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Paper

# Detection method and application of a self-resonating water jet based on the flow signal within the pipeline

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## ABSTRACT

The self-resonating water jet is characterized by the high-frequency pressure oscillation and strong cavitation. Accurately grasping the jet characteristics is a prerequisite for the application research of self-resonating water jet. In this paper, a detection method for self-resonating water jet characteristics based on the pressure signal within the pipeline was studied. The pressure sensors were arranged in the front pipeline outside the high pressure tank to avoid the influence of high ambient pressure. The test results show that the spectral characteristics acquired from the pressure signal in the pipeline agree with the signal in the chamber and theoretical calculations results. Furthermore, this detection method was successfully applied for studying the influence of nozzle lip geometry on the characteristic of self-resonating water jet.

## 1 INTRODUCTION

Self-resonating water jet is a kind of high-efficiency jet with the advantages of cavitation jet and pulse jet, which can significantly improve the erosion effect under high confining pressure environment. So the self-resonating water jet technology has a promising prospect in deep-sea mining, submerged cleaning and petroleum drilling(Johnson et al. 1984 and Li et al. 2005).

The characteristics of the self-resonating water jet – high frequency pressure oscillation and strong cavitation - directly determine its erosion effect. Therefore, accurately grasping the characteristics of the self-resonating water jet is the prerequisite for the application and research of self-resonating water jet. The traditional detection methods for the characteristic of self-resonating water jet mainly include the strike test method and detection of the pressure signal in the nozzle cavity. The strike test method is to add a sensor on the target plate to detect the oscillating characteristics of the self-resonating water jet(Chahine et al. 1983, Hu et al. 2015, Li et al. 2016). However, this method indirectly acquires the pressure oscillation characteristics of the self-resonating water jet through the target vibration, it has strong interference and low precision. The signal detection method in the nozzle cavity acquires the fluid signal directly from the nozzle(Chahine et al. 1983, Ma et al. 2016). The signal is very powerful with less disturbance and high precision, but the sensor arrangement is difficult especially for the small-sized nozzle. Besides, both detection methods are unable to overcome the influence of high confining pressure environment. As the confining pressure increases, the reliability of the sensor and target is significantly reduced and the effectiveness is drops dramatically.

To solve the above problems, this paper proposes a method for detecting the characteristics of self-resonating water jet based on pressure signal propagating within pipelines. The pressure sensor was installed on the pipeline right before the nozzle outside the high pressure tank, to acquire the pressure signal resulting from the self-resonance.

## 2 EXPERIMENT

### 2.1 Facilities

The self-resonating water jet is usually applied in a confining pressure environment, and the advantages of the technology can only be fully exerted under the confining pressure condition. For this purpose, a test device with high confining pressure conditions is built, as shown in Figure 1. The high pressure tank is used to simulate a high confining pressure environment. The confining pressure is controlled by the relief valve, and the test nozzle is placed in the high pressure tank. The adjustment of the incoming pressure, the confining pressure and the target distance can be realized by the control cabinet. The pressure sensor installed on the wall is used to collect the confining pressure parameter, and the flow rate is recorded by the rotameter.

There are 3 measuring points in the test device. The measuring point 1 and the measuring point 2 are used for collecting the pressure signals inside the pipeline, which are respectively arranged near the outlet of the high pressure pump and on the pipeline right before the high pressure tank, as shown in Figure1. Measuring point 3 is used to collect the signals from the pressure sensor arranged on the side wall of the nozzle inside the high-pressure tank as a comparative test. The output of transducers was captured with the data logger (Model: LMS SCADAS Mobile SCM05) which is connected to the computer. The time-domain and frequency-domain characteristics can be obtained in real time.

