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Research on the mechanics of underwater supersonic gas jets

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An experimental research was carried out to study the fluid mechanics of underwater supersonic gas jets. High pressure air was injected into a water tank through converging-diverging nozzles (Laval nozzles). The jets were operated at different conditions of over-, full- and under-expansions. The jet sequences were visualized using a CCD camera. It was found that the injection of supersonic air jets into water is always accompanied by strong flow oscillation, which is related to the phenomenon of shock waves feedback in the gas phase. The shock wave feedback is different from the acoustic feedback when a supersonic gas jet discharges into open air, which causes screech tone. It is a process that the shock waves enclosed in the gas pocket induce a periodic pressure with large amplitude variation in the gas jet. Consequently, the periodic pressure causes the jet oscillation including the large amplitude expansion. Detailed pressure measurements were also conducted to verify the shock wave feedback phenomenon. Three kinds of measuring methods were used, i.e., pressure probe submerged in water, pressure measurements from the side and front walls of the nozzle devices respectively. The results measured by these methods are in a good agreement. They show that every oscillation of the jets causes a sudden increase of pressure and the average frequency of the shock wave feedback is about 5–10 Hz.

underwater supersonic gas jet, pressure oscillation, flow visualization, shock wave feedback

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A gas jet injection into liquid can be often seen in different technological fields, e.g., aeration treatment of wastewater [1–3], underwater cutting [4] and jet propulsion of underwater vehicles [5]. At lower speed, a submerged gas jet usually turns into bubbly flow, which can be well described by a theoretical model [6]. He et al. [7] simulated a supersonic gas jet in water using the Level Set method. However, as indicated by Shi et al. [8], because many complicated phenomena are involved in the injection of a submerged supersonic gas jet, much work needs to be done in order to clarify the flow field.

The problem was extensively studied in metallurgy field from the 1970's when severe erosion of tuyere refractory was found in supplying oxygen gas into steelmaking furnaces. Hoefele and Brimacombe [9] carried out high speed photography and pressure measurement of gas discharging into liquids. Both straight and convergent-divergent tuyeres were used. They found that as the increase of the gas injection pressure, the rate of pressure pulsation was reduced, which was undergone a flow transition from bubbling to jetting. Then they got an idea that the tuyere erosion could be reduced by pushing the gas jet away from the wall surface through increasing the jet velocity. Based on the work of Hoefele and Brimacombe [9], Mori et al. [10], Ozawa and Mori [11] continued to investigate the optimum operation condition of tuyeres. They found that the bubbling-jetting transition of gas jets injected into water or mercury occurs when the jet velocity at the nozzle exit reaches sonic. They also reported that the frequency of bubble knocking could be decreased by increasing the jet velocity.

In 1982, Aoki et al. [12] published an important paper to describe that the major factor of causing tuyere refractory

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erosion is the gas jet blowing backward along the main flow direction and impacting on the front surface of tuyere. They defined the jet blowing phenomenon as "back-attack" and they found that it occurs after the jet necking. Following the idea of Aoki et al. [12], Taylor et al. [13] performed an experiment to show that Ozawa and Mori's conclusion [11], that the back-attack frequency is reduced by increasing the gas flow rate, is incorrect. Later, Yang et al. [14] and Yang and Gustavsson [15] studied the "back-attack" frequency, cavity growth and associated tuyere erosion. They suggested that the erosion is caused by cavitation during smaller bubbles collapse on the surface. Wei et al. [16] compared the "back-attack" behaviors of rotating and non-rotating gas jets in a water model.

Despite the past extensive studies [9–16], many fluid mechanics questions remain to be answered. For example, Aoki et al. [12] only tested straight type of nozzles by which the maximum jet velocity is sonic. According to our recent work of generating underwater supersonic gas jets, it has been found that the "back-attack" always appears no matter how the gas jet is in under-expansion, full-expansion or over-expansion [17,18]. The "back-attack" is just a phenomelogical description of the event but it has not dealt with the physics of the flow filed. It is necessary to study the problem from the point of view of aerodynamics and fluid mechanics. It is commonly known in aerodynamics that in a supersonic flow disturbances do not propagate upstream. For a supersonic gas jet in air, there is a so called "acoustic feedback" phenomenon [19,20]. The "acoustic feedback" is that sound waves travel backward to the nozzle. The sound waves come from shock waves interaction with the jet boundary, vortex, temperature or density inhomogeneity [21]. The feedback is the source of screech tone. The measurements of static pressures in a submerged under-expanded gas jet by Loth and Faeth [22] and Qi at al. [23] provide strong evidence that a shock wave cell structure for external expansion is present in the jet. On the other hand, a supersonic gas jet in water is highly turbulent and unsteady [24,25]. When shock waves in the jet meet the unsteady gas/jet boundary, they have to accumulate their energy again and then to reflect backward to impact on the nozzle surface. Consequently, the reflection and impact bring about the rapid bubble expansion on the nozzle surface. Therefore, the "back-attack" is actually a kind of shock wave feedback phenomenon. Through this paper's results, readers may understand this.

