Research Article

Effect of Prebreakdown Time on Shock Wave Generation Characteristics of Underwater Plasma Sound Source

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Acoustic array bunching is an effective method to realize the directional radiation of underwater plasma sound source (UPSS). The prebreakdown time is one of the decisive factors for the performance of acoustic array bunching. The working characteristics of the underwater plasma sound source and the prebreakdown process of underwater plasma arc discharge are deeply analyzed. The precondition of plasma sound source array bunching is given by analyzing the waveforms of electrical signals and acoustic signals. Through the experiments of arc discharge based on different aqueous solutions, a feasible scheme of underwater plasma sound source array bunching in salt water is proposed. Through the arc discharge experiments based on different system discharge parameters, the variation of prebreakdown time under the influence of different charging voltage, conductivity, and other parameters was studied. The experimental results show that the prebreakdown time decreases with the increase of charging voltage and conductivity. At the same time, the discharge current increases, the oscillation time decreases, and the energy injection rate on the electrode accelerates. The research results are helpful to understand the prebreakdown mechanism of plasma sound source and optimize the underwater plasma sound source array bunching scheme and the acoustic shock wave waveform.

1. Introduction

The high-power underwater strong sound source has a strong military and civilian demand background. During its development process, there have been many underwater strong sound sources with different generation mechanisms [1, 2], such as active material driven, electromagnetic, explosive, laser, parametric array, fluid driven, and plasma. Compared with the traditional underwater strong sound source, the discharge of UPSS can be divided into two forms: underwater high-voltage pulsed arc discharge and underwater corona discharge [3, 4]. The shock waves generated by the two kinds of discharges have the advantages of high instantaneous emission power, wide frequency coverage, high electro-acoustic conversion efficiency, good repeatability, and controllable acoustic radiation direction [4–6]. By using the acoustic lens method, curved surface reflection method and array bunching method, high intensity bunching acoustic shock wave with sharp directivity can be formed in the specified direction [7–10]. Therefore, this technology has been widely used in many fields, such as marine strategic resources development, oil pipeline blockage removal, medical extracorporeal shock wave lithotripsy, underwater ultra-wideband target detection, and remote secure communication [3–6, 11, 12].

The traditional acoustic lens method and curved reflector method are based on the geometric law to achieve acoustic bunching, and their radiation directivity and bunching gain are limited by the focus of the lens or curved reflector [7]. Therefore, for high-power UPSS, in order to flexibly control the radiation directivity and further improve the radiation intensity, the UPSS array bunching method can be used to form a strong bunching acoustic shock wave in a specified area [8–10]. This method not only reduces the requirement for the emission power of a single plasma sound source but also improves the safety and reliability of the
system. However, the UPSS will undergo a variety of complex physical and chemical processes in the process of instantaneous discharge. For example, it will produce physical phenomena such as huge pulse current, electromagnetic radiation, acoustic shock wave, and bubble pulsation. This process is called the “electrohydraulic effect” [3–5, 11]. In this paper, the arc discharge process of UPSS is divided into five stages [10, 12–17], including the prebreakdown stage, plasma channel formation (water breakdown) stage, acoustic shock wave formation stage, sound shock wave propagation and bunching stage, bubble pulsation, and bubble wave generation stage.

In order to achieve multi-source array bunching, it is necessary to ensure that the arrival time of the acoustic shock wave generated by each source (array element) at the bunching center point is consistent. However, the arc discharge process of UPSS is very complex, and there are many factors affecting the array bunching of the shock wave. Taking the bunching of two sound sources as an example, in order to realize the acoustic shock wave bunching at a specified position, the arc discharge of plasma sound sources must be synchronized well. In particular, the triggering of the dual-channel trigger switch should be synchronized, and the prebreakdown time and the generation time of the acoustic shock wave should also be consistent. The research results of references [10, 18] show that after the trigger switch of the underwater plasma sound source is turned on, the time interval between the time of shock wave generation and the time of plasma channel formation is strictly consistent. However, the time dispersion of the bubble wave generated by the bubble pulsation is larger. Therefore, in theory, as long as the plasma channel formation time of the two sound sources is controllable, the acoustic shock wave can be bunched at a specified position. After that trigger switch is a trigger and turned on, the formation of the acoustic shock wave still needs to go through two stages of prebreakdown and plasma channel formation, wherein the plasma channel formation is complete instantaneously. Therefore, it is very important to study the effect of prebreakdown time on plasma source array bunching.

In this paper, the prebreakdown process in the arc discharge process of UPSS is analyzed in depth, and the effect of prebreakdown time on the UPSS array bunching is studied through experiments. At the same time, the influence of different discharge parameters, such as water conductivity, discharge voltage and discharge current, on the prebreakdown time is analyzed to provide theoretical support for the subsequent research and design of UPSS array bunching.

