Research paper

Acoustic emission characteristics of underwater pyrotechnic combustion from a feedback cavity

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Abstract

In order to research the acoustic radiation characteristics of underwater pyrotechnic combustion, a feedback cavity was introduced and the effects of its main structural characteristics on underwater acoustic radiation were studied by acoustic testing. The results show that the addition of the feedback cavity similar to a Hartmann acoustic generator significantly improved the sound pressure level (SPL) of underwater pyrotechnic combustion, especially the peak of SPL that was increased by 13 dB from 149 to 162 dB at the frequency of 125 Hz. But the addition of the feedback cavity had little effect on the frequency. These results indicated that the feedback cavity is effective for improving SPL in underwater pyrotechnic combustion. There was a change of 6.8 dB in the magnitude of the SPL at a frequency of 100 Hz as the charge nozzle diameter was increased from 10 mm to 15 mm. The frequency of the underwater pyrotechnic combustion changed slightly when the charge nozzle diameter or the feedback cavity diameter was increased.

Keywords : pyrotechnics combustion, underwater, acoustic emission characteristics

1. Introduction

Pyrotechnics composed of oxidant, combustible agent and adhesive are self-contained oxygen systems as the oxidant provides oxygen for the combustion[1], and through continuous and steady underwater combustion, it can produce a large amount of high temperature gases and solid residues which produce certain sound effects. Li[2] has researched on the bubble movement characteristics during underwater pyrotechnic combustion. According to previous studies[3] on the effects of pyrotechnic charge nozzle noise and thermite content on the acoustic radiation characteristics during underwater pyrotechnic combustion, the intensity of the nozzle noise is proportional to the acceleration of the bubble volume. The pyrotechnic exotherm has an impact on the underwater sound radiation at the band sound pressure level (SPL) of about 150 dB. In order to further enhance the SPL of underwater pyrotechnic combustion, we have introduced a feedback cavity similar to a Hartmann acoustic generator[4] into the underwater pyrotechnic combustion system and the effects of the Hartmann acoustic generator on the system's sound radiation characteristics have been studied.

A Hartmann acoustic generator consists mainly of a nozzle and a circular feedback cavity (Figure 1). It is characterized by simple construction, low cost and an ability to produce high intensity sound in liquids. Hartmann acoustic generators can be effectively used in numerous fields such as coagulation and precipitation of dust and smoke using sound waves[5], atomization[6)–8] and ignition[9)–11].

These experiments in the research was to apply the feedback cavity which was adopted by a circular structure in underwater pyrotechnic combustion and to study its effectiveness, as well as the changes in the SPL, as a function of its main structural characteristics, including the charge nozzle diameter (D_c) and the feedback cavity diameter (D_r).

2. Experimental

2.1 Materials

Pyrotechnics composed of oxidant (potassium perchlorate), combustible agent (magnesia-alumina) and adhesive (nitrocellulose) were compressed into grains with density 1.8 g cm^{-3}, diameter 18 mm , and the total mass of sample 5 ± 0.01 g, combustion heat (ΔQ) 9.34×10^3 kJ g^{-1},

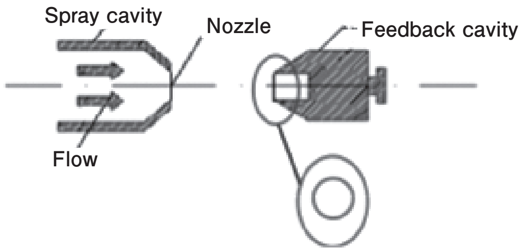


Figure 1 Schematic diagram of a Hartmann acoustic generator.

burning velocity of the propellant (u_b) 2.4 mm s^{-1}, the volume of gaseous products approximately 6.2 m^3(kg)$^{-1}$ (the combustion heat and the volume of gaseous products are calculated by theory and the burning velocity of the propellant is measured). The grains were installed in the spray cavity and positioned with a feedback cavity on the same axis as the pyrotechnic charge nozzle. The distance between the hydrophone and the sample was 0.5 m.

