A Supersonic Underwater Discharge as a High-Power Ultrasound Source

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Abstract—A supersonic underwater discharge system, driven by a pulsed power generator with 235 ns voltage rise time, was developed to be used as a powerful ultrasound source. The article presents details of the system’s components and the various diagnostic methods used, together with the main findings obtained during the first experimental campaign. The system generated a peak pressure of 184 kPa at 1-m distance, with an efficiency of energy conversion from electrical to acoustic estimated as 0.8%. The pressure profile was found to display a resemblance to the radiation pattern generated by a dipole antenna. Using an ultrahigh-speed camera, a study of the interelectrode discharge revealed details of the prebreakdown streamer dynamics and an estimate for the lifetime of the postbreakdown plasma column. The way forward includes testing the system at a very high repetition rate.

Index Terms—Pulsed power, pulsed pressure, plasma, streamer, ultrasound.

I. INTRODUCTION

HIGH-POWER underwater electric discharges have been fundamental to pulsed power technology for decades. Namely in pulsed power switching, but also in a large number of industrial applications including: underwater welding and electro-hydraulic forming [1], shockwave generation for industrial sludge treatment, removal of foreign deposits from pipe walls or materials fragmentation, separation, reduction, and recycling [2]–[4], for mining applications such as blasting [5] and drilling [6], for demolition [6], wastewater treatment and sterilization [7], bio-fouling control [8], removal of algae [9], and special biomedical applications. A number of these applications are well-described in a book dedicated to the pulsed electric breakdown of liquid phenomena [10].

This article is related to using electrical discharges to produce high-power acoustic waves with large amplitudes, short duration, and wideband frequency. Such acoustic waves, termed high-power ultrasound (HPU) [11], have often been used in maritime applications [12], [13]. There are two main regimes by which HPU can be generated: subsonic (by oscillating bubble-based mechanism) and supersonic (by streamer-based mechanism).

The subsonic technique is achieved by a relatively slow (tens of microseconds) application of a high voltage (HV) across electrodes immersed in water, resulting in a Joule-heated creation of a gas bubble within which electrical breakdown of the water gap occurs. The discharge-driven periodic expansion and collapse of the bubble produces HPU by virtue of the bubble’s surface performing the role of the membrane in a loudspeaker. A single discharge may produce several oscillations over hundreds of microseconds, up to tens of milliseconds, depending on the water conductivity and the electric field strength applied. Recently, more attention has been given to understanding the physics of subsonic HPU sources [13]–[17]. Owing to the long discharge period, it is not practical to achieve a high pulse repetition frequency (PRF) operation with subsonic discharges.

In contrast, the supersonic technique requires a very fast voltage impulse, with a rise time of tens to hundreds of nanoseconds. This impulse is normally applied to an electrode geometry specifically designed to generate an intense and highly inhomogeneous electric field distribution, such as point-plane. The key processes involved in the supersonic electric breakdown of water are thus facilitated: field emission and field ionization, field acceleration and impact ionization. Through a combination of these processes, conducting ionization paths known as streamers propagate across the electrode gap with a tree-like structure. Upon the successful connection of the electrodes by an ionized path, current is mainly directed through it, forming a highly conductive plasma channel. The corresponding Joule energy is delivered to the surrounding water, causing the water to violently expand and generate a powerful shock wave.

The HPU generated under these circumstances is different from that produced with the bubble-based subsonic technique, as the energy is deposited much more rapidly, resulting in a much shorter duration (microseconds) acoustic pulse with a considerably wider bandwidth (up to a few megahertz).

The literature surrounding supersonic prebreakdown (streamer) phenomenon has been comprehensively reviewed in [18] and the physics of the fast breakdown process in [19], [20]. However, the application of these processes to generate HPU remains an unexplored field, to the best of the authors’ knowledge.