In the second part of this paper, the working characteristics of UPSS are introduced, the experimental equipment of underwater plasma arc discharge is given, the typical electrical signal waveform and acoustic signal waveform are analyzed, and the concept of prebreakdown time is given; in the third part, the design idea of UPSS double-sound source array bunching experimental device is proposed, and the prebreakdown process in different aqueous solutions is analyzed; in the fourth part, the influence of different discharge parameters on the prebreakdown time is analyzed; finally, the research conclusions and future research directions are summarized.

2. Operating Characteristics OF UPSS

The arc discharge working process of UPSS is to convert the electric energy stored in the energy storage capacitor into sound energy. The arc discharge occurs between the discharge electrodes. When the field strength between the discharge electrodes reaches $10^3$–$10^4 \text{V/cm}$ [14]; that is, the injected electric energy is enough to dissociate and ionize the water medium, the high-voltage electrode in the discharge electrode will extend some “leaders” with high conductivity to the low-voltage electrode [12]. This process is usually called the prebreakdown process, or the electro-thermal breakdown process. When one of the leaders reaches the other electrode, the high field strength is still maintained between the tips of the electrodes, an electron avalanche will occur, and a highly conductive plasma discharge channel will be generated, the prebreakdown process will end, and the arc discharge stage will begin [14, 19]. At the moment when the plasma discharge channel is formed, the acoustic shock wave radiates omnidirectionally into the water, and gradually attenuates into a direct wave (shock wave) acoustic pulse in the process of propagation. If the acoustic shock wave needs to be radiated directionally to improve the radiation intensity in the specified direction, the center of the discharge electrode can be placed at the geometric focus of the curved reflector, and the direct wave will converge according to the geometric law to form a bunched shock wave [7]. With the end of the arc discharge between the discharge electrodes, the plasma discharge channel gradually extinguishes and evolves into a bubble with high temperature and high pressure inside. The bubble makes an expansion-contraction motion and produces a strong bubble shock wave [13–16]. The bubble collapses gradually during the pulsation process, and the arc discharge process ends at this time.

In this paper, the experimental device diagram of UPSS arc discharge is shown in Figure 1. The experimental device is mainly composed of five parts: high-voltage charging system, discharge circuit, high-voltage trigger system, charge and discharge control system, and measuring device. Directional radiation of a single sound source can be realized through the ellipsoidal reflector, that is, the discharge electrode is placed at the first focal point of the ellipsoidal reflector, and the generated shock wave will be reflected by the ellipsoidal reflector and form a bunching wave at the second focal point. The discharge voltage on the discharge electrode was measured by high-voltage probe, the discharge current on the discharge electrode was measured by Rogowski coil, and the acoustic shock wave waveform (including direct wave (shock wave), bunching wave, and bubble wave) was measured by the pressure sensor. The sound wave measuring point is located in the direction of the sound axis of the ellipsoidal reflector, 240 mm away from the center of the sound source. The measured electro-acoustic characteristics of UPSS during arc discharge are shown in Figure 2.
According to Figure 2(a), in addition to the acoustic shock wave signal measured by the pressure sensor, the electromagnetic interference (EMI) signal can also be clearly seen. The EMI signal is caused by the trigger pulse and the intense discharge current crosstalk to the pressure sensor. The EMI signal corresponds to the discharge voltage start time \(6.0 \text{ ms}\) and the discharge current start time \(6.252 \text{ ms}\) measured on the discharge electrode, as shown in Figure 2(b).

In Figure 2(a), the direct wave propagating to the measurement point 240 mm appears at 6.416 ms, so the propagation time is

\[
t = \frac{L}{C} = \frac{240 \text{ mm}}{1480 \text{ m/s}} \approx 0.162 \text{ ms}. \tag{1}
\]

Here, \(L\) is the propagation distance of the direct wave (shock wave), \(C\) is the propagation velocity of the direct wave in water. The sound velocity is related to many factors, and it is approximately 1480 m/s in this paper. Therefore, the formation time of the direct wave is

\[6.416 \text{ ms} - 0.162 \text{ ms} = 6.254 \text{ ms}. \tag{2}\]

The experimental results show that the direct wave is formed at the moment when the strong oscillating discharge current (6.252 ms) appears, rather than at the moment when the discharge voltage appears on the secondary side of the trigger switch after the trigger switch is turned on. The strong oscillating discharge current mentioned here means that when the plasma channel discharges violently, the resistance in the channel is very small, so the discharge current shows an underdamped oscillation \[12\]. The secondary of the trigger switch is connected to the discharge electrode, and the discharge electrode is placed in the water medium. When the trigger switch is turned on, the plasma arc discharge does not occur immediately, but after a period of time, the plasma arc discharge and acoustic shock waves are generated. This period of time is called the prebreakdown time. That is to say, the prebreakdown time starts at the moment when the secondary discharge voltage of the trigger

Figure 1: Experimental device diagram of UPSS arc discharge.

