Effects of Water Pressure on Plasma Sparker’s Acoustic Characteristics

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Abstract—Acoustic signals can be generated with a corresponding bubble oscillation induced by spark discharge. Plasma sparker has been applied in the oceanic seismic exploration for decades. In order to get high resolution seismic exploration at great water depth, the so-called deep-towed plasma sparker was proposed. In this paper, the acoustic characteristics under the water pressure ranging from 0.1 to 1.0 MPa are demonstrated. The experimental results indicate that the expansion pulse peak has nothing to do with the water pressure ranging from 0.1 to 1.0 MPa. However, the collapse pulse peak changes violently with the increasing of the ambient pressure. The collapse pulse peak falls by half approximately from 0.1 MPa to 1.0 MPa, and is not stable comparing to the expansion pulse peak. In addition, the acoustic energy and electro-acoustic energy efficiency decrease when the ambient pressure increases. The fundamental frequency increases dramatically from 500 to several thousand Hertz with the increasing of ambient pressure.

Keywords—Spark discharge, ambient pressure, acoustic characteristic

I. INTRODUCTION

Underwater spark discharge can generate acoustic waves and plasma-containing bubbles [1]. There are mainly two types of spark discharge, pulsed arc discharge and pulsed corona discharge. The old sparker is based on arc discharge, it generates discharge between a pair of electrodes [2], [3]. The plasma sparker based on corona discharge has been applied in the field of oceanic seismic investigation from the end of 1990s. For instance, GEO-Resource and SIG have developed their new plasma sparker. It has a longer electrode lifetime and better repeatability. During the past decade, we have developed our own plasma sparker which has been applied in several offshore construction projects, such as prospective of nuclear power plant, oversea bridge and geophysical survey and so on. It can operate perfect in shallow water. However, when the water depth increases, the horizontal resolution is reduced by the increasing width of the first Fresnel zone. And the penetration depth decreases by more transmission loss. A useful solution to overcome these two problems is make the source deep-towed. There are several deep-towed sources developed [4]–[7]. In our previous work [8], we have proposed a deep-towed plasma sparker based on corona discharge. A deep-towed plasma sparker means the plasma sparker is deployed near the seabed (about 100 m), and up to 2000 m in depth so far.

The water pressure has little influence on both types of spark discharge [9]. To developing a deep-towed plasma sparker, the influence of ambient pressure on acoustic waves should firstly be taken into consideration. The water pressure has obvious effect on expansion pulse and collapse pulse. The collapse pulse will vanish when the water pressure reach to a certain value [8]. However, the water pressure has little influence on the expansion pulse generated by pulsed arc discharge when the water pressure ranges from 0.1 to 1.0 MPa [10], [11]. Meanwhile, the water pressure has serious influence on bubble oscillation. It results in the increasing of fundamental frequency. Moreover, the seawater temperature changes when the depth increases. The spark discharge will be more intensive with the increasing temperature [12]. In order to study the influence of water pressure (0.1–1.0 MPa) on pressure pulse peak especially expansion pulse, and give more details to support the design of deep-towed plasma sparker, the acoustic characteristics of plasma sparker under different water pressure (0.1–1.0 MPa) are studied.

II. EXPERIMENTAL SETUP

Fig. 1 shows the experimental setup already used in our previous work [12]. Here, the simplified schematic of experimental setup is still introduced. A pulsed power source with an output energy from 5 J to 30 J with a step of 5 J is used to generate spark discharge at the tip of the electrode immersed in water. The voltage is varied from -2.3 to -5.6 kV with a capacitance of 2 µF. The electrode is made of a copper rod with a diameter of 1.4 mm covered by an insulating layer with a diameter of 5.5 mm. The pressure-resistant stainless reactor is grounded, and the inner and outer diameter is 260 mm and 280 mm, respectively.

The water conductivity and temperature are approximately 50 mS/cm and 25°C. The water pressure in the reactor can be varied from 0.1 MPa to 1.0 MPa by a pressure pump, and measured by a pressure gage. The acoustic pulses are measured by a hydrophone TL-30 (201 dB re 1 V/µPa, Wuxi Hongzhi Transducer Technology Co., Ltd., Wuxi, China) installed horizontally, and the distance between the hydrophone and the electrode tip is approximately 75 mm. An oscilloscope Tek DPO 7054 is used to record the signals.

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The key point to design a deep-towed plasma sparker is the intensity of acoustic pressure at the range of frequency bands for high-resolution seismic investigation. The more intensive acoustic pressure, the higher source level. In fact, the source level and frequency band are the two key indexes of the plasma sparker. The higher source level means more powerful acoustic signals, and the proper fundamental frequency determined the resolution. Hence, the effects of water pressure on the pressure pulse peak is required to be investigated. Meanwhile, from the point of energy efficiency, the electro-acoustic energy efficiency is another important point to evaluate the performance of plasma sparker. It is important to know that how much electric energy is required with the increasing of water pressure.