This article is dedicated to the development of a supersonic HPU source using a bespoke pulsed power generator. The major interest in developing this type of source is the unique
capability to drive this low-energy system at very high PRF. There are applications in the biomedical domain [21], [22], food processing technology [23], and geological survey that require a HPU source with such characteristics. The system described, although only demonstrated in single-shot mode in the present work, was therefore designed specifically for future 1 kHz PRF operation.

The structure of this article is presented below. Section II describes the pulsed power generator, the electrodes, and the practical arrangement in a laboratory water tank. Diagnostic instrumentation and a technique for the synchronization of their outputs are also presented in detail. Section III presents the main findings, and Section IV comprises the conclusions along with a plan for future development.

II. PRACTICAL ARRANGEMENT

A. Pulsed Power Generator

The main requirements for the design of the pulsed power generator were to produce a 100 kV output and to operate at a PRF of 1 kHz. In a preliminary phase of this research, a Tesla transformer-based generator, using a closing switch based on a corona stabilized closing switch, was successfully tested up to 1 kHz PRF [24].

The present work is based on an improved HPU system, with the electrical scheme of this faster 235-ns rise time generator presented in Fig. 1. A low-inductance capacitor type 37331 (General Atomics [25]) capable of operating at 1 kHz PRF and having a capacitance \( C_1 = 153 \text{ nF} \) is mounted in the primary winding circuit of a magnetic core transformer. For single-shot operation, the closing switch \( (S_1 \text{ in Fig. 1}) \) is a trigatron type SG-101M-75C (R. E. Beverly III and Associates [26]), triggered with a trigger head pulse transformer type THD-02B-02. The pulse transformer is controlled by a trigger generator type PG-103D4-02a via a 20 m fiber optic isolation link. For single-shot operation at a charging voltage of \( V_0 = 12 \text{ kV} \), the trigatron operates pressurized with 1 bar pressure \( N_2 \). In these conditions and including all components, the primary winding circuit has a total equivalent resistance of \( R_b = 122 \text{ m\Omega} \) and a leakage self-inductance of \( L_b = 200 \text{ nH} \). The transformer, which will be described in detail elsewhere [27], has a turn ratio of 1:12 with a single-turn primary winding made from thin copper strip having a self-inductance \( L_1 = 5 \mu\text{H} \) and a secondary winding of 12 turns made from a round copper conductor 2 mm in diameter mounted on a conically shaped coil former and having a self-inductance \( L_2 = 709 \mu\text{H} \). The transformer core is made from Metglas type AMCC367S [28], which achieves a magnetic coupling coefficient of \( k = 0.99 \). The transformer is mounted inside a small-size plastic oil tank together with the HV capacitive load \( C_2 = 1.1 \text{ nF} \) containing 16 identical TDK UHV-3A 4 nF/20 kV ceramic capacitors mounted as two parallel connected stacks, each stack having eight series connected 4 nF units. The total equivalent resistance of the secondary winding circuit is \( R_s = 10 \Omega \), with the total leakage self-inductance being \( L_s = 0.8 \mu\text{H} \).

B. Underwater Discharge Electrodes and Their Ancillary Equipment

The discharge electrodes are formed of a pin–plane pair, with the plane taking the form of a hemisphere, 60 mm in diameter, and the cylindrical–conical pin having an outer diameter of 5.8 mm and a tip radius of about 500 \( \mu\text{m} \). For high PRF testing, the electrodes will be manufactured from copper or sintered Cu–W. However, for convenience, in the single-shot experiments reported here, the hemisphere was made from brass and the pin electrodes from stainless steel. The electrodes were coaxially mounted at an adjustable distance inside a watertight acrylic tube filled with deionized water. It was experimentally demonstrated that for minimizing the Joule losses during the prebreakdown phase, the electrodes must be covered as much as possible with an insulating material to increase the underwater assembly total equivalent resistance. This requirement proved to be difficult to implement in practice. During the preliminary phase of this research, the most significant issues observed after operating with long bursts at a high PRF (see Fig. 2) were as follows:

1) unwanted electric breakdown at the insulator–metal–water triple point
2) destruction of insulators caused by strong shock waves.