1 Experimental devices and methods

Figure 1 shows the setup of the experimental system. It mainly consists of an air compressor, a gas tank, a pressure adjusting valve, a solenoid valve, a transparent water tank and a nozzle assembly. The air compressor can provide a working pressure of compressed air up to 3 MPa. The gas tank has a volume of 0.8 m^3, which can ensure a testing time of about 5 s while keeping the pressure of the compressed air constant. The pressure adjusting valve is for changing the stagnation pressure in the plenum chamber of the nozzle. The solenoid valve is for opening or closing the gas injection. The water tank is made from PMMA plates, which is 280 cm long, 50 cm wide and 55 cm high. During the experiment, the nozzle assembly was submerged 15 cm beneath the water surface and the water temperature was in room temperature. In flow visualization, a CCD camera (BASLER A602f type) was employed to observe the flow pattern of underwater supersonic gas jets. A strobe lamp was used as the light source.

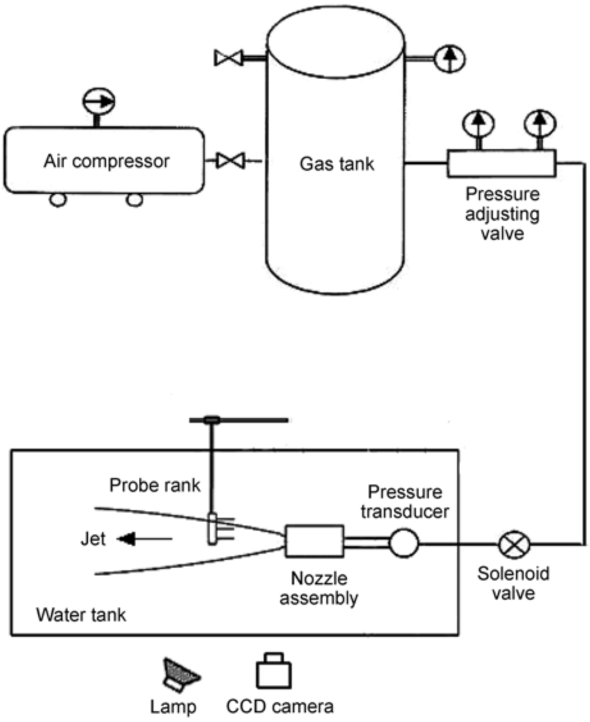

Figure 1 The experimental setup of underwater supersonic gas jets.

Three kinds of pressure measurements were applied in the experiment. The first is that using a rank of pressure probes to measure the downstream pressures in underwater supersonic gas jets. The second is the pressure measurement at the side wall of a nozzle assembly. The third is the pressure measurement at the front wall of a composed nozzle device. The experimental devices for accomplishing these three measurements are given as follow.

Figure 2 shows the structure of the probe rank for static pressure measurement. The three probes which are vertical in one row are equally spaced with a distance of 1 cm and are made from 1.5 mm diameter stainless tubes. They are installed on the front wall of an aluminium frame and each probe is connected to a piezo-resistant pressure transducer (NS-2 type) which is fixed on the backside of the frame. The probe has a sharp tip and the measuring hole of static pressure is drilled at the position of 12 mm away from the

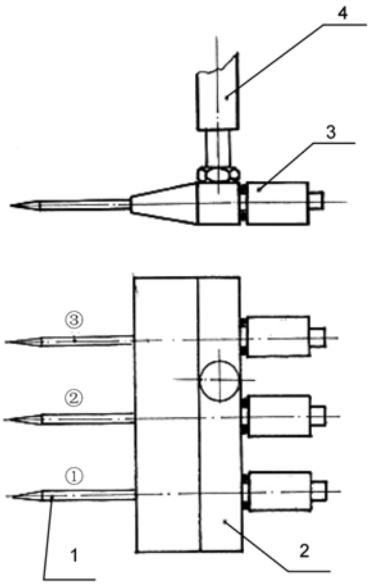

Figure 2 Structure of the probe rank for static pressure measurement. 1, Static pressure probe; 2, frame of probe rank; 3, pressure transducer; 4, supporter.

tip. The probe rank is set up on a three-dimensional traverse which allows that the pressure measurement at different downstream distance can be performed. With this probe rank, the pressures in the jet center, in the gas/liquid mixing regime and in water can all be measured simultaneously.

