Propagation characteristics of underwater plasma pulse sound source

Zhenyang Chen, Bing Yan, Xiaobing Zhang
College of Weapons Engineering, Naval University of Engineering, Wuhan 430033, China
Chenzhenyang_86@163.com

Abstract. The signal propagation characteristics of underwater plasma pulsed sound source have important guiding significance for the research and application of underwater directional radiation technology. In this thesis, the model propagation method is used to analyze the signal propagation law of underwater plasma pulse source with different depths. Firstly, the propagation model of underwater plasma sound source is established. Secondly, the distribution characteristics of underwater sound field at different depths are simulated. The research results show that the simulation results can express the underwater sound field characteristics at different depths, which proves the effectiveness of the simulation model, and lays a foundation for further research on underwater pulse directional radiation technology and improving the underwater application of pulse sound source.

1. Introduction
Underwater directional sound is a directed energy technology that can be used for underwater interference attacks. The plasma sound source is an important underwater directional strong sound source, which can generate a much higher pulse sound pressure level than the traditional transducer, and has the characteristics of small volume, frequency bandwidth, and controllable emission mode. The sound source is based on "electro-hydraulic effects", which is a high-power pulse capacitor that discharges high-voltage, high-current pulsed water between the electrodes to form an underwater high-temperature plasma, which produces super-impact sound pulses. At present, it has been widely used in many fields such as industry, science, medicine, military, etc., and such as submarine geological exploration, sewage treatment, extracorporeal shock wave lithotripsy, pipeline unblocking, underwater target detection, underwater defense, etc. The underwater plasma sound source is one of several kinds of strong sound pulse sources with large sound power and wide spectrum. The directional radiation technology can also make the strong sound shock wave converge into a specific direction to form the directional sound energy with concentrated energy. It is currently a cutting-edge hotspot technology in the field of underwater attack and defense. In recent years, many universities in China, such as Dalian University of Technology and the Institute of Electrical Engineering of the Chinese Academy of Sciences, have carried out detailed research on the corona discharge plasma sound source system, and developed underwater multi-electrode spark source and conducted corresponding tests. The National Defense University of Science and Technology, Northwestern Polytechnical University and other units have intensively studied the arc discharge type underwater plasma strong sound source system, and obtained higher than higher sound pressure through near field focusing. The corona discharge type multi-electrode plasma sound source mainly obtains certain beam directivity by means of array synthesis, and has the advantages of stable waveform and good repeatability, but the sound source
level is usually low and the arc discharge type plasma sound source passes. The energy focusing of the ellipsoidal reflecting surface can obtain a higher sound pressure at a close fixed focus, but will accelerate the diffusion after passing the focus, and cannot be used for long-distance propagation.

2. Generation mechanism of underwater plasma strong acoustic pulse

The underwater plasma discharge theory is developed from the theory of Townsend's discharge. The underwater plasma discharge process can be simply described as follows: After the alternating current is rectified, the pulse capacitor is charged, and when the predetermined voltage is reached, the additional spark gap is broken, that is, the trigger switch is turned on. The high pressure is rapidly loaded to both ends of the discharge electrode placed in the water, and the aqueous medium between the electrodes is excited, ionized and collided with a plurality of chemically active particles under the action of a strong electric field (on the order of $10^4$ to $10^5$ V/cm). The filamentous, dendritic or brush-like precursor of an electrode is produced and developed, a process known as pre-breakdown. When some "pilot" of high conductivity turns on the positive and negative poles, the electric energy will be released in a surge manner, forming a plasma channel, and the thermal breakdown process will end and enter the pulse discharge phase. Because the discharge time is extremely short, the channel expands at a high speed, and the surrounding water medium has weak compressibility and inertia, thus forming a strong acoustic shock wave to propagate outward. This strong acoustic shock wave is also called shock wave. In the later stage of the discharge, the plasma discharge channel forms bubbles, and the bubble repeats the attenuation movement of expansion and contraction, and radiates pressure waves outward, which is called bubble wave. The bubble gradually annihilates during the pulsing process until the end of the discharge process, as shown in Figure 1.