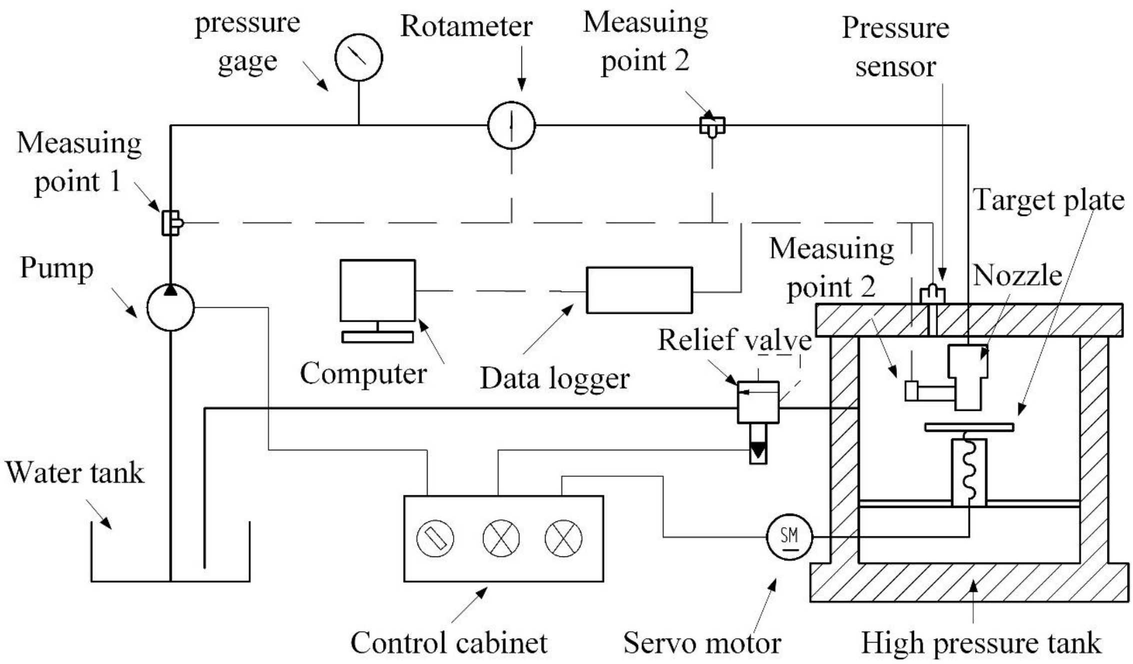


Figure 1. Schematic of the experimental setup

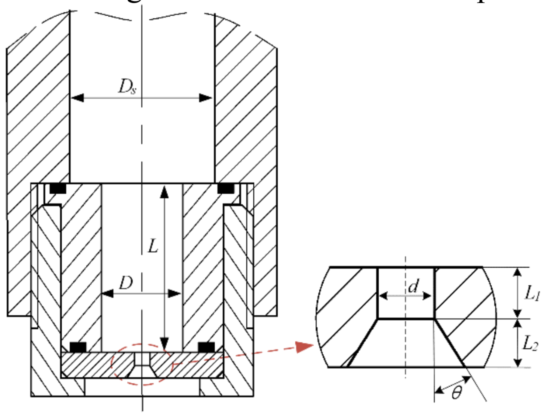


Figure 2. Schematic diagram of the organ-pipe nozzle and lip geometry.(a) Organ-pipe nozzle; (b) Enlarge of the nozzle lip

## 2.2 Nozzle geometry

Due to its strong erosion ability, low flow resistance coefficient and simple structure, the organ -pipe nozzle has been extensively studied and applied, thus the organ-pipe nozzle was used to produce self-resonating water jet in this experiment. A schematic of the organ-pipe nozzle is shown in Figure 2. Organ-pipe nozzle consists of an upstream area contraction (*Ds/D*), a downstream area contraction (*D/d*), and a resonant chamber with a length of *L* and a diameter of *D*. Peak resonance will occur when the acoustic natural frequency of the organ-pipe is close to the self-excited frequency(Johnson et al. 1984).

The self-excited frequency $f^*$, corresponds to the Strouhal number $S_d$ , can be defined as

$$f^* = S_\mathrm{d} \frac{v}{d} \tag{1}$$

where, $d$ and $v$ are the diameter and velocity of the jet individually.

Organ-pipe's acoustic natural frequency $f^n$ is determined by the chamber length $L$ which is expressed below:

$$f^n = K_n \frac{c}{L} \tag{2}$$

For $Ds/D > 1$, the "mode parameter" $K_n$ is given by

$$K_n = \begin{cases} n/2\,, & \frac{D}{d} < 1/\sqrt{\mathrm{M}} \\ (2n-1)/4\,, & \frac{D}{d} > 1/\sqrt{\mathrm{M}} \end{cases} \tag{3}$$

In these expressions $n$ is the mode number of the organ-pipe, M stands for the Mach number(Johnson et al. 1984).

The major challenge in designing an organ-pipe nozzle is that the initial self-excited frequency has to match with the chamber's acoustic natural frequency. This can be described by the following equation:

$$f^* \approx f_n \Rightarrow L/d = \frac{K_n}{MS_d(1+\beta)} \tag{4}$$

Based on the above principles, the organ-pipe nozzle was designed, and the parameters are listed in Table 1.