2.2 Methods

A schematic diagram of the underwater pyrotechnic combustion test is shown in Figure 2. The test sample was placed in an acrylic cube tank (950 × 750 × 1100 mm), located 0.7 m from the water surface and ignited by electric firing. A hydrophone placed in the tank transformed the captured sound pressure into electrical signals, which were then conditioned by Brüel & Kjaer Type 2692 charge amplifiers and transferred through a Pulse Front-end 3560C. The data were collected and processed by the software PULSE LABSHOP. The sensitivity of a Brüel & Kjaer type 8104 at 250 Hz is ± 0.25 dB. The distance between the hydrophone and the charge nozzle was 100 ± 5 cm. The spectra were calculated over one-third octave bands using PULSE LABSHOP. The one-third octave bandwidth, noise band sound pressure level, Lpoi (reference value : 1μPa), and broadband SPL (Lpo) were calculated as follows :

$$Lpoi = 20\log_{10}\left(\frac{U_i}{U_0}\right) - M_0 - K \quad (1)$$

$$L_{po} = 10\log_{10}\sum_{i=1}^{n} 10^{0.1L_{poi}} \quad (2)$$

where U_i is the output voltage of the measured system in V, U_0 is the reference voltage ($U_0 = 1V$), M_0 is the free field voltage sensitivity of the hydrophone in dB (reference value : $1V/\mu P_a$), K is the gain of the system in dB and n is number of 1/3 octave band in the band. Measurements were made extremely close to the source to maximize the component of the signal due to sound directly radiated from the source. The objective of using underwater detecting system was to obtain underwater pyrotechnic radiation characteristics by the feedback cavity ; thus the true free field radiated noise levels were not measured, and the results are purely comparative. The results are the average of three replicate measurements.

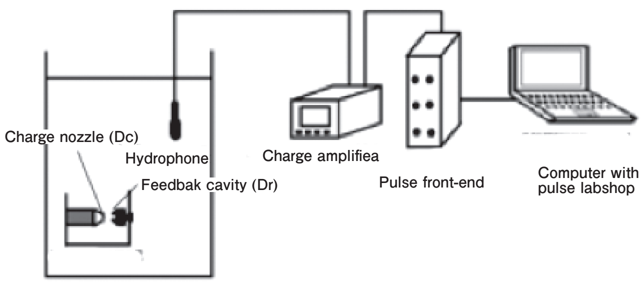


Figure 2 Schematic diagram of the underwater pyrotechnic combustion test.

3. Results and discussion

3.1 Effects of feedback cavity on SPL of underwater pyrotechnic combustion

The experiments using an acoustic measurement system were carried out with and without a feedback cavity. The results are shown in Figure 3.

Figure 3 shows that the addition of the feedback cavity of a Hartmann acoustic generator could significantly improve the SPL of underwater pyrotechnic combustion, especially the peak of SPL that was improved by 13 dB from 149 to 162 dB at the frequency of 5 Hz. But the feedback cavity has no influence on the frequency of the underwater pyrotechnic combustion and the tendency of the variation of SPL with frequency is nearly the same whether the feedback cavity was present or not. At frequencies lower than 125 Hz, the SPL improved with increasing frequency whether the feedback cavity was present or not. At frequencies greater than 125 Hz, the SPL reduced with increasing frequency. These results indicate that adding the feedback cavity is effective for improving SPL in underwater pyrotechnic combustion.