The design of the pin electrode used for the single-shot operation during this stage of the research features a threaded head, which allows for interchanging the electrode to investigate alternative geometries and replacing a damaged head without disassembly of the entire electrode support system. It does, however, leave a small metallic area uncovered at the interface between the electrode and its support. For increasing the efficiency while operating the system using freshwater, this area had to be covered.

The solution to minimize damage to the hemisphere electrode insulation was to cover less of its surface (in close proximity to the plasma discharge) with epoxy resin, while...
also implementing a small angle between the insulator and the metal, to tackle the triple point field enhancement.

Fig. 3 shows the pair of electrodes used in the present work, and Fig. 4 presents the electric field distribution predicted by the computer simulation technology (CST) software [29]: for 1 V applied to the pin for an interelectrode gap of 4 mm, the peak field generated under these circumstances reaches 10 V/cm.

For the purpose of connecting the electrodes to the generator via a (several meter) long transmission line, a HV 50-Ω coaxial cable was not suitable as its characteristic capacitance (about 100 pF/m) would introduce a capacitance into the circuit comparable to \( C_2 \). Therefore, two flexible HV cables were used: the core of a 150 kV coaxial cable type 212A [30] connecting the pin electrode to the HV terminal and a 40 kV cable type 167-9180 [31], connecting the hemisphere to the ground. Tests performed during the preliminary phase of this research demonstrated that for most efficient operation of the HPU source, the pin should be positively charged. Fig. 5 presents the experimental arrangement used for testing the HPU source, with an acrylic tube assembly containing the electrodes and filled with deionized water immersed into the 1.5-m³ plastic water tank with dimensions \((x, y, z) = 1.25 \times 1.68 \times 0.8\) m.

During the present preliminary testing, many hundreds of shots were fired in single-shot mode. Some erosion to the electrodes was observed, but at 4 mm electrode separation this did not affect the reliability of discharge.

C. Diagnostics

1) Electrical:

1) Voltage: two voltage probes were used (VP in Fig. 1). VP₀ is a type PVM-1 probe [32] used for DC measurements, while VP₅ is a type PVM-100 probe, capable of measuring a peak of 150 kV with 90 MHz bandwidth [32].

2) Current: Two Current Transformers (CT in Fig. 1) type 2877 [33] (peak current 100 A, bandwidth 200 MHz) were installed as a pair, to provide both a positive and a negative output, allowing for the identification and removal of unwanted capacitive coupling. As the peak plasma current can reach values in excess of 1 kA, this exceeds the capability of the above-mentioned transducer. To safely use the current transducers, the HV cable attached to the ground was connected to an assembly made of 12 short, parallel, connected wires and the two current probes were installed on a single wire, thus each measuring about 1/12 of the total current. As the currents are not exactly evenly distributed through the 12 wires, the output of these probes was separately calibrated using two, lower frequency bandwidth, type 410 current monitors [33], mounted directly on the HV cable attached to the ground.

3) \( \frac{dI}{dt} \): a simple magnetic pick-up probe, calibrated as an I-dot probe (see Fig. 1), was mounted inside a small helical coil made from the HV cable attached to ground.
4) Voltage across electrodes: the VP$_S$ probe measures the voltage across $C_2$, which can be written as

$$VP_S = L_i \frac{dI_L}{dt} + RLIL $$

where $L_i$ is the self-inductance of the HV transmission line, $R_L$ is the time-dependent equivalent resistance of the load, and $I_L$ is the current flowing through the load circuit. During the experiment, $R_L$ varies with many orders of magnitude, while the voltage $V_L$ across the electrodes

$$V_L = R_LIL $$

is important for calculating the Joule energy. As $VP_S$, $I_L$, and $(dI_L)/(dt)$ are all measured by specific probes, the instantaneous power $P_L$ absorbed by the load can be easily obtained if $L_i$ is known

$$P_L = V_LIL = \left( VP_S - L_i \frac{dI_L}{dt} \right)I_L $$

5) Time integration of this power provides the energy $W_L$ absorbed by load at a time $t$:

$$W_L(t) = \int_{0}^{t} P_L(t')dt' $$

The precise value of $L_i$ was obtained using (1) in experiments with a mock-up HV transmission line having the same topology as the real transmission line and connected to a 34-$\Omega$ HV resistor that replaced the time-varying load resistance $R_L$. For the arrangement used in the present work $L_i$ was found to be 9.5 $\mu$H.

