Water Injection for Bubble Noise Reduction

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Abstract

Underwater exhaust noise is potentially a significant contributor to the acoustic signature of a conventional diesel electric submarine. The design of an underwater exhaust outlet has an impact on the radiated noise levels, particularly the flow noise generated at the exit. This paper details the results of an experimental study of the acoustic performance of air-water mixture through a simple exhaust outlet. The acoustic emission of the exhaust jet at airflow rates from 0.32 l/s to 1.72 l/s and water injection rates between 0 l/s to 0.08 l/s was investigated. It was found that noise reductions of approximately 10 dB could be obtained by injecting approximately 10% water, by volume, uniformly into the discharging air. It is also important to ensure good mixing between the water and gas phases in order to achieve optimum noise reductions

Introduction

Underwater exhaust noise is potentially a significant contributor to the acoustic signature of a conventional diesel electric submarine. The design of an underwater exhaust outlet has an impact on the radiated noise levels, particularly the flow noise generated at the exit. Studies of a naval exhaust system have demonstrated that bubble exit, and the bubble clouds from the exhaust are key sources of noise, [1]. Bubble formation, bubble coalescence and fragmentation, and bubbles bursting at the free surface generate acoustic emissions. Many studies on sound generation by bubbles [2] have focused on a single bubble, or bubble formation at a low flow rate. The acoustic frequency generated by the formation of a bubble at a nozzle at low gas flow rates can be theoretically calculated and has been used to size bubbles, [2]. However, at higher flows, bubble-acoustic signals become irregular because multiple bubbles are involved, and no simple theory can predict the acoustic field [3 4 5].

Quantitative experimental studies designed to improve the understanding of the mechanisms of noise generation by bubbles have been reported, [5, 6, 7]. They confirmed that gas flow rate and the orifice dimension controlled the interactions of bubbles. It has been found that the bubble noise generated by an underwater gas jet is closely related to the size of the bubble, which detaches from the orifice at a high gas flow rate, [7]. For a low gas flow rate or a small orifice, an increase in both orifice size and gas flow rate result in a significant increase in the generated noise over a wide frequency band (100Hz to10kHz). For a high flow rate or a big orifice, acoustic emission is not as closely related to airflow rate or orifice size as for low flow rates. Based on the study, it was confirmed that the bubble-bubble interaction and highly turbulent gas jet play an important role in the generation of noise, particularly the size of the bubble that detaches from the orifice.

Bubble break-up and coalescence are dominant dynamic features in air discharging through an underwater orifice, thus the reduction of gas jet noise may be achieved by controlling these complicated processes. Bubble break-up and coalescence depend strongly upon the size of the bubble and the inertial force acting on it by the surrounding flow [7 8 9]. The larger the bubble, the stronger the tendency for bubble to break up and to amalgamate. The aim of this work was to study the acoustic performance of water injection into air jets. The relationship between the radiated noise and the gas/water ratio and the effect of outlet configuration are investigated.

Experimental Apparatus

The experiments were carried out in a small water tank, 900×600×600 mm, Figure 1. The orifice was fed with regulated, filtered compressed air and water via a flow meter. The airflow rate was determined by timing the collection of air in a large inverted beaker. Four hydrophones (Bruel & Kjaer Type 8103) were set at vertical locations as shown in Figure 1. The signals were conditioned by Bruel & Kjaer Type 2635 charge amplifiers and recorded on a Sony Digital 216Ax DAT recorder, at a sample rate of 40 kHz per channel. The spectra were calculated over third octave bands using an HP Analyser; for one-third octave bands from 50 Hz to 16 kHz. Measurements were made as close to the source as possible to maximize the component of the signal due to directly radiated sound from the source. This was a parametrical study looking at relative changes caused by water-injection and airflow rate; thus a measurement of the true free field radiated noise levels was not sought, and the results are purely comparative..

Eight airflow rates and two water-flow rates were used to test the effect of water injection on noise generation. The test conditions are listed in Table 1. Three outlets – a single orifice with $d = 16mm$, a T-head and circular-head each with four orifices $d = 8mm$ - were used to study the effect of outlet design.