The addition of a feedback cavity in front of the pyrotechnic charge nozzle changed the mode of action between the combustion products and water. The high temperature products of the underwater pyrotechnic combustion leaving the charge nozzle in the absence of a feedback cavity interacted with the water in the tank. When the feedback cavity was present, the combustion

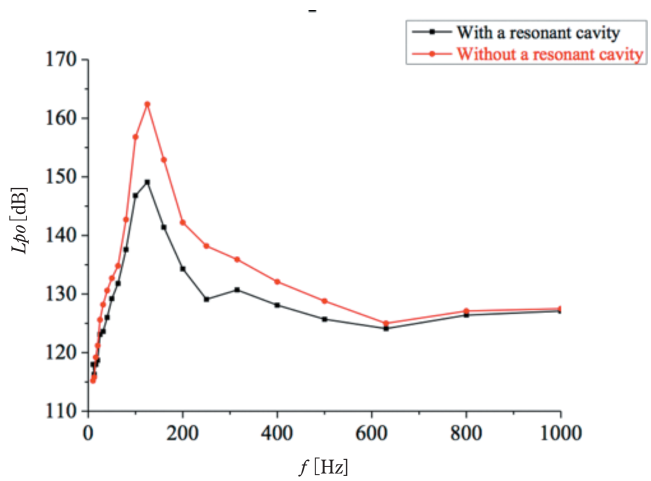


Figure 3 Frequency of a feedback cavity similar to a Hartmann acoustic generator on the SPL of underwater pyrotechnic combustion (D_c = 10 mm, D_r = 12.5 mm, the distance between the cavity charge nozzle and the feedback cavity was 10 mm).

Figure 4 The bubble pattern of underwater pyrotechnic combustion without a feedback cavity (charge cavity on the left).

products entered the resonant cavity, and then the flow was reflected from the feedback cavity outwards and collided with the incident flow. Dowling and Williams[12] showed that the mean velocity at the exit of nozzles were same. The device without feedback cavity will have higher shearing area which would decrease the jet velocity faster compared with the device with feedback cavity. We assume that the velocity of gas emitted from the nozzle as U_{mean}. It may be noted that noise emitted from jets vary as U_{mean}. Besides, the bubble pattern of the charge nozzle was different because the mode of action between the combustion products and water was changed. Figures 4 and 5 show the bubble patterns of underwater pyrotechnic combustion without and with the feedback cavity respectively, both at time intervals of 66 ms.

As illustrated in Figure 4, the high temperature gases from the flame-enclosed charge nozzle flow into the water and result in the formation of bubbles. The bubbles move away from the charge nozzle due to the combined effects of viscous resistance, buoyancy, gravity, and inertial force. When the feedback cavity was added in front of the charge nozzle, the reflected combustion products covered the nozzle inside the bubble and collided with the incident flow. The bubbles became larger because of the growing volume of gases and gradually separated from the nozzle under the effect of buoyancy.

The bubbles produced by the underwater pyrotechnic combustion were treated as spherical approximations and their diameters were 10 and 12 cm, as judged by the ruler attached to the water tank and the scale conversion at a time of 330 ms. Quantitative experimental studies[13), 14)] confirm that the generation of underwater exhaust noise is closely related to the size of the bubble, which becomes detached from the orifice at a high gas flow rate and the break-up and coalescence of bubbles which generate an acoustic effect strongly dependent on their size. Increasing the bubble size through the addition of a feedback cavity is the important reason for the improvement of the SPL. Furthermore, the turbulent noise, known as quadrupole sound source, is also a significant source of noise[15)]. The result of bubbles in a turbulent flow field is a combination of monopole and quadrupole sound sources.

Crighton and Ffowcs Williams[16)] showed monopole sources of sound arise from the forced response of the bubbles at the frequency characteristic of the turbulence. They lead to an efficiency proportional to the fifth power of Mach number, which is the variation usually ascribed to quadrupole sources. In fact it is shown that the monopole intensity is just that of the usual Lighthill quadrupoles, but augmented by the factor $(c_\alpha/c_m)^4$. c_α/c_m can easily exceed 10, so that the presence of bubbles in a turbulent flow will very greatly increase the acoustic power output.