![Fig.1 Principle of underwater plasma acoustic wave generation](image)

The underwater plasma discharge system can be divided into four parts: high voltage generation system, charging system, discharge system and charge and discharge control system. The design of the discharge electrode, the design of the trigger electrode, the selection of the storage capacitor, the design of the charge and discharge control system, and the design of the ellipsoid reflector are key components of the underwater discharge system, as well as other auxiliary components such as the choice of aqueous solution. It will have a certain impact on the generation of underwater plasma sound sources and the efficiency of electro acoustic conversion. In addition, the design of the water tank, the selection of measuring equipment and the choice of measuring points will have an impact on the measurement results.

The function of the discharge electrode is to break down the aqueous solution between the electrodes under the action of instantaneous high voltage, forming a plasma channel between the two poles, and generating a huge shock wave. The component can be divided into an arc discharge electrode and a corona discharge electrode depending on the discharge mode. For the arc discharge electrode, according to the arc discharge generation mechanism, the pilot can be generated when the electric field intensity of the electrode surface exceeds a threshold of several kilovolts per centimeter. Therefore, a tip-plate or tip-tip electrode can be used to form a non-uniform electric field in order to
obtain the necessary maximum field strength. When a discharge occurs, a very large current (on the order of 1 kA to 100 kA) will be passed through the discharge electrode in a very short period of time (on the order of μs), so that the aqueous solution between the electrodes is rapidly ionized to form a plasma channel in the plasma channel. The temperature can reach $2 \times 10^4$ K ~ $5 \times 10^4$ K and the pressure can reach 1 GPa. This requires the electrode material to have a high melting point, high strength, good electrical conductivity, and easy processing. Commonly used electrode materials are copper, copper-tungsten alloy, silver tungsten alloy, graphite, brass and beryllium copper. Copper-tungsten alloy is generally used because copper-tungsten alloy has high conductivity, low loss rate and high tungsten. It has the advantages of melting point and is easy to process. The choice of the discharge electrode spacing is critical to improve the system's electroacoustic conversion efficiency, with a pitch of mm, and the discharge electrode spacing can be determined experimentally. When designing the electrode, attention should also be paid to the design of the discharge contact, the choice of materials, and the design of the insulation layer. For corona discharge, the geometry of the electrodes plays an important role. There is no through-plasma discharge channel formed during corona discharge, and the electrode spacing of the discharge is much larger than the electrode spacing of the arc discharge, generally in the order of cm, which can be generated when the voltage is low. The polarity of the corona discharge depends on the polarity of the electrode having a small radius of curvature. The electrode can be designed as a monopole head corona, a multi-head corona or a needle array corona. In addition, when the arc discharge electrode pitch is increased to a certain extent, the discharge form is converted into a corona discharge.

The high voltage trigger switch plays an important role in any pulse power system. This is because the technical parameters and characteristics of the switching elements have the most direct and most sensitive effects on the output power level, repetition frequency, pulse rise time, amplitude, etc. of the system. In the whole system, the energy stored in the capacitor is turned on by the trigger switch, and the discharge electrode is momentarily applied with high voltage for the purpose of accurately controlling the timing of the high-voltage pulse discharge of the entire discharge system. Among the underwater plasma sound source generating devices, the most common types of switches are: insulated gate bipolar transistors, thyristors and spark gap switches.

The storage capacitor is the energy storage mechanism of the whole system, which plays the role of storing and releasing energy. The high-power pulse capacitor is the main part of the charging and discharging system. It has a cylindrical shape and a rectangular shape in appearance; the outer casing material is made of iron, magnetic shell, bakelite and hybrid. The voltage ranges from a few thousand volts to hundreds of thousands of volts, and the capacitance ranges from tens of microfarads to hundreds of microfarads when 0.1 to 10n microfarads are used. In addition, because the bleed time is very short (on the order of μs), the energy is very large, which will quickly decompose and vaporize the oil in the faulty capacitor, causing a large pressure in the capacitor, which may cause an explosion hazard, in the method, connecting the energy absorbing resistor as a capacitor.

3. Propagation model of underwater plasma pulse acoustic wave

When the discharge energy of the underwater plasma sound source signal is high, the main frequency is low and the negative half-wave amplitude is small; when the discharge energy is low, the main frequency is high and the negative half-wave amplitude is high. When the discharge energy of the underwater plasma signal is higher than 10kJ, most of the energy is in the range of several hundred hertz, and the pressure wave does not have a strong negative half wave. At this time, the underwater plasma signal is approximately a half cycle sine wave.