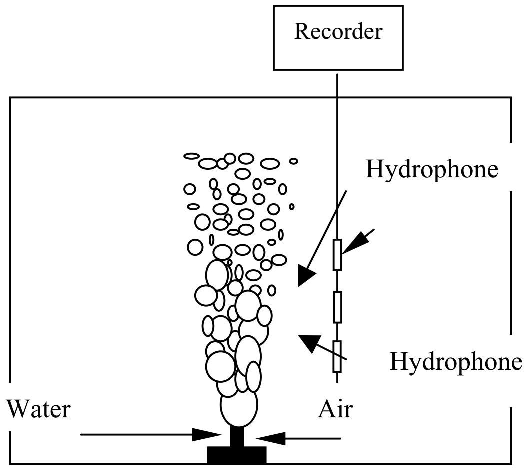
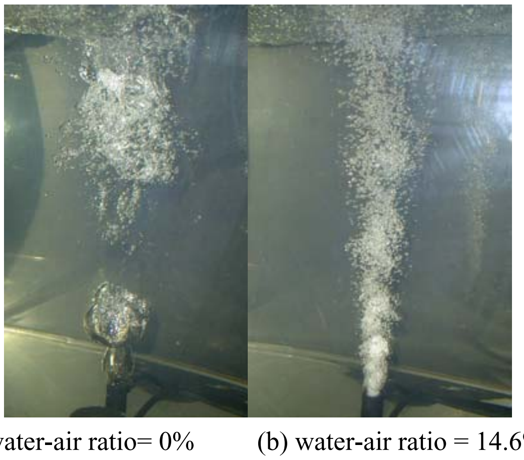


Figure 1 Schematic of experimental apparatus

Results and Discussion

Noise generations by an air jet and air-water jet

Figure 2 shows the bubble stream for an air jet and the air-water jet for a single orifice. For the air jet, a gas pocket formed on the orifice causing a large bubble to form and then detach (Figure 2a). This large bubble then underwent a violent fragmentation as it rose. The flow became highly turbulent with complex bubble interactions. In contrast, the injection of water into the air produced a well-mixed bubbly plume with many small bubbles were distributed uniformly in the jet (Figure 2b). The bubble coalescence near the orifice was avoided and the bubble fragmentation was effectively weaker.



(a) water-air ratio= 0% (b) water-air ratio = 14.6%

Figure 2 Visualisation of air jet without and with air injection, for an air flow rate of 0.53l/s.

The sound levels measured for the two jets are shown in Figure 3. For the air jet, the generation of the broadband noise was mainly due to bubble coalescence near the orifice and the formation of many different size bubbles due to fragmentation downstream. It can seen from Figure 3 that an injection of 14.6% water produced a significant reduction of acoustic emission over the entire frequency range, achieving approximately a 10 dB decrease. A maximum 15 dB decrease was obtained for frequencies greater than 1kHz. The injection of water effectively prevented the formation of a large bubble at the orifice, which produces a large excitation when it detaches. Furthermore it avoided the violent fragmentation of the big bubble downstream. This resulted in weak bubble-bubble interaction which led to a weaker acoustic emission. This result also confirms that the bubble-bubble interaction (bubble coalescence near the orifice) produce stronger excitations compared with those generated by an individually releasing bubble, [3].

Effect of air-water ratio

The effects of different air-water ratios are demonstrated in Figure 4 for an airflow rate of 1.4 l/s. Without water injection (Figure 4a), a “bubbling” regime was observed and the features of coalescence, fragmentation and constriction are present, similar to Figure 2a. However, at this higher airflow rate, the “bubbling” regime started to transform into a “jetting” regime.

Upon injecting a moderate amount of water, corresponding to water-air ratio of 3.6%, the air no longer underwent as significant an expansion at the orifice as in the case of plain air discharging, which resulted in the formation of a smaller bubble near the orifice (Figure 4b). However, coalescence, fragmentation and constriction still occurred, albeit with the smaller bubble.

With an increase in the water-air ratio to 6.0%, a bubbly “jetting” regime was observed, containing many smaller bubbles. The formation of a large bubble near the orifice ceased, and a well-mixed bubbly plume was obtained. The injection of the water effectively weakened the bubble-bubble interaction, Figure 4c. It would be expected that a further decrease in bubble size could be achieved with a higher water-air ratio. However, the maximum achievable water flow rate of 4.78l/min limited the water-air ratio for higher airflow rates.

