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Analysis of sound pressure levels generated by nozzle-emitted large bubbles

Filippo Nelli,1,a) Grant Deane,2 Andrew Ooi,3 and Richard Manasseh1

1 Faculty of Science, Engineering and Technology, Swinburne University of Technology, Hawthorn, Victoria 3122, Australia
2 Scripps Institution of Oceanography, University of California, La Jolla, California 92037, USA
3 Department of Mechanical Engineering, The University of Melbourne, Parkville, Victoria 3010, Australia
fnelli@swin.edu.au, gdeane@ucsd.edu, a.ooi@unimelb.edu.au, rmanasseh@swin.edu.au

Abstract: The sound radiated by newly formed bubbles can be used to determine their properties. However, details of the fluid dynamics driving the acoustic emission remain unclear. A neck-collapsing model has been proposed to explain the sound generation at bubble pinch-off. The model uses a forcing function which drives the Rayleigh-Plesset equation and is linked to the bubble acoustic pressure. Here, the model is tested on bubbles of diameter up to 7 mm generated in distilled water, tap water, and alcohol-water solution. The model works well for bubbles less than 2.2 mm radius but the error increases up to 71% for larger diameters. © 2022 Author(s). All article content, except where otherwise noted, is licensed under a Creative Commons Attribution (CC BY) license (http://creativecommons.org/licenses/by/4.0/).

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1. Introduction

Bubble acoustics is a long-standing topic in fluid dynamics. The first bubble-acoustic study was on a highly non-linear process, cavitation, a complex phenomenon involving the collapse of vapour and gas bubbles due to pressure reduction. This was undertaken by Rayleigh (1917), who derived a non-linear equation for collapse of a spherical cavity. This equation was subsequently improved introducing surface tension, vapour pressure, and viscous stress effects, leading to the Rayleigh-Plesset-Noltingk-Neppiras-Poritsky (RPNNP) equation (Neppiras and Noltingk, 1951; Noltingk and Neppiras, 1950; Plesset, 1949; Poritsky, 1951). However, a linearised representation of the physics of volumetric bubble oscillations was independently developed by Minnaert (1933) assuming harmonic and small-amplitude behaviour of the bubble. Small-amplitude volumetric oscillations lead to the emission of audible sounds from bubbles formed in many natural processes, such as rain drops impacting a water surface (Chicharro et al., 2020; Gillot et al., 2020; Pumphrey and Crum, 1990) and breaking waves (Deane and Stokes, 2010; Farmer and Vagle, 1988). Minnaert’s equation is now understood as a linearisation of the RPNNP equation, and has been generalized to provide a relation between a bubble’s radius ($R_0$) and its natural frequency ($\omega_0$),

$$\omega_0 = \frac{1}{R_0\sqrt{\rho_0}} \sqrt{3\kappa \left( P_0 - p_v + \frac{2\sigma}{R_0} \right) \frac{2\sigma}{R_0} + p_v - \frac{4\mu^2}{\rho_0 R_0^2}}$$

(1)

where $\kappa$ is the polytropic index of the gas, $P_0$ is the equilibrium total pressure of the bubble, $p_v$ is vapour pressure, $\sigma$ is surface tension, $\mu$ is shear viscosity, and $\rho_0$ is fluid density. Minnaert’s work has been extensively used whenever passive acoustic emissions measurements were the only tool available to reconstruct bubble sizes using their natural frequencies. Examples of applications range from underwater gas-leak detection (Leighton and White, 2012), and investigation of bubble streams rising from the seafloor (Li et al., 2020; Nikolovska et al., 2008; Vazquez et al., 2015). A particularly important application is the estimation of bubble sizes from breaking ocean waves (Bass and Hay, 1997; Deane and Stokes, 2010; Farmer and Vagle, 1988; Manasseh et al., 2006), thought important in controlling oceanic absorption of carbon dioxide (Li et al., 2021). Monitoring of chemical engineering processes is of great interest (Boyd and Varley, 2001; Forte et al., 2021; Manasseh and Ooi, 2009).