Figure 3 is the design of the nozzle assembly which mainly consists of a Laval nozzle (3), an outer shield (2) and a plenum chamber (6). The nozzle assembly is fixed on a supporter (7) and its end (8) is connected to the pipeline of the compressed air. The stagnation pressure of the plenum chamber is monitored by a piezo-capacitive pressure transducer (1) (Setra 280E type) which is connected to an electric voltage meter. In the experiment, the required gas stagnation pressure was achieved by turning the pressure adjusting valve (see Figure 1). On the side wall of the nozzle assembly, there are two pressure measuring holes (4). The first and second holes are 10 and 50 mm away from the nozzle exit respectively. The measuring hole is connected to a piezo-resistant pressure transducer (5). With this device, when the shock wave feedback occurs in the injection of underwater supersonic gas jets, the induced oscillatory pressures in the upstream fluid can be detected. In this paper, the measuring results from the first hole are given.

Figure 4 is the design of a composed nozzle device. The testing nozzle is inserted in a flange on which there are 6 pressure measuring holes. The holes of No. 1 and 2 are 7 mm from the nozzle center. The holes of No. 3 and 4 are 17 mm from the nozzle center. The holes of 5 and 6 are 12 mm

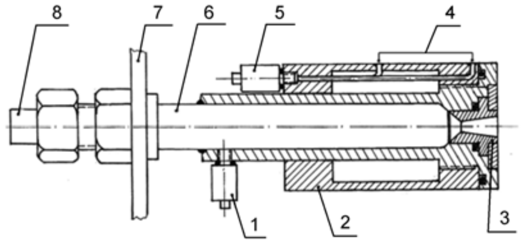

Figure 3 Structure of the nozzle assembly. (1) Piezo-capacitive pressure transducer; (2) nozzle outer shield; (3) Laval nozzle; (4) pressure holes on the side wall; (5) piezo-resistant pressure transducer; (6) plenum chamber; (7) supporter; (8) connector to high pressure gas.

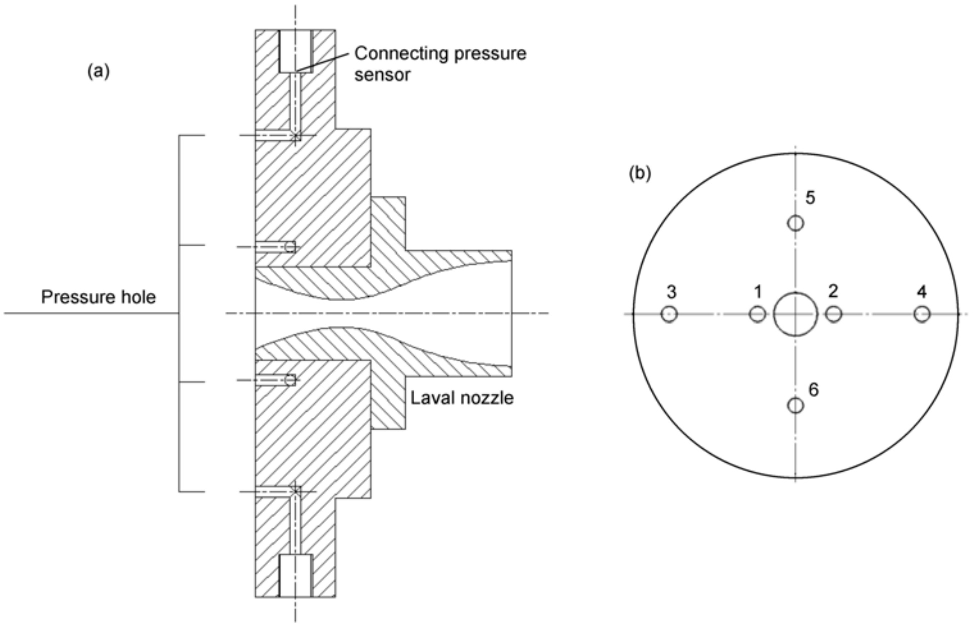

Figure 4 Structure of a composed nozzle device. (a) Cross sectional view; (b) front view.

from the nozzle center. The 6 holes are connected to piezoresistant pressure transducers (NS-2 type). This device is for measuring the fluid impact pressure on the nozzle front wall when the shock wave feedback drives the jet blowing backward. Taylor et al. [13] once used this idea.

The design shown in Figure 3 has an advantage that the testing nozzle can be easily changed according to different requirement for nozzle Mach number. Two sets of Laval nozzles were tested, which have 4.3 mm and 5.4 mm throat diameters respectively. The nozzles geometries are given in Table 1. The operation conditions for the over-, full- and under-expansions are given in Table 2.