A. Expansion pulse peak and collapse pulse peak

The water pressure cannot inhibit the spark discharge, whereas it has serious influence on acoustic characteristics. Fig. 2 shows the typical acoustic waves under 0.1 MPa, 0.5 MPa and 0.9 MPa, respectively. There are two pressure pulses for each acoustic wave, the first one is expansion pulse, the second one is collapse pulse and a rarefaction pulse between them. The details can be found in [13]. In our previous work [14], we found that the electric pulse width has a significant effect on expansion pulse width. Here, the water pressure has no influence on the width of the expansion pulse. The expansion pulse peak under different water pressure is shown in Fig. 3. The expansion pulse peak at large discharge level has an apparent oscillation. The expansion pulse peak at 20 J/Pulse decreases by less than 6% from 0.1 MPa to 1.0 MPa. Hence, the expansion pulse peak has nothing to do with the water pressure ranging from 0.1 to 1.0 MPa. This result shows an agreement with the results of Lu et al. [10], Cook et al. [11]. However, the experimental results show that the expansion pulse peak falls by half when the ambient increasing from 0.1 MPa to 1.1 MPa [8]. The collapse pulse peak under different water pressure is given in Fig. 4. The experimental results show that the collapse pulse exhibits a strong water pressure dependence. The collapse pulse peak falls by half approximately from 0.1 MPa to 1.0 MPa. The collapse pulse vanishes when the ambient pressure more than 5.1 MPa [8]. The reasonable explanation for this result is that the bubble volume induced by spark discharge decreases when the ambient pressure increases. During the collapse process, the bubble energy dissipates to work against the high water pressure. Hence, the acoustic energy derived from the bubble energy decreases. It can also be found that the repeatability of the collapse pulse is weak compared with the expansion pulse at high discharge energy level.
B. Acoustic energy, electro-acoustic energy efficiency and fundamental frequency

In section A, the amplitudes of expansion pulse and collapse pulse are demonstrated. Here, the acoustic energy, electro-acoustic energy efficiency and fundamental frequency are taken into consideration. The electro-acoustic energy efficiency is an important index to evaluate the performance of plasma sparker. The fundamental frequency determines the resolution of seismic exploration. The acoustic energy is calculated by Eq. (1). The electro-acoustic energy efficiency is the percentage of discharge energy converted into acoustic energy. The fundamental frequency equals to the reciprocal of the first bubble period, namely the time interval between the expansion pulse and the collapse pulse. The calculation equations are as follows:

\[ E_a = \frac{4\pi r^2}{\rho c} \int p^2 \, dt \]  
\[ \eta = \frac{E_a}{E_{dis}} \]  
\[ f_{\text{fundamental}} = \frac{1}{\tau_b} \]

where, \( E_a \) and \( E_{dis} \) are the acoustic energy and discharge energy, respectively. \( r \) is the distance between the discharge electrode and the hydrophone, \( p \) is the pressure recorded by the hydrophone, \( \rho \) is water density, \( c \) is sound speed in water. \( \eta \) is the electro-acoustic energy efficiency, \( f_{\text{fundamental}} \) is the fundamental frequency, \( \tau_b \) is the time interval between the expansion pulse and the collapse pulse.

The acoustic energy under different water pressure is shown in Fig. 5. According the acoustic waves shown in Fig. 2, the acoustic waves at great ambient pressure has violent oscillation after the collapse pulse. In order to get the exact results of acoustic energy, the integral time in Eq. (1) is set from the beginning of expansion pulse to the end of collapse pulse. Hence, the calculated acoustic energy comprises three parts, such as expansion pulse, rarefaction pulse and collapse pulse. The acoustic energy at discharge energy level (5 J/Pulse, 10 J/Pulse and 15 J/Pulse) decreases gradually with the increasing of the water pressure. However, there is a fluctuation for high discharge level (20 J/Pulse, 25 J/Pulse and 30 J/Pulse). The explanation for this fluctuation maybe the rarefaction pulse peak increases with the increasing of ambient pressure. The acoustic energy decreases from the range 37–297 mJ to the range 11–198 mJ. Moreover, the acoustic energy at high discharge energy decreases less, with a range 34–70% when the water pressure increases. It indicates that larger discharge energy maybe more suitable for deep-towed plasma sparker. Fig. 6 gives the dates of electro-acoustic energy efficiency calculated by Eq. (2) under different water pressure. There is also a fluctuation at high discharge energy level. The results show that the larger discharge energy, the greater electro-acoustic energy efficiency. The electro-acoustic energy efficiency under 0.1 MPa is around 1%, it decreases with a range 0.21–0.65% at 1.0 MPa. The plasma sparker is based on corona-like discharge, the electro-acoustic energy efficiency is less than 3% [13]. The solution for improving the energy efficiency of deep-towed plasma sparker maybe to improve the discharge energy and re-design the emission array.

To yield high resolution seismic exploration, the plasma sparker is operated at a frequency range of from several hundreds to thousands hertz. The fundamental frequency is an important index of acoustic characteristics. According to Eq. (3), the fundamental frequency is the reciprocal of the bubble period, namely the time interval between the expansion and collapse pulse [8]. Fig. 7 shows the variation of fundamental frequency versus ambient pressure. The results of bubble period are from [15]. The fundamental frequency increases dramatically from 500 to several thousand Hertz with the increasing of ambient pressure. The explanation for this is that the bubble period decreases with the increasing of water pressure. The bubble costs more energy to overcome the higher water pressure. In addition, the larger discharge energy, the lower fundamental frequency. It indicates again that larger discharge energy is preferred in terms of obtaining low fundamental frequency of deep-towed plasma sparker.
IV. CONCLUSION

In this paper, the acoustic characteristics of plasma sparker under different water pressure have been studied, including pressure peak, acoustic energy and fundamental frequency, the main conclusions are as follows:

1) The expansion pulse peak has nothing to do with the ambient pressure ranging from 0.1 to 1.0 MPa, whereas the collapse pulse peak decreases violently with the increasing of water pressure.

2) Both of the acoustic energy and electro-acoustic energy efficiency decrease when the water pressure increases. The larger discharge energy, the larger electro-acoustic energy efficiency.

3) The fundamental frequency increases dramatically when the water pressure increases. The larger discharge energy generates lower fundamental frequency, which indicates that greater discharge energy is preferred for deep-towed plasma sparker.

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