While the relationship given by (1) between bubble radius and natural frequency of volumetric oscillation is well-known, a comprehensive and universally valid relationship between radius and the amplitude of the pulse of sound radiated by the volumetric oscillations of newly formed bubbles is still unclear. However, the amplitude relationship is important for estimating bubble size distributions and bubble creation rates in situations where bubble pulses overlap and,

a)Author to whom correspondence should be addressed.
consequently, other factors of the formation mechanism are involved such as neck shape and jet properties. This is more evident whenever multiple bubbles interact with each other and their complex interaction makes it hard to predict their radius (Roshid and Manasseh, 2020). It is easy to obtain a spectrum of sound from a complex bubbly flow (showing the acoustic energy distribution over frequencies), but obtaining a bubble-size distribution from the spectrum is way more complicated, in part because different-sized bubbles create sounds with different amplitudes as well as different frequencies. Complex, empirical signal post-processing is often required whenever multiple bubbles interact with each other (Al-Masry et al., 2005; Forte et al., 2021), or restrictive presumptions must be made about the distribution (Gavrilev et al., 2019; Pandit et al., 1992).

Air bubbles generated by an underwater nozzle have been studied for the purpose of understanding the relation between bubble characteristics and acoustic-pulse properties, owing to the ease of controlling their generation. The process of bubble pinch-off from a nozzle is a controllable paradigm for bubbles fragmenting from a parent body of gas in very many situations in nature. This technique also represents a bubble-formation process in industrial aerators, for which acoustic techniques of bubble-size measurement have been tested (Al-Masry et al., 2005; Boyd and Varley, 2001; Manasseh and Ooi, 2009). Bubbles show harmonic oscillations and emit a short acoustic pulse when they detach from the nozzle (pinch-off) (Longuet-Higgins et al., 1991a; Minnaert, 1933).

Pumphrey and Crum (1990) showed that a bubble’s acoustic emissions radiate as a simple acoustic source whose size is much smaller than a wavelength of the sound that it emitted. Usually, when dimensions are much smaller than the wavelength of the sound being radiated, the bubble will act as a monopole, radiating sound equally well in all directions (Russell et al., 1999).

Several studies have proposed mechanisms for the acoustical excitation of newly formed bubbles (Longuet-Higgins, 1993), mechanisms that might in principle provide the sought-after relations between bubble size and amplitude. When the bubble detaches from a nozzle [see Fig. 1(a)], the portion of the bubble closer to the nozzle, commonly known as the neck, forms a jet as it retracts inside the bubble on a timescale that is short relative to the bubble breathing mode period (Manasseh et al., 2001). The jet has been proposed as the mechanism causing compression of the gas in the bubble, and thus initiating the emission of sound (Longuet-Higgins et al., 1991a; Thoroddsen et al., 2007; Thoroddsen et al., 2018). However, an alternative hypothesis for the origin of bubble sound emission proposed that it was due to the non-linear interaction of bubble shape modes with the volumetric mode (Longuet-Higgins, 1989). Deane and Czerski (2008) proposed an analytical model of the acoustic excitation driven by changes in bubble volume. This model calculates the volume decrease due to the neck collapse post pinch-off, which drives a newly formed bubble’s oscillation and the subsequent acoustic emission. According to Deane and Stokes (2008), this process is driven by surface tension and it can be modelled as a forcing function (2) included in the linearised RPNNP Eq. (3),

\[
f_m(t) = -\frac{9\kappa \sigma \eta P_0 (1 + \eta^2)^{1/2}}{4 \rho R_0^2} t^n,
\]

\[
\frac{\partial^2 \epsilon}{\partial t^2} + \left[ \frac{4(\mu + \mu_\theta)}{\rho R_0} + \frac{k R_0}{1 + k^2 R_0^2} \right] \frac{\partial \epsilon}{\partial t} + \left[ \frac{3\kappa R_0}{\rho R_0^2} - \frac{2\sigma}{\rho R_0^2} + \frac{k^2 R_0^2}{1 + k^2 R_0^2} \right] \epsilon = f_e(t),
\]

where \(\sigma\) is surface tension, \(\eta\) is bubble’s neck angle (as shown in Fig. 1), \(\epsilon\) is the fractional increase in bubble radius, \(\mu_\theta\) is a viscosity introduced to model thermal losses, \(k\) is the wave number, \(\omega\) is the angular frequency of the bubble at resonance, \(t\) is time after the pinch-off, and \(n\) is the exponent of the model power law. In Deane and Stokes (2008) a value of \(n = 2\) has been proposed, known as the ideal case, and a time-varying relation \(n = 469.5 t + 1.955\) to take into account neck deceleration occurring in the first 400 \(\mu s\). Here, both values have been tested to check model accuracy. The acoustic forcing, especially at the early stage, is assumed to be significantly driven by the effects of the neck collapse: the model forcing function \(f_m\) is that of Deane and Czerski (2008), and the experimental forcing function \(f_e\) can be measured. If the