2) Acoustical:

1) Low-frequency hydrophone: Teledyne Reson type TC4034 [34], having a usable frequency range from 1 Hz to 480 kHz. The spherical active region of the TC4034 piezoelectric hydrophone is aligned with the center of the electrode gap, in the x- and z-directions, with a separation of 1 m in the y-direction (Fig. 5). This hydrophone is omnidirectional across its bandwidth.

2) High-frequency hydrophone: Precision Acoustics type NH2000 [35], suitable for measurements in the frequency range from 100 kHz to 10 MHz. The NH2000 2 mm needle PVDF hydrophone is highly directional, particularly for high frequencies, and so great care was taken during its alignment. The active part of this hydrophone, at the tip, was mounted at a separation of 1 m from the electrode gap (Fig. 5).

3) Details of hydrophone mounting and operation: The two hydrophones were mounted using supports [see Fig. 5(b)] and placed at the minimum separation from one another that allowed for the full pressure wave to be captured by each hydrophone before the reflection from the other would be detected and influence the signal. The minimum separation was calculated to be 3.5 cm, and a 4 cm separation was used. The hydrophones were also separated from the tank walls and the surface of the water sufficiently to prevent reflections from these surfaces from interfering with the direct pressure wave received from the HPU. Both hydrophones displayed a strong sensitivity to the powerful electromagnetic noise generated by the pulsed power generator. Due to the conductivity of water, it was not possible to implement proper cable shielding. However, by placing battery-powered oscilloscopes inside Faraday chambers, it was possible to reduce the interference, the hydrophone upset, and the recovery time following a strong electromagnetic disturbance.

4) Software and data analysis: A Mathcad [36] program was developed to analyze the data obtained from the two hydrophones. To help with the alignment of the highly directional NH2000 hydrophone, the software was used to test the agreement with the TC4034 signal in the overlapping receiving bandwidth (i.e., 100–480 kHz). As neither hydrophone was individually capable of covering the ultrawide spectrum generated by the HPU, the software was used to perform the fast fourier transform (FFT) of the pressure signals and then trim and stitch the two signals in the frequency domain, before performing the inverse FFT to obtain the pressure signal in the time domain corresponding to the entire bandwidth.

3) Optical: An ANDOR sCMOS iStar ultrafast camera [37] was operated with a 3 ns exposure and increased microchannel plate (MCP) gain, to allow for clear images to be obtained. When longer exposure times were used, the very fast motion of the streamers resulted in blurred images. A NIKON Sigma 150 mm f/2.8 APO Macro EX DG camera lens was coupled to a number of extension tubes (Fotga Auto Focus Macro Extension Tube) to enlarge the image falling on the camera sensor [see Fig. 5(a)]. To protect the camera against the electromagnetic interference, it was housed inside a dedicated Faraday chamber, suspended above the water tank. A chamber extension with an optical window lid allowed underwater operation, thus minimizing the distance between the camera lens and the HPU source [Fig. 5(a)].

4) Synchronization: The complete synchronization scheme, which only includes the fast electrical and optical diagnostics, is presented in Fig. 6, where the “Closing switch S1” is switch $S_1$ in Fig. 1 and the “D-dot” is a differential electric field sensor measuring the level of electromagnetic “noise” and also used for triggering and synchronization purposes.