The effects of water-air ratio on the acoustic emissions are illustrated in Figure 5. The sound pressure level in one-third octave bands for four airflow rates with three different water injection rates are shown. A 5-to10 dB reduction for frequencies above 1000 Hz, was obtained with the injection of water for all airflow rates. The reduction increased with an increase in water-air ratio.

These reductions may be explained by referring to the flow visualisations. The injection of water produced many smaller bubbles at the orifice leading to the weakening or absence of the bubble coalescence, fragmentation and constriction, which resulted in the reduction of acoustic emissions.

Table 1 Test conditions, Water-air ratio

		Airflow rate (l/s)						
Water flow l/s		0.32	0.53	0.72	0.88	1.04	1.40	1.72
	0	0%	0%	0%	0%	0%	0%	0%
	0.048	14.0%	8.7%	6.6%	5.5%	4.7%	3.6%	2.9%
	0.079	23.3%	14.6%	11.1%	9.1%	7.9%	6.0%	4.9%

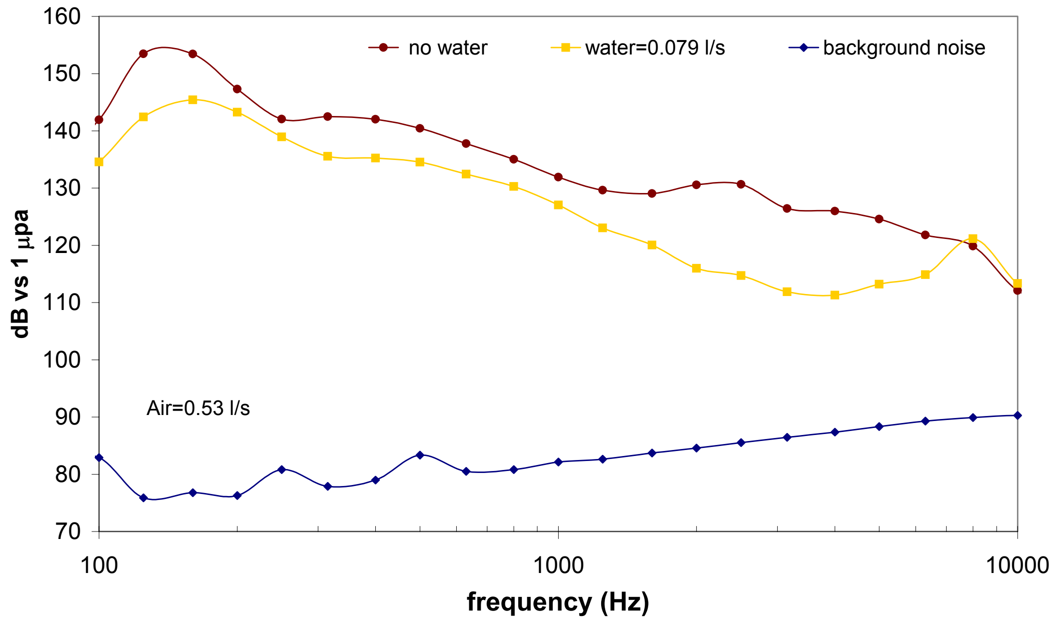
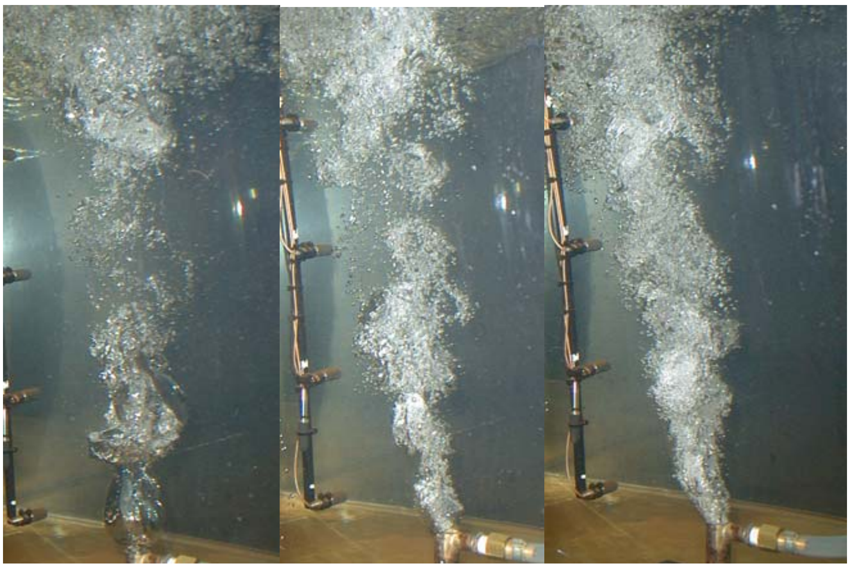