Figure 2: Waveform of electro-acoustic signal in arc discharge process of plasma sound source. (a) Is the acoustic shock wave waveform. (b) Is the discharge voltage and current waveforms.
switch appears, and ends at the moment when the secondary discharge voltage oscillates rapidly or the strong oscillating discharge current appears. Good prebreakdown time consistency is one of the important prerequisites for UPSS array bunching. In this paper, the prebreakdown process and the electrical parameters affecting the prebreakdown time are analyzed through experimental research, which provides a reliable guarantee for the realization of UPSS array bunching.

3. Analysis of Prebreakdown Process

During the underwater plasma arc discharge, the discharge electrode is placed in water. When the field strength in the discharge electrode gap is strong enough to dissociate and ionize the water medium, the prebreakdown process will be affected not only by the energy release rate on the energy storage capacitor but also by the electric energy injection rate on the discharge electrode [12, 14].

In this paper, the design idea of the dual sound source array bunching experimental device based on UPSS is proposed. The experimental principle diagram is shown in Figure 3. The high-voltage charging system is used to charge two groups of energy storage capacitors respectively, and the capacitance values of the two groups of energy storage capacitors are the same. In order to ensure the synchronous triggering of the two sound sources, the same trigger signal is used to control the two sets of high-voltage trigger systems respectively, and the two sets of high-voltage trigger systems have the same structure. The high-voltage trigger systems of the two channels are connected with two sets of discharge electrodes, and the two sets of discharge electrodes are placed in the same water medium. Based on this design idea, on the premise of satisfying the experimental conditions, as long as the prebreakdown time of the dual sound source is strictly controlled, the bunching of the dual sound source based on UPSS can be realized.

However, for the prebreakdown process, the main factors affecting the prebreakdown time include the synchronization of trigger switches, the distance between discharge electrodes, discharge voltage, discharge current, conductivity, and so on. Secondly, discharge electrode material, discharge electrode structure (tip-tip or tip-plate structure), water temperature, and other factors will also affect the prebreakdown time [20–24]. In the experimental study, it is assumed that the trigger switch has good synchronization performance, and the discharge electrode adopts a tip-to-tip structure, which can reduce the discreteness of plasma channel formation. In addition, the two sets of discharge electrode materials and electrode spacing are the same, and the water temperature is constant at 15°C. On this basis, the feasibility of array bunching is analyzed, and the influence of different discharge voltage, discharge current, conductivity, and other parameters on the prebreakdown time is discussed.

UPSS is usually used in tap water or salt water, that is, the water medium has a certain conductivity. Under the influence of the conductivity of the water medium, the “leader” with high conductivity will propagate towards the other end of the discharge electrode. After a period of time, that field strength of the leader head increases, causing the movement of the conductive particles to accelerate, thus preparing for the vaporization and ionization of the aqueous medium. When the density of the water medium conductive particles in the discharge electrode gap is high enough, the leader continues to propagate to the other end of the discharge electrode, thus forming a high-voltage arc across the two electrodes. At this time, the energy will continue to be injected, forming a plasma arc discharge channel, which will achieve water dielectric breakdown [14, 20]. It can be seen that the influence of the conductivity of the water medium on the prebreakdown time is more obvious. Next, we will analyze the prebreakdown time in the process of plasma discharge in tap water and salt water through experiments.

The experimental conditions are as follows: the material of the discharge electrode is copper, the structure is tip-tip, the water temperature is 15°C, the capacitance of the energy storage capacitor is 5 μF, the charging voltage is 20 kV, the conductivity of tap water is 0.3 mS/cm, and the conductivity of salt water is 17.8 mS/cm. For a single plasma sound source, the arc discharge is discrete. [7] Under the repeated experimental conditions, five groups of arc discharge experiments were carried out in tap water and salt water respectively, and the changes of the secondary discharge voltage of the trigger switch were measured. The measurement results are shown in Figure 4 and Figure 5, respectively.