The camera was operated in the External trigger mode with a Pretrigger option. In this mode, two input signals are needed: the first one is applied at $t_0$ as a Pretrigger, preparing the camera sensor, while the second is applied at $t_2$ as an External trigger that (after a short time delay) activates the image intensifier to acquire a photograph. The spark-gap triggering system is activated at a time $t_1$, with $t_0 < t_1 < t_2$; see Fig. 6.

III. EXPERIMENTAL RESULTS
A. Influence of the Interelectrode Gap on the Peak Pressure Generated by the HPU Source

The tests reported here were performed with water at a temperature between 20 $^\circ$C and 22 $^\circ$C. The results of the study to find the optimum interelectrode gap to generate the maximum peak pressure with the present single-shot system are presented in Fig. 7. As the gap increases, the relative
peak pressure increases from 84%, corresponding to a gap of 3.1 mm, to 95% for a 4 mm gap and finally to 100% for a gap of 5 mm. The corresponding breakdown voltage is presented in Fig. 8. As the gap increases from 3.1 to 5 mm, the breakdown voltage increases from 92 kV, to a value very close to 100 kV. Although the 5 mm gap is apparently the best separation for maximizing pressure, in practice 30% of shots were unsuccessful (“misfire”), with no voltage breakdown and no substantial pressure generated. For the 4 mm gap, the experimentally determined chance of misfire was only about 1%, while for the 3.1 mm gap there were no misfires. All shots presented in this work were performed with a 4 mm gap.

B. Characteristic Pressure Pattern Generated by the HPU Source

The results of the study to determine the pressure pattern generated at (about) 1 m distance by the HPU source is presented in Fig. 9, where polar coordinates are used with the maximum corresponding to a peak pressure of 184 kPa. Due to reflections by the dome electrode, the pressure pattern has lobes similar to the electromagnetic pattern lobes generated by a dipole antenna.

C. Data From a Typical Shot

The electrical data from a typical shot is presented in Fig. 10. The prebreakdown phase in Fig. 10(a), represents the time from the beginning of the discharge at \( t = 0 \) ns (closure of \( S_1 \) in Fig. 1) up to the moment the breakdown takes place at \( t = 330 \) ns. During this phase, while the voltage increases to its peak, an extremely small displacement current flows through the water, closing the load circuit. This is due to the fact that the rise time (10%–90%) of the voltage impulse is only 235 ns, while the relaxation time of the deionised water is much larger, that is, \( \varepsilon_0\varepsilon_r/\sigma_d = 3.54 \mu s \), where \( \varepsilon_0 \) is the permittivity of free space, \( \varepsilon_r = 80 \) is the permittivity of water at 20 °C, and...
σ_{dw} = 2 \mu \Omega \text{cm} is the conductivity of the deionized water used in the tests.

The time variation in the Joule energy absorbed by the source is shown in Fig. 11, with the final energy converging to \( W_{L}^{\text{max}} = 7.4 \text{ J} \). This energy is larger than 5 J stored in \( C_2 \) (of Fig. 1) when charged to 100 kV, showing that even after the breakdown, energy from the primary circuit continues to be pumped into the secondary load circuit.

The optical data in Fig. 12 represents a collection of photographs taken from a number of “identical” (i.e., having the
same initial conditions) shots. To easily correlate the streamer dynamics with the electrical data, the time at which each photograph was acquired in relation to the electrical signals of Fig. 10 is clearly indicated by letters $a - o$. It is interesting to note the various stages such as streamer formation and dynamics during the prebreakdown phase, the generation of the luminous central plasma column at breakdown, the slow decay of the streamers, and the even slower decay of the plasma column. The first light [Fig. 12(b)] is detected around 140 ns, when the voltage applied on the pin electrode is 28.5 kV [Fig. 10(a)]. Using the data of Fig. 4(c), the corresponding peak electric field is estimated as 285 kV/cm.

The electric breakdown at 330 ns [Fig. 12(g)] corresponds to 100 kV applied on the pin and a peak electric field of 1 MV/cm.