Figure 3 Sound levels in third octave bands for air jets with and without water injection for the outlet of a single orifice (d=16 mm)



(a) (b) (c)

Figure 4 Visualisation of the jet at different water-air ratios for airflow rate equal to 1.4 l/s (a single orifice=16 mm).

The reductions of radiated sound level as a function of water-air ratio are shown in Figure 6. An increase in water-air ratio generally results in an increase in the reduction up to a maximum value. A further increase in water-air ratio beyond this didn’t result in further improvement in the radiated sound levels. It can be seen from Figure 6 that the optimum water-air ratio varies for different frequencies. For frequencies greater than 3 kHz, the optimum water-air ratio is around 8%. While, for frequencies lower than 400 Hz, the optimum water-air ratio lies between 8~10%.

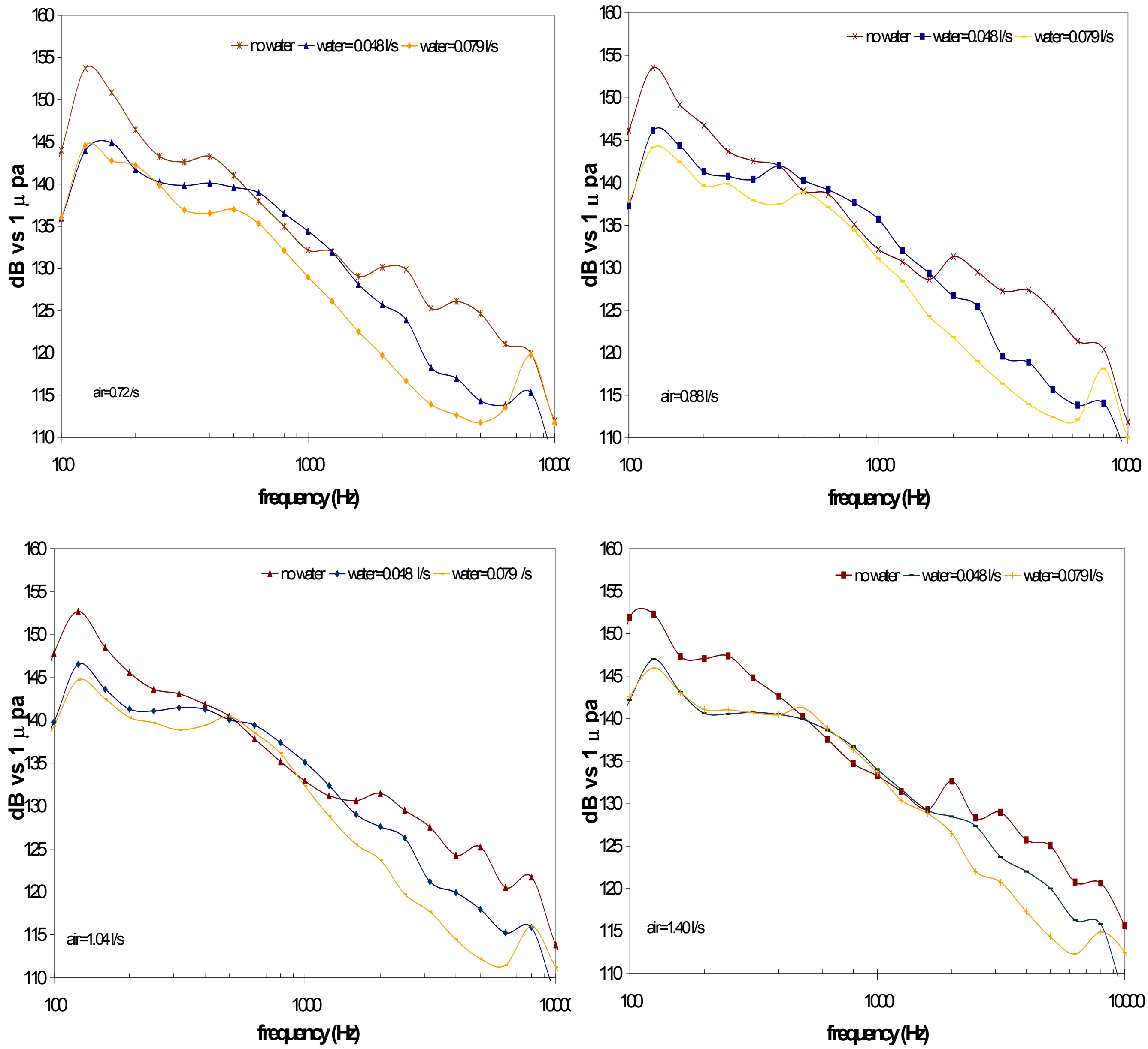


Figure 5 Comparison between sound levels for the jet of different air-water ratios for the outlet of a single orifice of 16 mm in diameter

Effect of the configuration of the outlet

The results presented above are for a single outlet orifice. However in many designs there are multiple outlet orifices. In order to investigate what effect this may have, two different multi-hole outlets were studied. A circular head (C-head) with 4 orifices and a T-head with 4 orifices, each orifice had a diameter of 8 mm, giving the same total outlet area as the single 16mm orifice.

The flow patterns at different water-air ratios for the two different outlets are shown in Figures 7 and 8. In general, without water injection, the features of bubble-bubble interactions are similar to those observed with the single orifice. Large bubbles formed at the outlet and there was coalescence, violent fragmentation and constriction (Figure 7a and 8a). For the C-head design weakening of bubble-bubble interactions was achieved with the injection of water, leading to the formation of a bubbly plume (Figure 7b). However, for the T-head, two different “bubbling” jets were observed, and air was not uniformly discharged through 4 orifices. It is clear, the feature of coalescence and constriction still occurred, but in a weaker state, (Figure 8b).

The effect of the water-air ratio and outlet configuration on the noise generation is demonstrated in Figures 9 and 10. For the C-head, up to 10 dB reduction was obtained for frequencies higher than 500 Hz with the highest water injection ratio. The reduction decreases to 7 dB with a decrease of water-air ratio (Figure 9b). In the low frequency bands (200 to 700 Hz) there is a small increase in the radiated noise for some water-air ratios (Figure 9b). Again, the reduction in the sound levels is