It is obvious from Figure 4 that in the process of plasma arc discharge in tap water, the prebreakdown time is random, ranging from tens of microseconds to hundreds of microseconds. This conclusion is consistent with that found in references [14, 20]. Therefore, in tap water, even if the parameters of each plasma sound source are the same, the prebreakdown time of each discharge is still quite different, so it is difficult to realize the synchronous discharge of two sound sources, let alone the array bunching of two sound sources.
It can be seen from Figure 5 that the conductivity of salt water is higher than that of tap water, the prebreakdown time in the arc discharge process is several microseconds, which is much less than that in tap water, and the time required for prebreakdown is very stable. Therefore, it is feasible to realize dual source array bunching in salt water. In order to further illustrate this conclusion, we set the charging voltage at 16 kV, 20 kV, and 24 kV, the capacitance of the storage capacitor at 10 μF, and other parameters unchanged. Five plasma arc discharge experiments were carried out for tap water and salt water respectively. The prebreakdown time comparison results obtained are shown in Table 1.

In Table 1 shows that the prebreakdown time in tap water is random, while the prebreakdown time in salt water is less random. In addition, in both tap water and salt water, the prebreakdown time decreases with the increase of the charging voltage. Observe the average value of the prebreakdown time when the capacitance of the energy storage capacitor is 10 μF and the charging voltage is 20 kV in Table 1, and observe the average value of the prebreakdown time when the capacitance of the energy storage capacitor is 5 μF and the charging voltage is 20 kV in Figure 4. It is also found that with the increase of the capacitance of the energy storage capacitor, the prebreakdown time becomes shorter and the randomness is smaller.

The above analysis shows that the prebreakdown time is related to the injection rate of the electric energy of the discharge electrode. By analyzing the changes of discharge voltage, discharge current, and conductivity, the variation law of prebreakdown time under different discharge parameters can be mastered. It provides theoretical support for the research of UPSS array bunching.

### 4. Variation of Prebreakdown Time under Different System Parameters

In this paper, the precondition of the underwater plasma dual sound source array bunching is that the trigger switches of the two sound sources are triggered synchronously, the arc discharge occurs synchronously, and the direct wave is formed synchronously. According to the research results of reference [10], the time discreteness of the direct wave and the bunching shock wave formed after the arc discharge of UPSS is small. Because the time interval between the formation time of the direct wave and the conduction time of the trigger switch is consistent. After the direct wave is reflected and converged according to the geometric law of the curved reflector, the bunching shock wave is formed. Therefore, there is also a strict time interval between the bunching shock wave and the direct wave. Therefore, after the trigger switch is turned on, as long as the prebreakdown time is consistent, the dual sound source array bunching can be realized. The prebreakdown time is affected by the charging voltage, the distance between the discharge electrodes and the conductivity. By studying the variation of

| Discharge voltage (kV) | 16 kV | 20 kV | 24 kV |
|------------------------|-------|-------|-------|
| Prebreakdown time in tap water (μs) | 292.0 | 93.0 | 62.0 |
| Prebreakdown time in salt water (μs) | 113.0 | 63.0 | 58.0 |
| Mean value (μs) | 165.4 | 79.82 | 71.08 |
| Prebreakdown time in tap water (μs) | 4.1 | 4.1 | 4.0 |
| Prebreakdown time in salt water (μs) | 4.1 | 4.0 | 4.0 |
| Mean value (μs) | 4.64 | 4.04 | 4.0 |

*Table 1: Comparison of prebreakdown time in tap water and brine.*
prebreakdown time under different system parameters, the experimental results are helpful for us to understand the prebreakdown process.

4.1. The Conditions of the First Experiment. The capacitance of the energy storage capacitor is 10 μF, the charging voltage is 16 kV, the water temperature is 15°C, the distance between the discharge electrodes is 4 mm, and the conductivities are 0.3 mS/cm, 22.1 mS/cm, and 44.1 mS/cm, respectively. Under different conductivity conditions, the waveforms of discharge voltage and discharge current measured in the experiment are shown in Figure 6.

The results show that the conductivity of the water medium has an obvious effect on the prebreakdown time. The larger the conductivity is, the smaller the prebreakdown time is, and when the conductivity is only 0.3 mS/cm (in tap water), the prebreakdown time will be greatly increased. In Figure 6(b), when the conductivity is relatively large, the discharge current will reach several tens of KA. At this time, the current density at the tip of the discharge electrode is very high, so that the water medium near the tip of the discharge electrode is continuously heated, gasified, and ionized to generate microbubbles. With the increase of the field strength between the electrodes, the “leader” quickly propagates and propagates to the other electrode, forming a plasma channel, and then triggering the water medium breakdown. When the conductivity is 0.3 mS/cm, the discharge current on the electrode occurs later and has a smaller amplitude. This is because when the discharge voltage is larger, the larger field strength between the electrodes will still make the “leader” propagate from the high-voltage electrode to the low-voltage electrode and then form the plasma channel discharge, and the discharge current will be generated on the electrode. Figure 6(b) also shows that with the increase of conductivity, the peak value of discharge current increases and the oscillation time decreases after the breakdown of the water medium. It is shown that the injection rate of electric energy in the discharge electrode increases and the waveform parameters of the discharge current directly affect the waveform parameters of the acoustic shock wave. The electric energy mentioned here means the electric energy injected into the discharge electrode after the prebreakdown time is determined, which can
be obtained by integrating the discharge current waveform and the discharge voltage waveform at the same time.