Fig. 13 presents the typical rough acoustical signals recorded with the hydrophones positioned at 1.076-m distance from the HPU source and at 340° (or −20°), as indicated in Fig. 9. Using the data analysis presented above, the resultant pressure pulse and its corresponding FFT are presented in Figs. 14 and 15, respectively. The maximum pressure recorded was 184 kPa (225 dB re 1 μPa/V).

**D. Efficiency of Energy Conversion**

The acoustic energy carried at a time $t$ by the pressure pulse generated by the HPU can be calculated based on the data of Figs. 9 and 14. Consider that the normalized pressure data $P_k$ of Fig. 9 has been collected at $N$ different angles $\alpha_k$, with $k = 1, \ldots, N$. In this case, the acoustic energy $W_a$ can be calculated as [16]

$$W_a(t) = \frac{2 \pi r^2}{\rho_0} \sum_{k=1}^{N} \left[ \frac{\cos(\alpha_{k-1}) - \cos(\alpha_k)}{2} \right] \int_0^t \frac{p(t')^2}{dt'}$$

where $r = 1.076$ m is the radius of the sphere on which the measurement is performed, $\rho = 10^3$ kg/m$^3$ is the mass density of water, and $v = 1480$ m/s is the speed of sound in water; the area of a spherical segment $A_k$ was calculated using spherical coordinates as

$$A_k = r^2 \int_{\theta_{k-1}}^{\theta_k} \sin(\theta)d\theta \int_0^{2\pi} d\phi = 2\pi r^2 \left[ \cos(\theta_{k-1}) - \cos(\theta_k) \right]$$

and finally, the time integral is performed using the pressure pulse $p(t)$ of Fig. 14. The result of the calculations is presented in Fig. 16 and it shows that the maximum acoustic energy carried by the pressure pulse is $W_{a,max} = 62$ mJ. The energy efficiency $\eta$ is therefore $\eta = (W_{a,max} / W_{L,100}) = 0.8\%$.

**E. Operation of the HPU With Freshwater**

A few tentative shots were performed with the acrylic tube filled with freshwater having a conductivity $\sigma_{fw} = 500$ μS/cm, with $\varepsilon_0\varepsilon_r/\sigma_{fw} = 14.2$ ns being smaller than the voltage
Fig. 16: Time dependence of acoustic energy carried by the pressure pulse of Fig. 14. The total acoustic energy is 62 mJ. The acoustic energy produced by the prebreakdown phenomena can clearly be identified as the small shoulder prior to the sharp rise corresponding to breakdown.

Fig. 17: Voltage and current signals during a typical shot with the HPU functioning with freshwater. During the prebreakdown phase, the conduction current reaches 0.28 kA. Due to this large value, the voltage is only able to reach about 80 kV.

Fig. 18: Pressure pulse measured with the TC4034 hydrophone at 1 m from the HPU source functioning with freshwater. The peak pressure is 78 kPa.

A pressure of only 78 kPa, representing 89% of the value generated by the source at the same position when using deionized water. The lower efficiency is due to the conduction current reaching 280 A during the prebreakdown phase, which corresponds to the amount of Joule energy being used less efficiently.

IV. CONCLUSION AND THE WAY AHEAD

A supersonic underwater HPU was demonstrated to generate a peak pressure of 184 kPa (225 dB re 1 μPa/V) at 1 m when operated in deionized water and 78 kPa in freshwater. The HPU uses only 7.4 J of electrical energy, and therefore it can be made very compact and at least in principle, by changing the HV charger, the closing switch, and the electrodes, it can be operated at a very high PRF. The pressure profile of the source was found to display a resemblance to a far-field dipole antenna radiation pattern. Using an ultrahigh-speed camera, an optical study revealed highly complex interelectrode plasma dynamics. When operated with deionized water, the efficiency of energy conversion from electrical to acoustic was estimated to be 0.8%.

Plans for future include a detailed analysis of plasma streamers using the Schlieren technique and operation of the HPU source at a PRF of 1 kHz.

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