Underwater plasmonic signal has always been valued. Research on underwater plasmonic signal has become an important subject for contemporary scientific development. From the 1950s, many scholars have The characteristics of underwater plasmonic signal are studied from an academic perspective. In recent years, many researchers at home and abroad have been working on the characteristics of underwater plasmonic sound source signals, and have achieved some meaningful results. Since the physical properties of the underwater plasmon signal are complex and the water is a
nonlinear fluid, the underwater plasmon signal propagation equations are nonlinear, and the characteristics of the underwater plasmonic signal are mainly determined. Because of these factors, it is difficult to theoretically establish an accurate equation. In order to more fully reflect the characteristics of underwater plasmon signal propagation, the waveform is expressed as follows:

$$y = -A \exp(-Ex)$$  \hspace{1cm} (1)

The amplitude $y$ of the underwater acoustic pulse is the amplitude of the initial underwater plasma pulse, the propagation distance $x$, and $E$ is the attenuation constant, where $E$ is related to seawater density, propagation direction, and water pressure. It can be represented by the following expression:

$$E = \rho^\alpha \cdot x^\beta \cdot \rho^\gamma$$  \hspace{1cm} (2)

Here, $p$ represents water pressure, $x$ represents propagation distance, $\rho$ represents density of water, and $\alpha$, $\beta$, and $\gamma$ represent nonlinear characteristics of correlation. The specific parameters in the above formula are shown in Table 1:

| Parameter                | Water pressure (p) | Propagation distance (x) | Water density (\(\rho\)) |
|--------------------------|--------------------|--------------------------|---------------------------|
| Numerical value (method) | \(\rho g H\)       | Vertical direction       | 1000kg/m³                 |

The propagation characteristics of the sound source are studied through simulation analysis. The results are shown in Figure 2 - Figure 3, which provides reference and guidance for practical engineering design. With the continuous development of underwater plasma sound source technology, it will exert greater potential in many fields such as ocean exploration, underwater communication, underwater attack and defense.

![Fig.2 Calculation results of attenuation constant](image)

Fig.2 Calculation results of attenuation constant

The acoustic pulse pressure wave emitted by the underwater plasma sound source itself has no directivity. In order to control the emission directivity of the sound source, improve the sound intensity of the specified propagation direction and the emission efficiency of the system, it can be formed by reflection or acoustic lens focusing technology. This physical phenomenon mainly includes several processes of pre-breakdown process, thermal breakdown, pulse discharge and bubble pulsation. In order to increase the effective working distance of the plasma sound source, it is necessary to collect the sound waves in a certain way. At this stage, it is difficult to precisely control the phase of the acoustic wave generated by the arc discharge plasma source. It is difficult to concentrate the acoustic wave by means of a phased array or an acoustic lens. In this paper, theoretical research and numerical simulation studies are carried out on the law of sound field reflected by the plasma source. A plurality of plasma sounding units can be used for array combination, and the direction of emission of the sound source is controlled by the directionality of the array. The curved surface reflection
method is another effective way for omnidirectional sound sources to gather sound energy and improve the propagation distance. It has been widely used in practice, such as reflector antennas, solar focusing reflectors, and ultrasonic probes. The principle is to converge the sound waves according to a certain geometric law to achieve a radiation or receiving mode that achieves a relatively high energy distribution at a specified position or direction. The focus of this approach is fixed, so it has certain stability as directional radiation.