Fig. 1. (a) Snapshot of the bubble pinch-off in alcohol-water solution (neck angle is highlighted), (b) the nozzle-hydrophone system, and (c) annotated example of bubble pressure at pinch-off.
model captures all important aspects of the physics involved, then \( f_w \approx f_c \) for all times. Czerski and Deane (2010) further extended the analysis of the neck collapsing model investigating the role of the pinch-off jet in generating acoustic emissions. Although it has been found that neck collapse plays a relevant role, it does not account for the total acoustic energy released throughout the process. Furthermore, the analysis is limited to diameters up to 4 mm and does not include the larger bubbles analysed here in this manuscript.

While the neck-collapsing model has been tested for bubbles having a diameter of 2 mm, it has not been tested for larger bubbles. Furthermore, according to Deane and Stokes (2008), an increase in bubble diameter is expected to reduce the peak acoustic pressure, a behaviour that needs to be verified for larger bubbles. The aim of this paper is to determine if the model of Deane and Czerski (2008) is viable for all the bubble sizes typically found in natural and industrial processes. If so, the model could be used to infer the true bubble-size distribution from the acoustic spectrum of a bubbly flow. However, this series of experiments can prove the reliability of the model only in a controlled laboratory environment. Although findings obtained from controlled experiments can be useful to analyse more complex setup, the forcing model needs to be expanded to take into account phenomena such as multiple bubbles fragmenting and coalescence.

An extension of Deane and Czerski (2008) is here presented to evaluate model predictions of bubbles with diameters up to 7 mm. An underwater nozzle (Fig. 1) is used for bubble generation experiments, coupled with an hydrophone placed 20 mm from the pinch-off area. Experiments are carried out in a tank filled with distilled water, tap water and an ethanol-water solution to test the model for different values of surface tension, liquid density, and viscosity. The experimental setup was first tested to exclude any reverberation effects using tap water (validation stage) and then filled with distilled water and ethanol for the actual testing (experimental stage).

First, the model forcing function, \( f_w \), was calculated for each bubble size, using Eq. (2). Second, the experimental forcing function values, \( f_w \), were obtained from acoustic pressure measurements. The acceleration of the bubble wall \( \partial^2 \epsilon / \partial t^2 \) was calculated from the acoustic pressure pulse as \( \partial^2 \epsilon / \partial t^2 = p_a / (\rho R_0^2) \) (Leighton, 1994), where \( p_a \) is the actual pressure measured experimentally and translated using the monopole assumption to the location of 1 m from the bubble wall. The bubble-wall velocity \( \partial \epsilon / \partial t \) and displacement \( \epsilon \) were then obtained by integrating the bubble wall acceleration over time. Finally, acceleration, velocity and displacement were used in the left side of Eq. (3) to calculate the experimental forcing function.

2. Experimental setup

Bubbles were generated in a 600 × 300 mm tank filled with tap water (in the validation stage), distilled water or a solution of distilled water and 20% ethanol (experimental stage). Air was injected in the nozzle using an external pump connected through pneumatic tubing and fitted with a small valve used to control the flow. Nozzles are simple brass terminals screwed at the end of the air line. The internal cavity creates an air reserve below the interface with water, slowly building up from the bottom tip of the cone up to the nozzle diameter. An example of bubbles pinching off is shown in the video (including nozzle drawings). Nozzles of different diameters were mounted at the fitting at the end of the tube to generate bubbles of variable sizes. Nozzle diameters, \( D \), ranged from 0.5 mm up to 7 mm (±0.025 mm). After being secured to the tube, the nozzle was fitted on a brass support at a distance of 20 mm (±0.025 mm) from the acoustic centre of the hydrophone [see Fig. 1(b)]. The hydrophone used in these experiments is a Reson TC4013, which has a uniform omnidirectional receiving sensitivity of −211 dB ± 3 dB re 1 V/μPa and a frequency range from 1 Hz to 170 kHz. The sound pressure level (SPL) was calculated as

\[
\text{SPL} = 20 \log \left( \frac{V}{211} \right) + 20 \log (w) - \text{Gain},
\]