Besides, they found the sound field from forced bubble motion. They assumed for the moment that pressure field $p(t)$ generating the bubble motion is that of a turbulent flow whose internal dynamics may be regarded as nearly incompressible. The Lighthill theory of aerodynamic noise showed a turbulent eddy radiates sound waves. The mean square acoustic pressure (P_m) at any point in the turbulent region increases linearly with the scale L^3 of the turbulent bubbly region. They also gave the contribution from the forced mode only. P_m is given by

$$P_m \sim \frac{1}{4\pi\rho_0 c_\alpha}\left[\left(\frac{\partial Q}{\partial t}\right)^2\right] l_0^3 L^3 \qquad (3)$$

where ρ_0 is the density in the very distant field. c_α is the sound velocity in α-phase (liquid). l_0 denote a correlation scale for the turbulent flow. L is the scale of turbulent bubbly region. Q is the effective rate of mass injection density into phase α. So from this equation we can see that P_m is proportional to the l_0^3 and L^3. The l_0 and L will become bigger when add the feedback cavity in front of the nozzle which will make the flow more turbulent.

Besides, the collision between the combustion products from the charge nozzle and the reflected flow results in a higher intensity of turbulence, which accounts for the vibration and isolation of bubbles in the fluid[17)]. This means that the bubbles are prone to rupture and merge.

3.2 Effects of nozzle diameter on the SPL of underwater pyrotechnic combustion

These tests aimed to investigate the relationship between the acoustic radiation characteristics of underwater pyrotechnic combustion and the charge nozzle diameter (D_c = 10, 12.5 and 15 mm) when the feedback cavity diameter was 37.5 mm and the distance between the cavity charge nozzle and the feedback cavity was 12.5 mm (Figure 6).

Figure 6 shows that the peak of SPL is 159.4, 159.8 and 157.4 dB respectively at a frequency of 100 Hz as the D_c is increased. The peak of SPL at D_c = 12.5 mm is the highest. The mean velocity and the shearing area at the exit of nozzles are different with different diameter of nozzle. The larger the diameter of nozzle is, the smaller U_{mean} and the bigger $S_{shearing}$ (shearing area) become. Besides, the D_c has only a slight effect on the frequency. The pulse volume source can be considered as a point source since the dimension of the sound source of the underwater pyrotechnic combustion is much smaller than the wavelength. The wave equation for a point source is

Figure 5 The bubble pattern of underwater pyrotechnic combustion with a feedback cavity (feedback cavity on the right and charge cavity on the left).

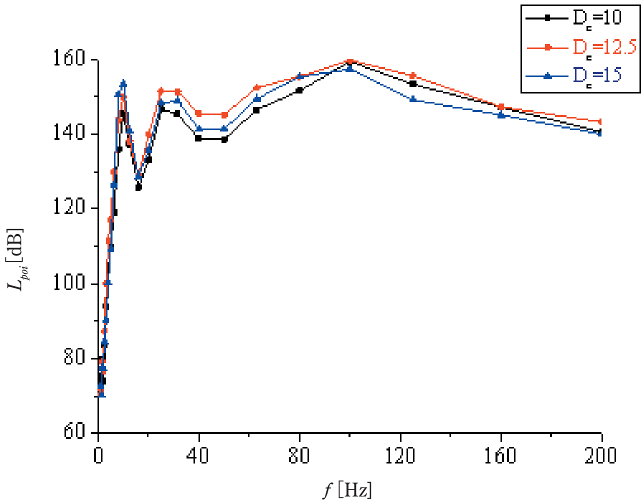


Figure 6 Effect of nozzle diameter on the SPL of underwater pyrotechnic combustion.