2 Experimental results

2.1 Flow characteristics of underwater supersonic gas jets

Figures 5 and 6 are the sequences of underwater fully-expanded and under-expanded air jets from a Ma = 2.0 nozzle. The throat and exit diameters of the nozzle are 4.3 and 5.6 mm respectively. In Figure 5(a), the jet is in normal situation. The jet has a turbulent boundary surrounding the jet core. The jet shape generally follows the similarity law, i.e., the jet diameter grows almost linearly. However, the jet starts to expand in Figure 5(b). Then it blows backward to impact on the nozzle surface to cause a large diameter bubble disc (Figures 5(c) and 5(d)). In Figure 6, the jet sudden expansion and reverse impact on the nozzle surface occur in Figures 6(c) and 6(d). The experiment of over-expanded air jets gives similar results [18,26].

Although the high-speed photography of Aoki et al. [12] and Yang and Gustavsson [15] shows an underwater high-speed gas jet whose maximum velocity is the sound speed generates the jet expansion and the so called “back-attack” phenomenon, the results of Figures 5 and 6 show that for an underwater supersonic jet, the jet vibration and reverse impact are much significant and play a dominant role in the flow field. This means that a supersonic gas jet in water can not be more stable than a subsonic one whereas the analyses of Chen and Richter [24] and Weiland et al. [25] give an opposite conclusion. The discrepancy between the present experiment and the previous analyses requires a new explanation of the jet instability mechanism. In fact, shock waves exist in an underwater supersonic gas jet and are confined within the gas/liquid boundary of the jet because the density ratio of water/air is ~10^3. The instability of the jet boundary is influenced by many factors such as turbulence, gas/liquid mixing, Kelvin-Helmholtz instability and Richtmyer-Meshkov instability so that the jet constriction as observed by Aoki et al. [12] may occur. When shock waves meet the constricted boundary, they are reflected back. The shock wave feedback brings gas as well as liquid to move upstream towards the nozzle surface.

2.2 Pressure measurement in the jet

From high-speed photography, it was found that the frequency of the shock wave feedback is about $f = 5$ Hz [18,26]. Depending on the experimental conditions, the frequency may approach to $f \approx 10$ Hz [27]. Now, let’s examine the results of static pressures in the downstream jet shown in Figure 7, which were measured using the apparatus of Figure 2. The measurement was done at the downstream distance of 2 cm of an under-expanded air jet from a Ma = 1.5 nozzle. Figure 7(a) is the pressure in the jet center, Figure 7(b) is the pressure in the gas/liquid mixing regime and Figure 7(c) is the pressure in water. Obviously, the static pressure decreases in the radial direction. This is in agreement with the measurement of Loth and Faeth [22]. The zero pressure in the figures represents atmosphere.

The pressure signals in Figure 7(a) are generated from three fluid mechanics processes. The low level and high frequency pressures of 0~18 kPa are caused by the jet turbulence. The high level and low frequency pressures of greater than 30 kPa have about 17 peak signals and the frequency is

Table 1 Geometries of two sets of supersonic nozzles

No.	Nozzle exit Mach number *Ma*	Nozzle exit diameter (mm)	
		Throat Dia. 4.3 mm	Throat Dia. 5.4 mm
1	1.50	4.7	5.9
2	1.75	5.1	6.4
3	2.00	5.6	7.0

Table 2 Stagnation pressures for the three operating conditions

Mach number *Ma*	Stagnation pressure (×10^5 Pa)		
	Over-expansion	Full-expansion	Under-expansion
1.50	3.0121	3.7652	4.5182
1.75	4.3953	5.4941	6.5930
2.00	6.5481	8.1852	9.8222

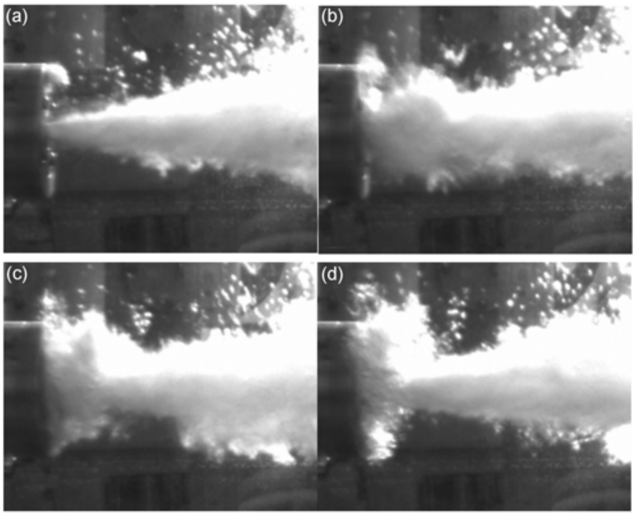

Figure 5 Vibration of a fully-expanded air jet in water from a *Ma* = 2.0 nozzle. Interframe time is 10 ms, the jet moves from the left to the right, the outer diameter of the nozzle assembly is 55 mm.