**Table1** Test parameters and self-resonating frequency

| ***$D_s$*(mm)** | ***D*(mm)** | ***d*(mm)** | ***L*(mm)** | **$f^n$(kHz)** |
|---|---|---|---|---|
| 23 | 10 | 2 | 24 | 14.9 |

As shown in Figure 2(a), the self-excited nozzle is constituted by the organ-pipe chamber and the orifice. A disk formed nozzle tip is bored the cylindrical orifice of diameter $d$, length $L_1$, and a conical expansion section of length $L_2$, angle $\theta$ (Figure 2(b)). In this study, the influence of nozzle lip geometry on the self-resonating water jet characteristic is studied by the above detection method. Table 2 lists the geometric properties of the nozzle lips investigated. The velocity of the jet is kept constant during the test, and the test parameters are shown in Table 3. At the flow rate, the motor speed is 621 $\mathrm{r \cdot min^{-1}}$, and the gearbox reduction ratio is 4.45. The pressure pulsation fundamental frequency $f_p$ caused by the three-piston high-pressure pump is 6.98 Hz.

**Table2** Geometry of the nozzle lips that employed

| **$L_1/d$** | **$L_2/d$** | **$\theta$(°)** |
|---|---|---|
| 15 | 1.0, 1.5, 2.0, 2.5, 3.0 | 20 |

**Table3** Test parameters and self-resonating frequency

| ***P*(MPa)** | **$v$(m.s$^{-1}$)** | **c(m.s$^{-1}$)** | **$f_p$(Hz)** |
|---|---|---|---|
| 15 | 165 | 1480 | 6.98 |

## 3 ANALYSES OF EXPERIMENT RESULTS

### 3.1 Pressure oscillation characteristics

To validate the detection method, pressure oscillation characteristics as the main characteristic of self-resonating jet, which are usually described by the time-domain and frequency-domain characteristics, were uncovered firstly.

#### 3.1.1 The time-domain characteristics

The measuring points 1 and 2 are selected for analysis. The test parameters are shown in Table 2. During the test process, the confining pressure and target distance parameters are adjusted to achieve peak resonance. The confining pressure is 1.6 MPa and the target distance is 3*d*. The time-domain pressure signals of the measuring points 1 and 2 are obtained as shown in Figure 3.

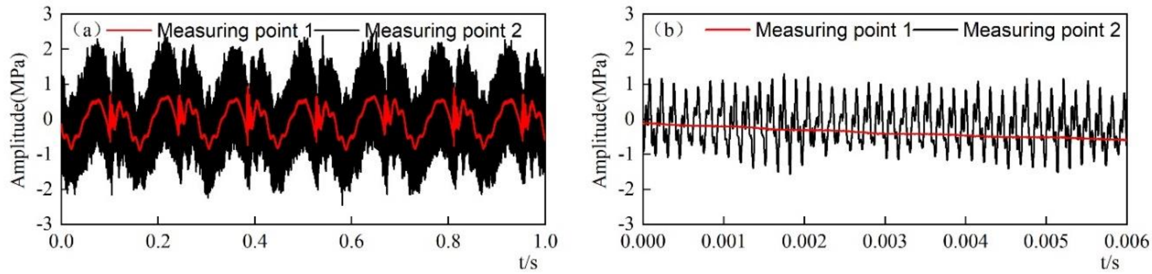


**Figure 3.** (a)Time-domain waveform of the pressure signal and (b) the locally amplified time-domain waveform

It can be seen from Figure 3(a) that the signal of the measuring point 1 is a low-frequency pressure fluctuation with an amplitude of about 0.8 MPa, but the signal amplitude of the measuring point 2 is about 2.0 MPa and contains the frequency component of point 1. It is also clear from the Figure 3(b)(the locally amplified time-domain waveform) that the signal of the measuring point 1 is approximately a straight line within 6 ms, showing a low-frequency characteristic, while the signal of the measuring point 2 exhibits obvious high-frequency periodic characteristics.

The measuring point 1 is close to the pump outlet, and the collected signal mainly comes from the low-frequency pressure pulsation caused by the reciprocating motion of the plungers and the random interference of the pipeline. The measuring point 2 is close to the test nozzle, and the signal acquired is mainly caused by high-frequency pressure oscillations and intense cavitation noise. Based on the acoustic theory, the high-frequency oscillation signal of measuring point 2 propagates upstream along the pipeline fluid, and the low-frequency pulsation signal of measuring point 1 propagates downstream. While the attenuation coefficient decreases as frequency increases. So the signal of measuring point 2 contains the component of the measuring point 1, while the signal of the measuring point 1 has almost no component of the signal 2. The time-domain pressure signal analysis results show that the pressure signal in the pipeline can clearly show the high-frequency pressure oscillation characteristics of the self-resonating jet. Nevertheless, the composition of the oscillating signal cannot be identified, and the pressure oscillation signal must be analyzed in the frequency domain.