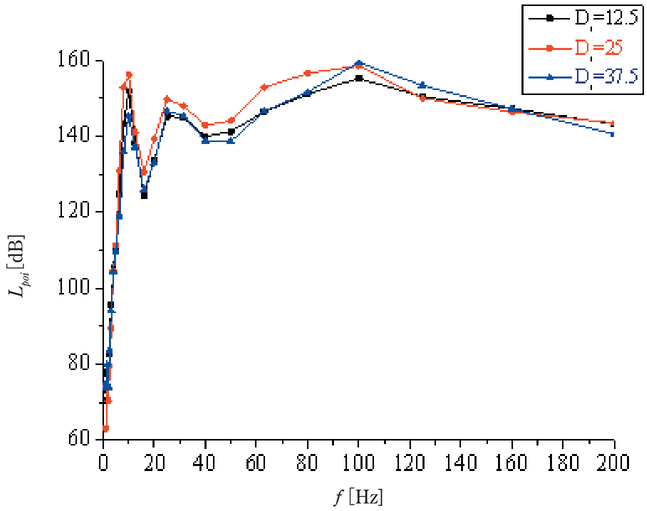


Figure 7 Effect of feedback cavity diameter on the SPL of underwater pyrotechnic combustion

solved as follows :

$$p'(r,t) = \frac{\rho_0}{4\pi r}\frac{\partial^2}{\partial t^2}Q\,(t - r/c_0) \quad (4)$$

where: $p'(r,t)$ is the sound pressure at distance r between the acoustic field and the point source, ρ_0 is the density of water, c_0 is the velocity of sound in water and $Q\,(t-r/c_0)$ is the volume of the point source. According to Equation (4) the intensity of the acoustic radiation is proportional to the product of the density of water and the point source volume acceleration. Since the density of water is approximately the same as the identical test samples and the environment, the acoustic radiation intensity is only proportional to the volume acceleration of the point source.

An increase in D_c from 10 to 12.5 mm resulted in an increase of the speed of the flow. Since the flow did not obviously increase, the volume acceleration of the point source was only slightly higher. This is the reason why the SPL increases 0.4 dB at a frequency of 100 Hz with the increase in D_c.

3.3 Effects of feedback cavity diameter on the SPL of underwater pyrotechnic combustion

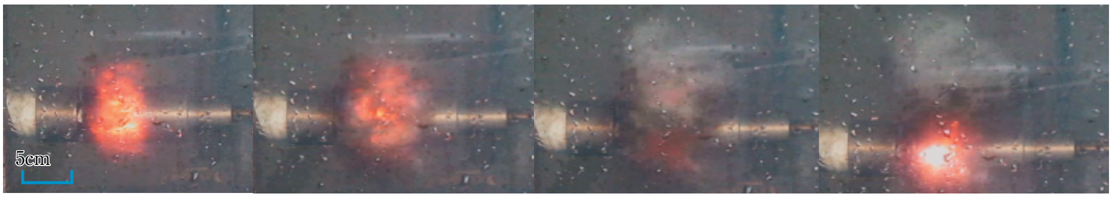
The effect of the feedback cavity diameter (D_r = 12.5, 25 and 37.5 mm) on the acoustic emissions is illustrated in Figure 7 when D_c was 10 mm and the distance between the cavity charge nozzle and the feedback cavity was 12.5 mm.

Figure 7 shows that the SPL of underwater pyrotechnic combustion changes as the D_r increases. SPLs for D_r of 25 and 37.5 mm are highest in the ranges 10-90 and 90-160 Hz respectively. However the magnitude of the change is only 4.2 dB at a frequency of 100 Hz. The peak of SPLs of underwater pyrotechnic combustion are 155.2, 158.5 and 159.4 dB respectively at a frequency of 100 Hz. Alteration of the feedback cavity diameter has a slight impact on the frequency of the sound radiation.

Due to the different feedback cavity diameters, the energy of the combustion products reflected by the feedback cavity varied and the bubble pattern is demonstrated in Figure 8, at time intervals of 66 ms.