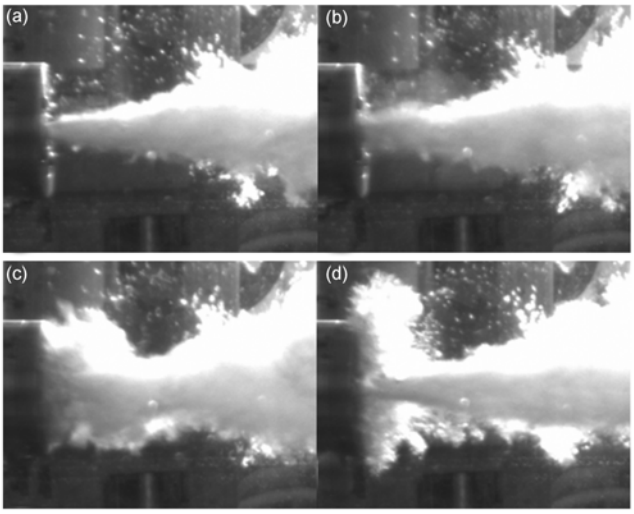

Figure 6 Vibration of an under-expanded air jet in water from a *Ma* = 2.0 nozzle. Interframe time is 10 ms, the jet moves from the left to the right, the outer diameter of the nozzle assembly is 55 mm.

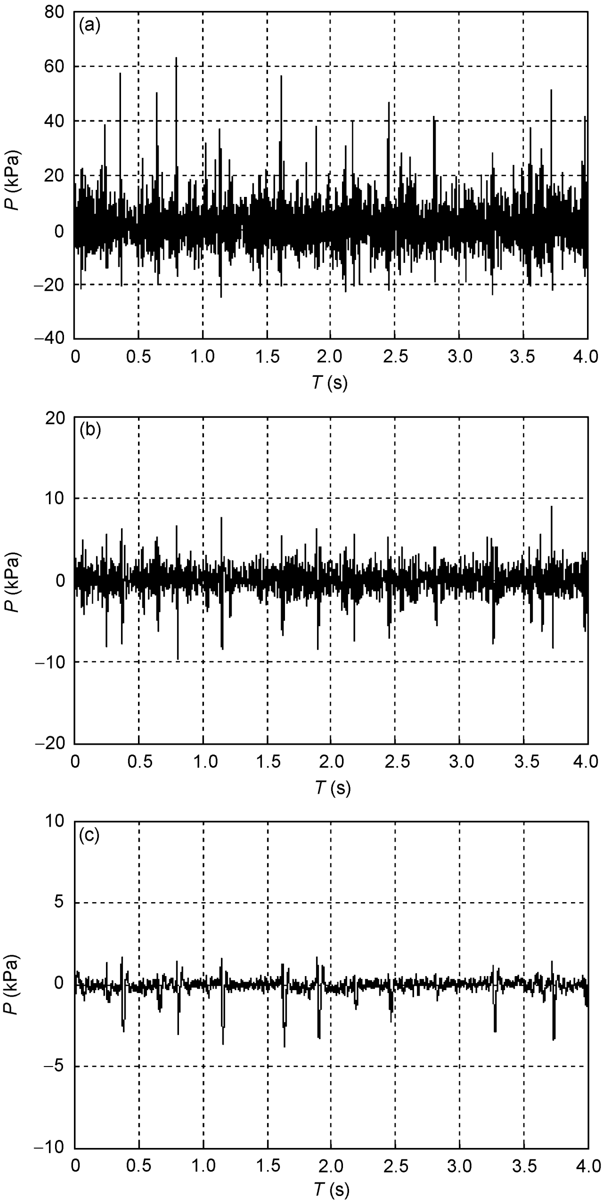

Figure 7 The jet static pressure at the downstream distance of 2 cm. Underwater under-expanded air jet from a *Ma* = 1.5 nozzle. (a) Pressure signal from probe 1; (b) pressure signal from probe 2; (c) pressure signal from probe 3.

calculated as f = 4.25 Hz. Therefore, the high level pressures are caused by the shock wave feedback. For the medium level pressures of 18~30 kPa, there are about 60 peak signals and the frequency is calculated as f = 15 Hz which is 3.52 times of the frequency of the feedback. In our most recent study [27,28], it has been found that before the shock wave feedback causes a large diameter bubble disc on the nozzle surface, bulge which has smaller amplitude appears on the underwater supersonic gas jet. The bulged bubble can occasionally touch the nozzle but it dose not collapse. Usually, the bulged bubble is swept away to the downstream. One shock wave feedback usually appears after the jet bulge has appeared several times. The bulging frequency can be 3 times or more of that of the feedback. Therefore, it is believed that the medium level pressures in Figure 7(a) are caused by the jet bulge.

