, the generation of strong shockwave and micro-jet will cause severe damage to the surface, thereby improving the jet performance significantly. Cavitation effect is another important characteristic of self-resonating waterjet. Its formation is closely related to the vacuolus primary condition, namely, jet flow state. However, jet flow state is subject to the nozzle structure. Therefore, using cavitation noise analysis method, the relationship between Helmholtz nozzle structure and jet's cavitation effect was investigated in this paper.

Section 2 presents that the Helmholtz nozzle was composed of a conical nozzle or organ-pipe connected with an oscillation cavity. Therefore, the flow regime of the Helmholtz nozzle jet was closely related to the parameters of the nozzle's upper portion. For the convenience of analysis and comparison, the experiments in Group 5 of Table 1 were performed.

This group of experiments adopted three kinds of nozzles, particularly, organ-pipe and conical nozzles; both nozzles can be regarded as the Helmholtz nozzle without an actual cavity. Thus, the three nozzles used in this group of experiments can be deemed as the three kinds of Helmholtz nozzles with different structures. The nozzle's outlet diameter was 2.5 mm, and the flow parameters were the same in all cases. In the experiments, after the cavitation noise under confining pressure was obtained using the hydrophone, the cavitation effect of the self-resonating waterjet was analyzed by the noise power spectrum. The experimental results are shown in Figure 8.

Figure 8a shows the power spectrum of cavitation noise produced by the Helmholtz nozzle jet, in which the peak amplitude was 100 dB·Hz^{-1}, the peak frequency was about 10 kHz, and the cavitation noise energy of the Helmholtz nozzle jet in unit time was 1.55×10^5 J/(s·m^2). Figure 8b shows the power spectrum of cavitation noise produced by the organ-pipe nozzle jet, in which the peak amplitude was 90 dB·Hz^{-1}, the peak frequency was about 6 kHz and the cavitation noise energy of the organ-pipe nozzle jet in unit time was 9.27×10^4 J/(s·m^2). Figure 8c shows the power spectrum of cavitation noise produced by the conical nozzle jet, where the amplitude fluctuated between 40-50 dB·Hz^{-1} without peak frequency and the cavitation noise energy of the conical nozzle jet in unit time was 1.66×10^3 J/(s·m^2).

For the Helmholtz nozzle jet, the noise power spectrum peak was 10 dB higher, and the peak frequency was 4 kHz higher, than the organ-pipe nozzle (Figure 8a and

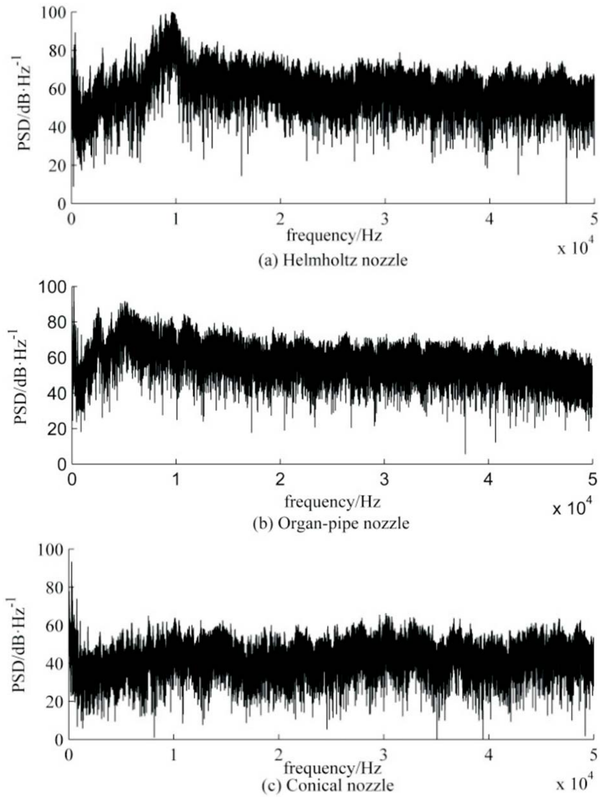


Figure 8. Power spectrum of the cavitation noise by different nozzle jets.

Figure 8b). At the high-frequency band of 20–50 kHz, the power spectrum density of the Helmholtz nozzle was maintained at 60 dB·Hz^{-1}, but the organ-pipe nozzle achieved an obvious attenuation trend, indicating that the bandwidth of the cavitation noise produced by the Helmholtz nozzle was wider than that of the organ-pipe nozzle. In the meantime, the cavitation noise energy of Helmholtz nozzle jet in unit time was 1.67 times of the organ-pipe nozzle jet. Since the organ-pipe nozzle structure was the same as the upper portion of the Helmholtz nozzle, the above analysis indicated that the Helmholtz nozzle with oscillation cavity exerted a stronger cavitation effect, suggesting that the oscillation cavity enhanced the cavitation effect of the self-resonating jet.

From Figure 8b and Figure 8c, the power spectrum of the cavitation noise produced by the organ-pipe nozzle jet showed an obvious peak, and the power spectrum remained 50 dB·Hz^{-1} at the high-frequency section. An obvious peak did not occur at the power spectrum of the conical nozzle jet, and the power spectrum fluctuated at a lower range throughout the entire frequency band. The difference showed that strong cavitation due to the presence of the organ-pipe nozzle, whereas none or less cavitation occurred for the conical nozzle. As a result, it was determined that both the organ-pipe nozzle and conical nozzle could be regarded as the upper portion of the Helmholtz nozzle which was considered to be related to the cavitation inception. Besides, the structure with optimized structural parameters, such as the organ-pipe nozzle, was shown to promote the cavitation generation.

In summary, the Helmholtz nozzle jet showed a strong cavitation effect. The upper portion of the Helmholtz nozzle promoted the cavitation generation, and the oscillation cavity enhanced the cavitation effect of the self-resonating waterjet. According to the results in section 4.1, the Helmholtz nozzle exhibited the best oscillating characteristic and produced high-frequency pressure oscillations. Through the comprehensive analysis of oscillation characteristics and cavitation effect, a significantly close relationship was found between the high-frequency pressure oscillation generated by the Helmholtz nozzle and the strong cavitation effect, whereas the internal mechanism requires further investigation.

5. Conclusions

(1) Compared with the organ-pipe nozzle and conical nozzle, the self-resonating waterjet produced by the Helmholtz nozzle held a high-frequency oscillating characteristic and strong cavitation. Under the same conditions, the pressure oscillation amplitude by the Helmholtz nozzle was 1.4 times of the organ-pipe nozzle and 2.8 times of the conical nozzle. At the same time, the Helmholtz nozzle's cavitation noise energy was 1.6 times of the organ-pipe nozzle and 93 times of the conical nozzle.

(2) The parameters of the Helmholtz nozzle's upper portion determined the generation and the frequency spectrum structure of the self-resonating waterjet. The Helmholtz oscillation cavity could selectively amplify the spectrum amplitude of the self-resonating waterjet. Furthermore, an optimal value existed but almost held no effect on the spectrum structure of the self-resonating waterjet.

(3) The upper structure of the Helmholtz nozzle promoted the cavitation generation, and Helmholtz oscillation

cavity enhanced the cavitation effect of the self-resonating waterjet. However, the identification and evaluation of the cavitation effect require further research.

Acknowledgments

The authors gratefully acknowledge the supports from the Fundamental Research Funds for the Central Universities of China [grant number FRF-TP-17-026A1]; General Financial Grant from the China Postdoctoral Science Foundation [grant number 2017M620621]; National Natural Science Foundation of China [grant number 5177 4019].

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Manuscript Received: May 24, 2018
Accepted: Nov. 12, 2018