When the conductivities are 22.1 $mS/cm$ and 44.1 $mS/cm$, respectively, the waveforms of the acoustic shock waves generated by the arc discharge are shown in Figure 7. As can be seen from Figure 7, when the conductivity is large, the peak pressure of the shock wave is large and the bottom width of the shock wave waveform is small. At the same time, due to the influence of prebreakdown time, the generation time of the shock wave is ahead of that of the shock wave generated when the conductivity is small. This shows that the parameters of the shock wave are related to the parameters of the discharge current and the prebreakdown time.

4.2. The Conditions of the Second Experiment. The capacitance of the energy storage capacitor is 10 $\mu F$, the conductivity is 22.1 $mS/cm$, the water temperature is 15°C, and the distance between the discharge electrodes is 4. The charging voltages are 16 kV, 20 kV, and 24 kV, respectively. Under different charging voltage conditions, the waveforms of discharge voltage and discharge current measured in the experiment are shown in Figure 8.

From Table 1 and Figure 8(a), we can see that during the arc discharge of UPSS, the prebreakdown time in salt water decreases with the increase of the charging voltage of the system, but the decrease is not obvious. As is evident from Figure 8(b), the peak value of the discharge current increases as the charging voltage increases. At this time, the electric field strength at the tip of the electrode is larger, and the prebreakdown time will be reduced. The peak value of the discharge current is approximately linear with the energy injection rate of the discharge electrode, the peak value, and the pulse width of the acoustic shock wave.

Figure 9 shows the acoustic shock wave waveforms under different charging voltage. It can be clearly seen that the waveform parameters of the acoustic shock wave are basically consistent with the waveform parameters of the discharge current, such as peak pressure, full width at half maximum (FWHM), and other parameters.
To sum up, the results of the two experiments can provide theoretical support for the design of acoustic shock wave parameters generated by UPSS arc discharge and UPSS array bunching.

5. Conclusions

In this paper, the prebreakdown process of UPSS arc discharge based on different aqueous solutions is studied, and the conclusion that UPSS array bunching can be realized in salt water is put forward. Through the UPSS arc discharge experiments based on different system discharge parameters, the change law of prebreakdown time under the influence of different system parameters is analyzed, and some meaningful conclusions are obtained:

(i) When the trigger switch is turned on, the secondary of the trigger switch will have a discharge voltage, which is called the prebreakdown initiation time. When the discharge voltage oscillates rapidly or a large oscillatory discharge current appears on the discharge electrode, it is called the end time of prebreakdown. At the end of the prebreakdown process, almost simultaneously, the arc discharge produces an acoustic shock wave. Therefore, the precondition of UPSS array bunching is that the prebreakdown time and the formation time of acoustic shock wave are controllable, and the synchronization is good.

(ii) The experimental results show that the randomness of the prebreakdown time is obvious when the arc discharge is carried out in tap water, while the prebreakdown time is more stable when the arc discharge is carried out in salt water. Therefore, UPSS array bunching can be realized in salt water with a certain conductivity.

(iii) The prebreakdown time decreases with the increase of the charging voltage and conductivity of the UPSS system. At the same time, the peak value of the discharge current on the discharge electrode increases, the oscillation time decreases, and the electric energy injection rate becomes faster, which makes the current density at the tip of the electrode increase, resulting in a faster prebreakdown heating process.

In this paper, when studying the change law of the prebreakdown time, it is assumed that the water temperature is constant, the discharge distance is fixed, the triggering conditions are consistent, and the ablation of the electrode material is negligible. The experimental research is carried out based on the above assumptions. In the followup, we will further study the arc discharge process of UPSS, the relationship between system parameters and waveform parameters, the statistical analysis of waveform generation characteristics, and the bunching of the dual sound source. These studies will provide theoretical support for the optimization design of UPSS array bunching and acoustic shock wave waveform, and have important guiding significance.

Data Availability

The data used to support the findings of this study are available from the corresponding author upon request.

Conflicts of Interest

The authors declare that they have no conflicts of interest.

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