2.3 Pressure measurement at the nozzle side wall

Figure 8 gives the results of upstream pressures when supersonic air jets from a *Ma* = 1.5 nozzle were tested at different conditions. The pressures were measured using the apparatus of Figure 3. When the jet was injected into open air, no oscillation was detected as shown in Figure 8(a). Figures 8(b)–(d) are the results when the jet was injected into water. Comparing the pressure magnitude in Figures

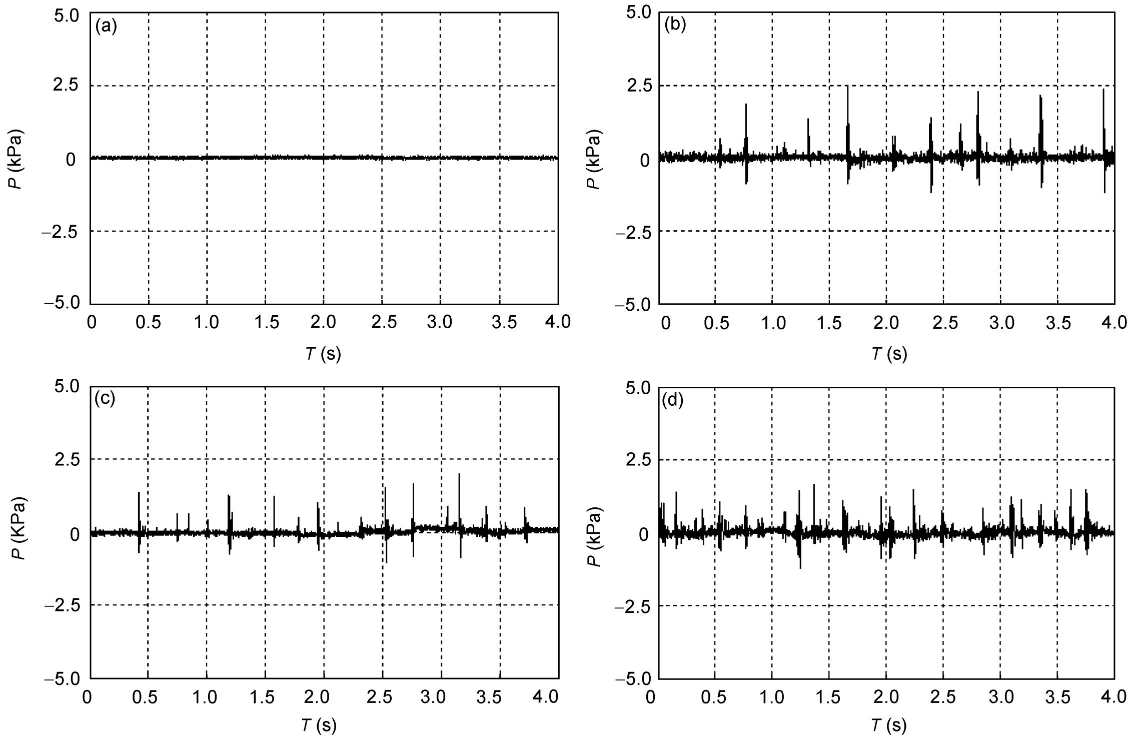

Figure 8 Upstream pressure on the nozzle side wall. The supersonic air jets from a Ma = 1.5 nozzle were at different operation conditions. (a) Fully-expanded air jet in air; (b) under-expanded air jet in water; (c) fully-expanded air jet in water; (d) over-expanded air jet in water.

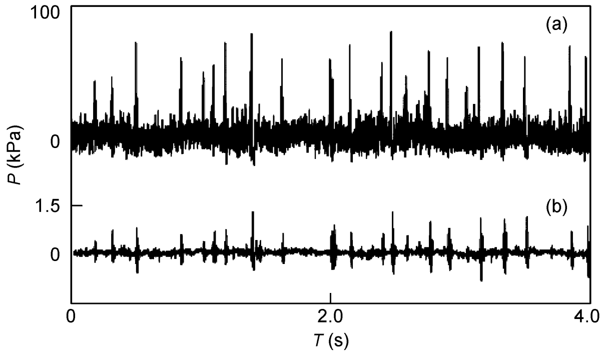

Figure 9 Comparison between the upstream and downstream pressures, underwater under-expanded air jets from a Ma = 1.5 nozzle. (a) Jet pressure at the downstream distance of 1 cm; (b) upstream pressure at the nozzle side wall.

8(b)–(d) with that in Figure 7(c), it is understood that the measured pressures at the nozzle side wall are the liquid pressures which are much less than that in the gas jet center. It is seen that in all three cases of under-, full- and over-expansions, the periodic flow oscillation (vibration) was detected. Figure 9 compares the downstream pressure in the jet center at 1 cm off-distance from the nozzle and the upstream pressure at the nozzle side wall. The 22 pressure peaks of greater than 30 kPa in Figure 9(a), whose frequency is f = 5.5, all precisely correspond each pressure peak in Figure 9(b) at the same time. This shows that the upstream flow oscillation is caused by the shock wave feedback through the fluid impact on the nozzle front wall.