#### 3.1.2 The frequency-domain characteristics

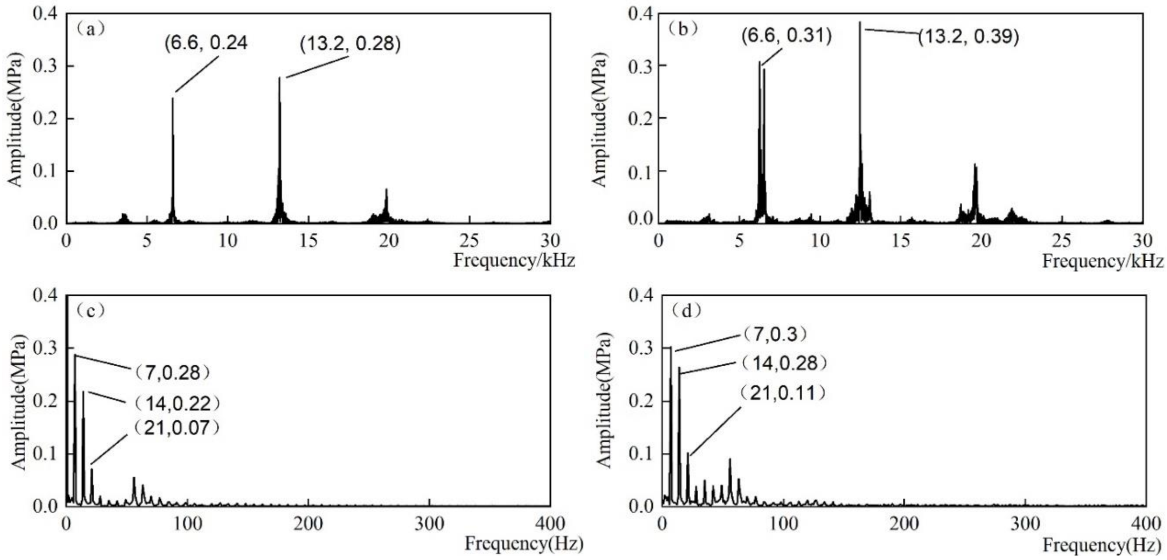


**Figure.4** Spectrum of the pressure signal: (a) spectrum at point 2; (b) spectrum at point 4; (c) low frequency spectrum at point 2; (d) spectrum at point 1

The test conditions are the same as above, and the pressure signals of measuring points 1, 2, and 4 are selected for analysis. The measuring point 4 is located on the nozzle inside of the high-pressure tank, to measure the pressure oscillating inside of the nozzle chamber. During the test process, the pressure signals of the measuring points 1, 2, and 4 are acquired synchronously.

Figures 4(a) and (b) show the signal spectrum of points 2 and 4 respectively. It can be seen that the spectra of both signals are composed of high frequency components of about 6.6 kHz and 13.2 kHz. The self-excited frequency is 13.2 kHz, and very close to the acoustic natural frequency of the organ nozzle $f^{n}$ = 14.9 kHz (Table 1). So the self-resonating water jet achieves the peak resonance at this time. The 6.6 kHz in the spectrum is the sub-harmonic of the self-excited frequency, also known as the half harmonic.

From the spectra, the spectrum structure of measuring point 2 and measuring point 4 is consistent, but the amplitude is slightly different (due to the attenuation of the wave ). The measuring point 4 detects the signal inside the nozzle, and the pressure fluctuations inside the nozzle system correlate with target plate pressure fluctuations(Chahine et al. 1983). Figure 4(c) is an enlarged view of the low-frequency part of Figure 4(a), which is compared with the spectrum of measuring point 1 (Figure 4(d)). The fundamental frequencies of them are 7 Hz, which is caused by the fluctuating frequency of high-pressure pump $f_p$ = 6.98 Hz.

The frequency-domain analysis of the pressure signal shows that the spectral analysis of the pressure signal in the pipeline can identify the composition and amplitude of the pressure oscillation characteristics, to characterize the self-resonating water jet.

### 3.2 Influence of nozzle lip length on frequency characteristic

Tthe influences of the nozzle lip length on frequency characteristic are studied by the above detection method. First, the evolution of self-excited frequency and the corresponding spectra as $L_2$ increases were given in Figure 5. It is clear from the figure that the self-excited frequency changes significantly with the increase of the $L_2/d$. In Figure 5(a), at $L_2/d$ = 1, only three peak frequencies are shown and the energy is very concentrated. However, with the increase of $L_2/d$, the self-excited frequency $f^*$ decrease as shown in Figure.5(b). At the same time, there appear many different frequency components. This resulted from that the self-excited frequency $f^*$ is far from the acoustic natural frequency where no strong resonating occur.