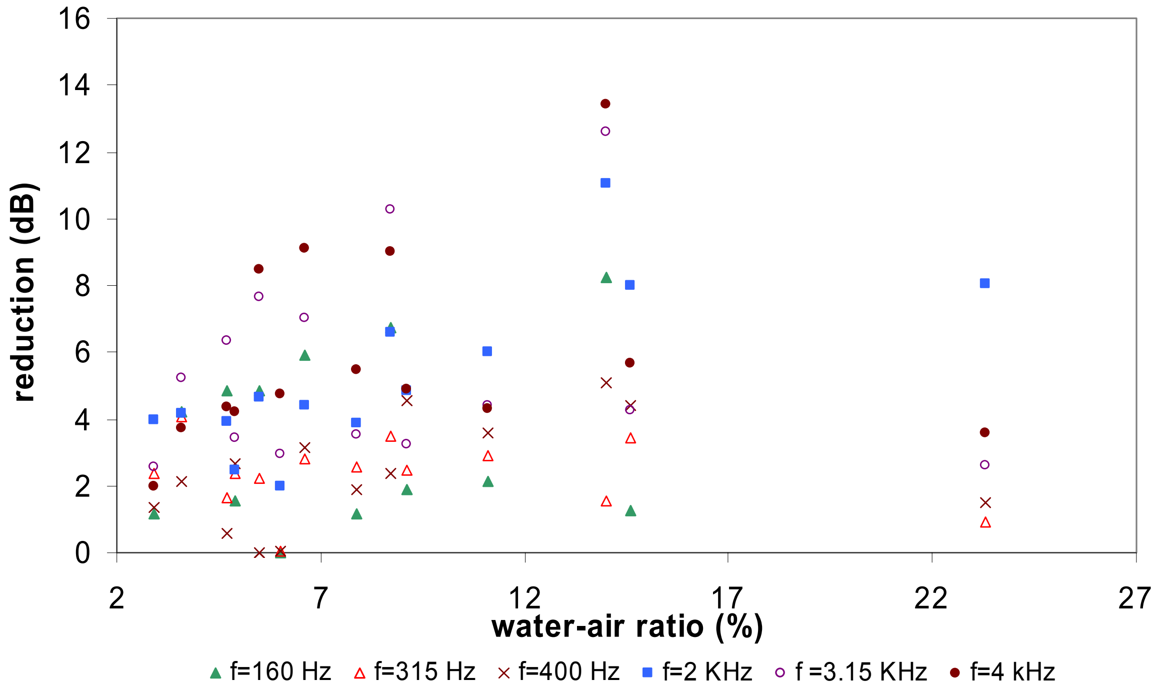


Figure 6 Reduction of sound levels for different water-air ratios
(for single orifice d=16mm)

attributable to the weakening of the bubble-bubble interaction.

For the T-head the bubble-bubble interaction appeared weaker, so a certain amount of noise reduction was still expected. It can be seen from Figure 10 that the reduction was much less compared with the single orifice and the C-head. For a high water-air ratio, a maximum reduction of 3 dB was obtained. With a decrease in water-air ratio to 3.6%, a 3dB reduction was only observed over narrowed frequency bands (125~500 and 3~5 kHz, Figure 10b). This is due to the non-uniform injection of water and the non-uniformly distributed bubble jet.

It can therefore be concluded that it is important to have the water injection uniformly distributed into the gas jet in order to achieve a better mixing process between water and air phases.

Conclusion

Bubble-bubble interaction, such as bubble coalescence, fragmentation and constriction are major contributors to the generation of noise by discharging gas through an underwater orifice. A 10 dB noise reduction can be obtained by injecting 10% by volume of water uniformly into the gas. The injection of the water effectively reduces the bubble-bubble interaction and leads to a decrease of the noise generation. When the injection of water produces a well-mixed bubbly plume, an optimum reduction of the bubble noise is obtained. It is also important to maintain a good mixing between water and air phases in order to achieve a maximum noise reduction, which means a good design of the exhaust outlet is necessary.

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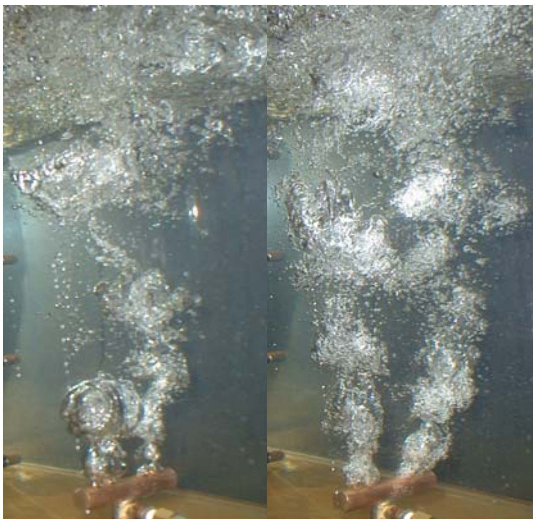
(a) water-air ratio=0 (b) water-air ratio=4.9%
Figure 7 Visualisations of air jet without and with injecting water for C-head



(a) water-air ratio=0 (b) water-air ratio=4.9%
Figure 8 Visualisations of air jet without and with injecting water for the T-head