2.4 Pressure measurement at the nozzle front wall

Using the apparatus of Figure 4, the pressures on the front wall of the composed nozzle device were also measured. The experiments of different nozzles and jet expansion conditions were done. Figure 10 gives an example of an underwater over-expanded air jet from a Ma = 2.0 nozzle, in which Figure 10(a) is the pressure from the No.1 hole and Figure 10(b) is the pressure from the No. 3 hole. The number of the pressure peaks of greater than 25 kPa is 16 in Figure 10(a) while it is 17 in Figure 10(b). It is clear that theses measurements provide direct evidences that the shock wave feedback drives the fluid to move upstream and to impact on the nozzle surface. It is the impact that the oscillatory pressures are generated.

It should be noted that the pressure on the nozzle front wall is greater than either the pressure in the jet or the pressure on the nozzle side wall. The reason for this may be that the measuring holes on the front wall are facing the flow direction so that the measured pressure is dynamic pressure but not static pressure. On the other hand, if the feedback brings liquid to impact on the nozzle surface, the impact pressure becomes a water-hammer pressure $P = \rho CV$ [29], where ρ is liquid density, C liquid acoustic velocity and V the impact velocity. This pressure is much greater than that caused by a gas jet impact.

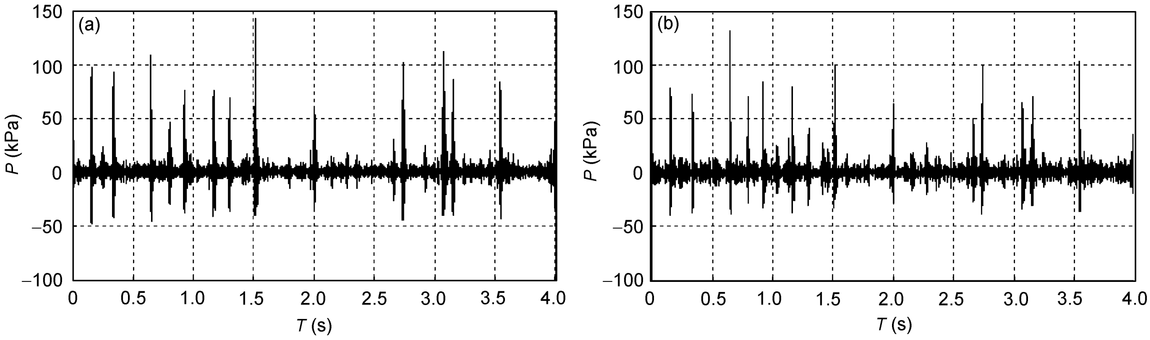

Figure 10 Pressure on the nozzle front wall, underwater over-expanded air jet from a *Ma* = 2.0 nozzle. (a) Pressure signal from No.1 hole; (b) pressure signal from No.3 hole.

3 Discussion on the flow field

Power spectrum analysis has been made and has indicated that the mechanical energy of the underwater supersonic gas jets mainly distributes in the frequency band of 0–500 Hz [17,26]. A typical power spectrum is given in Figure 11. We have found that the jet oscillation occurs no matter what the jet is in under-, full- or over-expansions. This is in agreement with the results in a recently released secret report of US Navy [30]. The flow types shown in Figures 5 and 6 visualized by the CCD camera have been well repeated in the experiments of horizontal and vertical supersonic gas jets injection into a 2 dimensional water tank [31].

The flow types of an underwater supersonic gas jet can basically be classified into two categories. The first is the relatively stable turbulent jet whose diameter generally grows linearly along the downstream distance. The second is the unstable intermittent jet sudden expansion and reverse impact on the nozzle wall. The instability analyses of Chen and Richter [24] and Weiland et al. [25] describe the first type of the flow. Their models successfully predict that an underwater supersonic gas jet is more stable than a subsonic one after the jet experiences the transition from bubbling to jetting. The experimental work of Aoki et al. [12] for an underwater sonic gas jet has shown that the second type of the flow always exists despite it appears in a much shorter time than that of the first type of the flow. The phenomenon has been called “back-attack” [12–16]. Although there may exist arguments about whether the phenomenon can be described as “shock wave feedback”, it is more realistic than those of ignoring the role of the shock waves [32,33].