The analysis above shows that the detection method can be used to quantify the performance of self-resonating water jet. Both reliability and accuracy are enough to uncover the influencing mechanism of different factors.

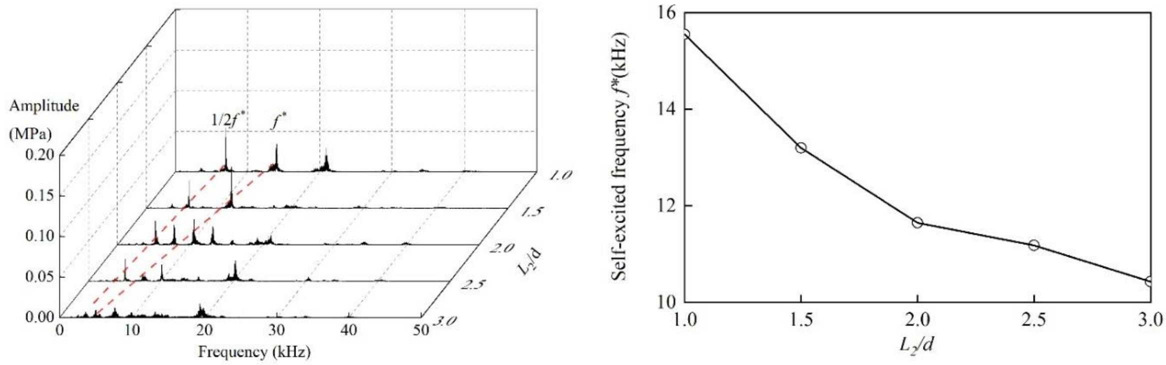


**Figure.5** Characteristics changing as a function of $L_2/d$.(a) Spectrum of the pressure signal spectrum at point 2; (b) self-excited frequency evolution as increasing of $L_2/d$.

## 4 CONCLUSIONS

(1) A method for detecting the characteristics of self-resonating water jet based on pressure signal within the pipeline is proposed. Compared with the existing methods, the method moves the pressure sensor from inside to the outside of the high-pressure tank to avoid the influence of confining pressure.
(2) The spectral characteristics of the pressure signal from inside the pipeline are consistent with the signal obtained inside the nozzle cavity, which can characterize the pressure oscillation characteristics of the jet fully.
(3) The detection method was successfully applied for studying the influence of nozzle lip geometry on the characteristic of self-resonating water jet, which verified its reliability and accuracy further.
(4) This method paves the way for the study of self-oscillation jet technology under high confining pressure. It can be used not only as a detection method for the characteristics of self-resonating nozzles in the laboratory but also as a control system for the performance of self-resonating nozzles in the field.

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## REFERENCES

Johnson Jr, Virgil E., et al. "The development of structured cavitating jets for deep-hole bits." SPE Annual Technical Conference and Exhibition. *Society of Petroleum Engineers*, 1982.

Li Gensheng et al. "Investigation and application of self-resonating cavitating water jet in petroleum engineering." *Petroleum science and technology* 23.1 (2005): 1-15.

Hu Dong et al. "Analytical and experimental investigations of the pulsed air–water jet." *Journal of fluids and structures* 54 (2015): 88-102.

Li Deng et al. "Effects of area discontinuity at nozzle inlet on the characteristics of high speed self-excited oscillation pulsed waterjets." *Experimental Thermal and Fluid Science* 79 (2016): 254-265.

Ma Fei et al. "Experimental study of self-resonating water jet frequency characteristics." *Journal of Mechanical Engineering* 52.14 (2016): 182-187.

Chahine Georges L., Andrew F. Conn, and Virgil E. Johnson Jr. "*Cleaning and cutting with self-resonating pulsed water jets.*" 2nd US Water Jet Conference. 1983.

Johnson Jr Virgil E., et al. *Research and development of improved cavitating jets for deep-hole drilling*. No. SAND-83-7461. Hydronautics, Inc., Laurel, MD (USA), 1984.

## NOMENCLATURE

$D$, organ-pipe diameter
$L$, organ-pipe length
$d$, orifice diameter
$L_1$, orifice length
$L_2$, lip length
$\theta$, lip expansion angle
$f^*$, self-excited frequency
$f_n$, organ-pipe's acoustic natural frequency
$f_p$, fluctuation frequency of pump
$S_d$, Strouhal number
$v$, jet velocity
$M$, Mach number
$c$, sound speed in water
$K_n$, mode parameter
$\beta$, end correction