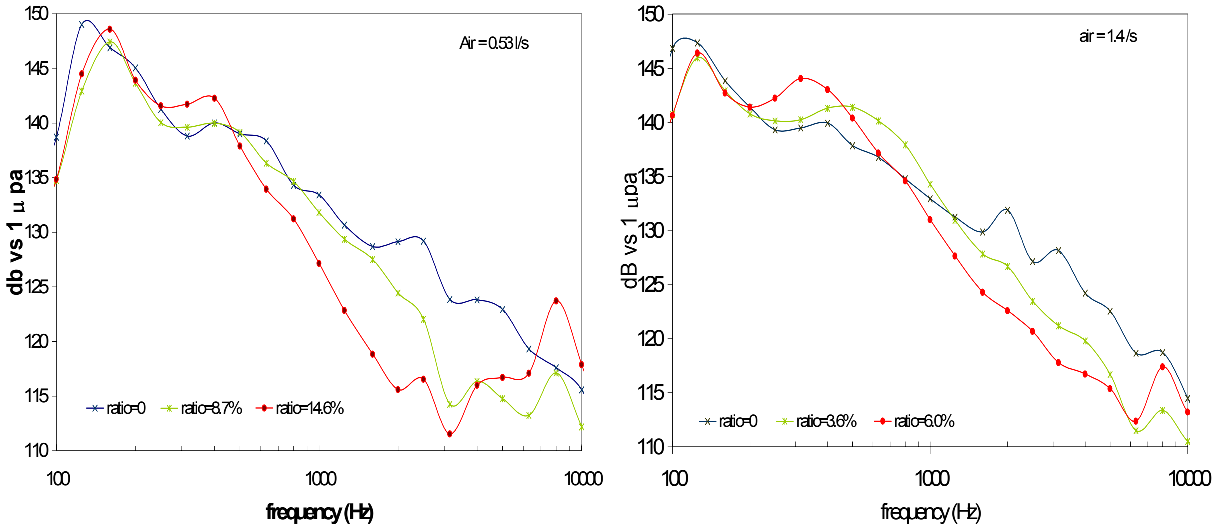


Figure 9 Sound levels in third octave band at different water-air ratio (C-head)

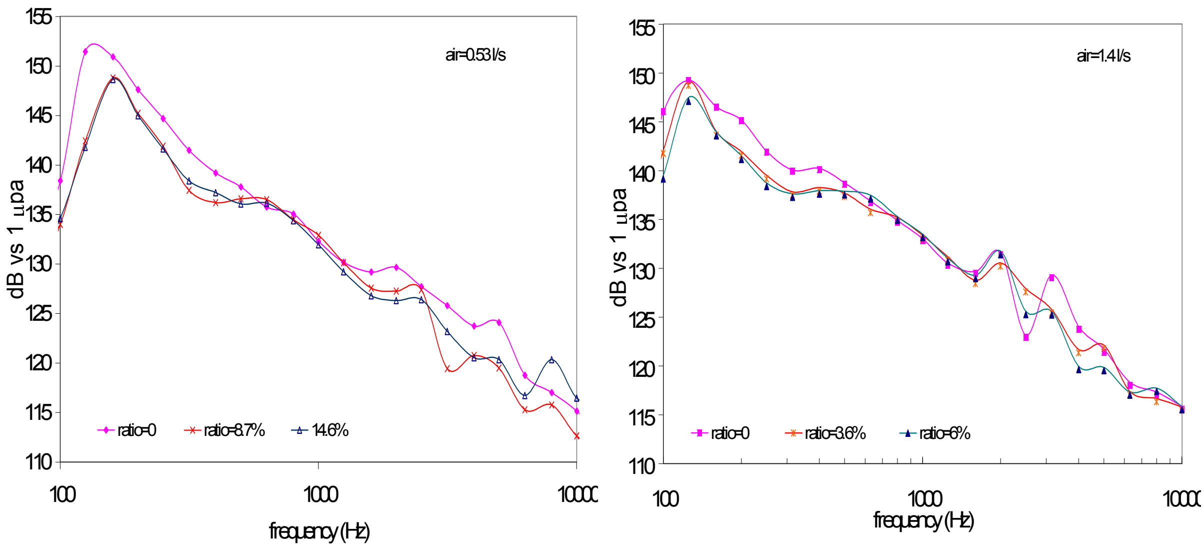


Figure 10 Sound levels in third octave band at different water-air ratio (T-head)