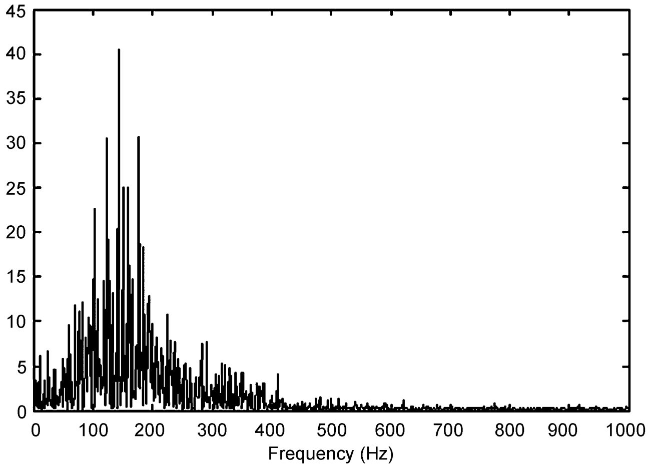

Figure 11 Power spectrum of the jet static pressure at the downstream distance of 1 cm. Underwater fully-expanded air jet from a *Ma* = 1.5 nozzle.

The non-dimensional parameter Strouhal number *St* can be used to describe the unsteadiness of the flow field, which is

$$St = \frac{fD}{V_j}, \tag{1}$$

where V_j is the jet velocity and D is usually the jet diameter or the nozzle exit diameter. f is frequency. Chen et al. [34] have found that for a fully expanded supersonic air jet in open air, the screech tone Strouhal number is in the order of 10^{-1}. The maximum sound level in their experiment is about 120 dB, which is 20 Pa. Our experiment is not aimed to detect the screech tone so that the pressure scale of 2.5 kPa in Figure 8(a) is too great to measure the acoustic feedback.

The research group of the University of Maryland has performed model tests of underwater propulsion engines [35,36]. Using subsonic air and helium gas jets injection into water, they find that the Strouhal number is in the order of 10^{-3}–10^{-4}. For the underwater supersonic air jets in the present study, St can be calculated to be in the order of 10^{-4}. The Strouhal numbers obtained from a gas/water system are about 2–3 orders of magnitude lower than that for an air/air system. This means that the mechanism for the underwater jet oscillation is different from that of screech tone in an air/air system. In fact, because of the high density ratio of water/air (~10^3), the interface prevents wave signals in the gas phase from transmitting into the liquid and it is impossible to develop into a supersonic shear layer whose speed is faster than the sound speed of water. The high inertia of the liquid attenuates the jet velocity. An underwater supersonic gas jet is more like as a "gas bag" enclosed by the surrounding water. In accordance with the Rayleigh-Plesset equation [37]:

$$R\ddot{R}+\frac{3}{2}\left(\dot{R}\right)^2=\frac{1}{\rho}\left(p_i-p_\infty-\frac{2\sigma}{R}-\frac{4\mu}{R}\dot{R}\right), \qquad (2)$$

where $R(t)$ is the bubble boundary. p_i and p_∞ are the pressures in the bubble and at infinity and they may be functions of the time t. σ, μ and ρ are the surface tension constant, the coefficient of the liquid viscosity and the liquid density, respectively. It has been known that the periodic perturbation in the environmental pressure p_∞ can cause the bubble oscillation [37]. From the pressure measurement shown in Figure 7, it is understood that the pressure in the bubble p_i is non-linearly oscillated, which certainly brings about the bubble oscillation. This is the source of resulting in the jet expansion and its reverse impact. The oscillation in p_i is believed to be due to the shock waves. The continuous supply of a compressible gas flow into the bubble will eventually produce a burst of the bubble.

4 Conclusions

A comprehensive study for understanding the fluid mechanics of underwater supersonic gas jets has been performed by using a CCD camera, a static pressure probe rank, a special designed nozzle assembly and a composed nozzle device. With these apparatuses, generation of the oscillatory pressures in the jet, the fluid impact on the nozzle surface and upstream propagation of the oscillatory pressures have been investigated thoroughly. It has been demonstrated that with or without a wave dumper on the water surface has no effect on the experimental results. This is in agreement with the measurement of Loth and Faeth [22].

For an underwater supersonic gas jet, the instability of the gas/liquid boundary occurs due to turbulence, mixing, Kelvin-Helmholtz instability and Richtmyer-Meshkov instability [38], etc. As a result, some local contraction of the jet starts but the jet compressible nature forces the contradicted area to bulge at a smaller amplitude. Accompanying several times of bulging, shock waves confined within the jet begin to accumulate their energy. Finally, the energy release results in a backwards reflection of shock waves and a globe expansion of the jet. This reflection is the shock wave feedback phenomenon which brings the surrounding fluids to move upstream to impact on the nozzle surface. The impact causes a large bubble disc on the surface. Consequently, the oscillatory pressures are transmitted to the fluid in the nozzle upstream position. The above process will repeat periodically. The jet oscillation may be explained by a model of a compressible "gas bag" bounded by an incompressible liquid. The shock waves and the gas compressibility generate nonlinear pulsating pressures in the bubble. As a result, the bubble starts to oscillate. Since the compressible gas is continuously supplied into the bubble, the pressure in the bubble increases until the bubble bursts. Then the next cycle comes again.

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