![Figure 3 Underwater plasma pulse source propagation characteristics](image)

4. Conclusion
The acoustic pulse emitted by the underwater plasma sound source is basically an isotropic spherical wave. If it is not treated, it will decay rapidly according to the square law, and it is difficult to form sufficient strength in the specified propagation direction. Therefore, it is necessary to design a reasonable concentrating reflection mechanism for the underwater plasma sound source to control the emission directivity of the sound source, improve the sound intensity in the specified propagation direction region, and also improve the transmission efficiency of the system. In the underwater defense, with the continuous development of underwater ships, submarines and torpedo technology, combined with the characteristics of the underwater plasma sound source, a plurality of plasma sound sources focused by the energy-concentrating reflector are arranged in an array according to a certain regularity. Acoustic pulse bunching is performed to increase the pressure of the focused sound pulse in a specified direction to suppress the torpedo self-guided system or the ship sonar system. The high-power acoustic pulse pressure wave approaches the torpedo at the speed of sound, making the torpedo difficult to avoid, and can hardly kill the torpedo, realizing the function of the “interceptor” and forming the underwater short-range defense barrier of the ship. This feature of underwater plasma sound source will become a powerful measure for offshore defense. This energy direct acting technology can effectively improve the ship's defense capability as an effective hard killing interceptor weapon.

References
[1] Fabio Menna, Panagiotis Arafiotis, Andreas Georgopoulos. State of the art and applications in archaeological underwater 3D recording and mapping [J]. Journal of Cultural Heritage, 2018, Volume 33, Pages 231-248
[2] Y. H. Sun, Y. X. Zhou, M. J. Jin, Q. Liu, P. Yan. New prototype of underwater sound source based on the pulsed corona discharge[J]. Journal of Electrostatics, 2005, Volume 63, Issues
6–10, Pages 969-975

[3] Mirella Vazzana, Monica Celi, Giulia Mariechiolo, Lucrezia Genovese, Francesco Filiciotto. Are mussels able to distinguish underwater sounds? Assessment of the reactions of Mytilus galloprovincialis after exposure to lab-generated acoustic signals [J]. Comparative Biochemistry and Physiology Part A: Molecular & Integrative Physiology, 2016, Volume 201, Pages 61-70

[4] Atsushi Yasuda, Eisuke Kuraya, Akiko Touyama, Osamu Higa, Shigeru Itoh. Underwater shockwave pretreatment process for improving carotenoid content and yield of extracted carrot (Daucus carota L.) juice [J]. Journal of Food Engineering, 2017, Volume 211, Pages 15-21

[5] Li-Min Gao, Hui Cao, Hui-Yun Han, Jian-Xing Li, Zhen-Jun Yang. Research on breakdown threshold and directivity of sound field generated by ultrashort laser pulses induced liquid breakdown [J]. Optik, 2018, Volume 158, Pages 257-265

[6] Y. Y. Neo, J. Hubert, L. J. Bolle, H. V. Winter, H. Slabbeukoorn. European seabass respond more strongly to noise exposure at night and habituate over repeated trials of sound exposure [J]. Environmental Pollution, 2018, Volume 239, Pages 367-374

[7] Donatas Bagocius, Piling underwater noise impact on migrating salmon fish during Lithuanian LNG terminal construction (Curonian Lagoon, Eastern Baltic Sea Coast) [J]. Marine Pollution Bulletin, 2015, Volume 92, Issues 1–2, 15 Pages 45-51

[8] Jianfeng Wang, Qingjie Sun, Laijun Wu, Yibo Liu, Jicai Feng. Effect of ultrasonic vibration on microstructural evolution and mechanical properties of underwater wet welding joint [J]. Journal of Materials Processing Technology, 2017, Volume 246, Pages 185-197

[9] Nathaniel D. Taylor, Gregory Fridman, Alexander Fridman, Danil Dobrynin. Non-equilibrium microsecond pulsed spark discharge in liquid as a source of pressure waves [J]. International Journal of Heat and Mass Transfer, 2018, Volume 126, Part A, Pages 1104-1110

[10] V. Lazic, J. J. Laserna, S. Jovicivic. Insights in the laser-induced breakdown spectroscopy signal generation underwater using dual pulse excitation — Part I: Vapor bubble, shockwaves and plasma [J]. Spectrochimica Acta Part B: Atomic Spectroscopy, 2013, Volume 82, 1 Pages 42-49

[11] Paolo Chiarotti, Milena Martarelli, Paolo Castellini. Acoustic beamforming for noise source localization – Reviews, methodology and applications [J]. Mechanical Systems and Signal Processing, 2019, Volume 120, Pages 422-448

[12] Kentaro Nakamura, Tomohiro Toki, Nobutatsu Mochizuki, Miho Asada, Kyoko Okino. Discovery of a new hydrothermal vent based on an underwater, high-resolution geophysical survey [J]. Deep Sea Research Part I: Oceanographic Research Papers, 2013, Volume 74, Pages 1-10