Figure 8a shows that a part of the combustion products sprayed into the feedback cavity were reflected and collided with new combustion products when the diameter of pyrotechnic combustion products was much larger than the feedback cavity diameter. The combustion products between the nozzle and the feedback cavity were inconsistently distributed as shown in Figure 8a. When the diameter of pyrotechnic combustion products was a little larger than the feedback cavity diameter, the products covered the feedback cavity and were almost reflected by feedback cavity in Figure 8b. When the diameter of pyrotechnic combustion products was nearly equal to the feedback cavity diameter, a majority of the combustion products were reflected by the feedback cavity in Figure 8c. Within a certain range, a larger feedback cavity diameter means more gases are reflected. When the diameter of pyrotechnic combustion products has a small difference with feedback cavity diameter, the collision range and intensity were greater. Furthermore, the disturbance of the surrounding water was stronger and the turbulence was strengthened, accounting for the increase in the SPL.

(a)



(b)

(c)

Figure 8 Pattern of pyrotechnic combustion bubbles with a feedback cavity diameter of (a) 12.5, (b) 25 and (c) 37.5 mm (feedback cavity on the right and charge cavity on the left, $D_c = 10$ mm, the distance between the cavity charge nozzle and the feedback cavity was 25 mm).

4. Conclusions

An experimental setup was developed to study the effect of a Hartmann acoustic generator on the sound radiation characteristics of underwater pyrotechnic combustion. The results show that the addition of the feedback cavity of a Hartmann acoustic generator can significantly improve the SPL (sound pressure level) of underwater pyrotechnic combustion, especially the peak of SPL which was increased by 13 dB from 149 to 162 dB at a frequency of 125 Hz.

In the context of the experimental parameters, the flow of combustion products increased with charge nozzle diameter and the volume acceleration of the point source improved somewhat. When the radial width of the combustion products is almost the same as the feedback cavity diameter, the disturbance of the aqueous medium is more violent and the turbulence is stronger.

Acknowledgments

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References

1) J. A. Conkling and C. Mocella, "Chemistry of pyrotechnics : basic principles and theory", 8–30, CRC Press (2010).
2) J. Li, H. Guan, D.M. Song, Q. Wang, and J. Du, Flow Turbul. Combust., 93, 249–258 (2014).
3) D. H. Ouyang, H. Guan, G. P. Pan, X. F. Du, L. Fan, and H. P. Lv, Acta Acust. (Beijing), 35, 641–645 (2010).
4) J. Hartmann and B. Trolle, J. Sci. Instrum., 4, 101–111 (1927).
5) L. E. Savory, Eng., 170, 99–100(1950).
6) A. Khandwawala, R. Natarajan, and M. C. Gupta, Fuel, 53, 268–273 (1974).
7) B. Li, G. H. Hu, and Z. W. Zhou, Appl. Math. Mech., 28, 1415–1426 (2007).
8) G. J. Sreejith, S. Narayanan, and T. J. Jothi, Proc. 37th AIAA Fluid Dynamics Conference and Exhibit, Miami (2007).
9) B. Phillips, A. J. Pavli, and E. W. Conrad, J. Spacecr. Rockets, 7, 620–622 (1970).
10) G. Raman, A. Mills, and S. Othaman, Proc. ASME fluid Engineering division summer meeting, New Orleans (2003).
11) G. Raman and A. Mills, J. Aircr., 41, 1306–1314 (2004).
12) A. P. Dowling and J. E. F. Williams, "Sound and sources of sound", E. Horwood (1983).
13) C. Jr. Devin, J. Acoust. Soc. Am., 31, 1654–1667 (1959).
14) C. Norwood, C. Li, Proc. ACOUSTICS, Gold Coast (2004).
15) M. J. Lighthill, "On sound generated aerodynamically-Ⅱ. Turbulence as a source of sound", 1–32, Proc. R. Soc (1954).
16) D. G. Crighton and J. E. F. Williams, J. Fluid Mech., 36, 585–603 (1969).
17) J. J. Gavigan, E. E. Watson, and W. F. King, J. Acoust. Soc. Am., 4, 1094–1099 (1974).