[13] Ben Liu, Deguo Wang, Yanbao Guo. Influence of water conductivity on shock waves generated by underwater electrical wire explosion [J]. Physics Letters A, 2018, Volume 382, Issue 1, Pages 49-54

[14] Chih An Wei, Tzu Hao Lin, Ruo Dong Chen, Yung-Che Tseng, Yi Ta Shao. The effects of continuously acoustical stress on cortisol in milkfish (Chanos chanos) [J]. General and Comparative Endocrinology, 2018, Volume 257, 1 Pages 227-234

[15] N. Li, J. G. Huang, K. Z. Lei, J. F. Chen, Q. F. Zhang. The characteristic of the bubble generated by underwater high-voltage discharge [J]. Journal of Electrostatics, 2011, Volume 69, Issue 4, Pages 291-295

[16] Batuhan Aktas, Mehmet Atlar, Patrick Fitzsimmons, Weichao Shi. An advanced joint time-frequency analysis procedure to study cavitation-induced noise by using standard series propeller data [J]. Ocean Engineering, Volume 170, 15 December 2018, Pages 329-350

[17] Jianfeng Wang, Qingjie Sun, Jiangkun Ma, Junbo Teng, Jicai Feng. Investigation of acoustic radiator affecting bubble-acoustic interaction in ultrasonic wave-assisted UWW at shallow water [J]. Journal of Manufacturing Processes, Volume 37, January 2019, Pages 563-577
[18] M. López-Claros, M. Dell'Aglio, R. Gaudioso, A. Santagata, J. J. Laserna. Double pulse laser induced breakdown spectroscopy of a solid in water: Effect of hydrostatic pressure on laser induced plasma, cavitation bubble and emission spectra [J]. Spectrochimica Acta Part B: Atomic Spectroscopy, Volume 133, 1 July 2017, Pages 63-71

[19] Avi Shupak, Hillel Pratt, Yehuda Arieli, Dror Tal. High-frequency sound transmissions under water and risk of decompression sickness [J]. Ultrasound in Medicine & Biology, Volume 29, Issue 1, January 2003, Pages 119-125

[20] Elisabeth Debusschere, Kris Hostens, Dominique Adriaens, Bart Ampe, Steven Degraer. Acoustic stress responses in juvenile sea bass Dicentrarchus labrax induced by offshore pile driving [J]. Environmental Pollution, Volume 208, Part B, January 2016, Pages 747-757

[21] Giorgio Tani, Batuhan Aktas, Michele Viviani, Mehmet Atlar. Two medium size cavitation tunnel hydro-acoustic benchmark experiment comparisons as part of a round robin test campaign [J]. Ocean Engineering, Volume 138, 1 July 2017, Pages 179-207

[22] A. De Giacomo, M. Dell'Aglio, O. De Pascale, M. Capitelli. From single pulse to double pulse ns-Laser Induced Breakdown Spectroscopy under water: Elemental analysis of aqueous solutions and submerged solid samples [J]. Spectrochimica Acta Part B: Atomic Spectroscopy, Volume 62, Issue 8, August 2007, Pages 721-738

[23] D. A Rusak, B. C Castle, B. W Smith, J. D Winefordner. Recent trends and the future of laser-induced plasma spectroscopy [J]. TrAC Trends in Analytical Chemistry, Volume 17, Issues 8–9, August–September 1998, Pages 453-461

[24] S. N. Samaddar. Sound wave propagation in a vertically inhomogeneous ocean [J]. Journal of Sound and Vibration, Volume 46, Issue 1, 8 May 1976, Pages 67-78

[25] Hyunku Park, Seung Rae Lee, Nak Kyung Kim, Tae Hoon Kim. A numerical study of the pullout behavior of grout anchors underreamed by pulse discharge technology [J]. Computers and Geotechnics, Volume 47, January 2013, Pages 78-90

[26] D. F St. Mary, Ding Lee. Analysis of an implicit finite difference solution to an underwater wave propagation problem [J]. Journal of Computational Physics, Volume 57, Issue 3, February 1985, Pages 378-390