where \( V \) is the voltage reading from the hydrophone combined with a CCA1000 conditioning charge amplifier, \( w \) is the distance (in m) between the hydrophone’s acoustic centre and pinch-off location, and Gain is the artificial gain added by the CCA1000 amplifier. Data acquisition was performed using a MCC DT9812 DAQ board at a frequency of 75 kHz. Video recordings of the experiments were obtained at 1215 frames per second with a Basler Ace acA1920-150 um high-speed camera. The camera was connected to the DAQ board in order to synchronize video and audio data streams over a 60 s acquisition window. Waveforms [see Fig. 1(c)] were extracted from the continuous signal after applying a bandpass filter removing the unwanted noise below 200 Hz and above 10 000 Hz. Waveforms were used to calculate the natural frequency of the bubble \( \omega_0 \) (as the frequency between two consecutive peaks) and the peak pressure was used to calculate the reference value of SPL for each test. Measurement uncertainties are similar to the values documented in Roshid and Manasseh (2020), where the same equipment was used for similar experiments.

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Preliminary tests were run to investigate the optimal experimental conditions and exclude any undesired effects such as reverberation coming from the lateral walls of the tank.

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3. Data validation

Preliminary tests were run to investigate the optimal experimental conditions and exclude any undesired effects such as reverberation coming from the lateral walls of the tank.
3.1 Water level tests

The pinch-off sound emissions of bubbles were measured at different water levels in the tank, in order to assess the role of the hydrostatic pressure and distance to the free surface on bubble generation. The water level in the tank was set at 200, 250, 300, and 350 mm, the maximum possible in this setup. Experiments were run using the whole range of nozzles, from 0.5 to 7 mm for each water condition, using the same range of air flows. Figure 2(a) shows the plots between sound level pressures recorded using different water levels and bubble diameters. The four curves are relatively insensitive to water level and a value of \( d = 250 \) mm was chosen for the experiments.

3.2 Reverberation tests

It is possible that sound waves reflected from tank walls could alter significantly the signal recorded by the hydrophone and compromise the final results. Although with a carefully chosen experimental geometry the monopolar sound emission from a single bubble can result in a very low reflected amplitude returning to the measurement point (Manasseh et al., 2008), each new setup should be checked. The suitability of the tank for these tests was checked reproducing the same experimental conditions in a bigger facility, a 2.4 \( \times \) 2 m glass tank. The larger scale of this facility, with more distance between nozzle and walls, allowed comparison of sound emissions on bubble pinch-off. Tests were completed using two water levels, 200 and 350 mm, to be consistent with the setup used in the smaller tank. Figure 2(b) shows the plots of sound level pressures recorded in the small and large tanks, using different water levels and bubble diameters. Results show no relevant difference between the two facilities, confirming the suitability of the 600 \( \times \) 300 mm tank for the experimental investigation.

Finally, it should be noted that in the bubble-production regimes studied, the bubble formation is very regular and the corresponding acoustic pulses are highly repeatable. The analysis of a series of 100 bubbles generated using the same nozzle and the same air flow showed bubble radius (and consequently natural frequency) variability limited to 0.67% between each bubble. The time interval between two consecutive bubbles was kept constant around 1 s in order to avoid any unwanted interaction and coalescence effect, which would have significantly altered the results. Each test was visually checked to ensure that each bubble pinched off independently and not prematurely inside the nozzle.

4. Results

4.1 Sound pressure levels versus bubble and nozzle diameters

The tap water experiments producing the data shown in Figs. 2(a) and 2(b) were repeated using distilled water and a solution of 80% distilled water and 20% ethanol. According to Vazquez et al. (1995) and Khattab et al. (2012), surface tension at 23\(^\circ\)C (room temperature) decreases from 72 to 38 mN m\(^{-1}\) for a 20% ethanol solution. Ethanol not only reduces the surface tension but also increases the neck angle from 76\(^\circ\) to 80\(^\circ\) (as shown in Fig. 1) and liquid viscosity from 0.00089 Pa s to 0.00176 Pa s (at 23\(^\circ\)C) and decreases liquid density from 1000 to 968 kg/m\(^3\). The speed of sound is also affected, increasing from 1480 to 1600 m/s (Meister, 2015). No significant neck angle variation was noticed for different bubble production rates, nozzle diameters and bubble radii.

Figure 3(a) shows the sound pressure levels (SPL) versus bubble diameters comparison for distilled water, tap water, and the water-ethanol solution. Bubbles in distilled water produced the lowest sound pressure level at pinch-off, closely followed by tap water, which has slightly different properties due to its different chemical composition. This is consistent with data released by Yarra Valley water, which classifies Melbourne’s tap water as “soft” (calcium carbonate less than 60 mg/L) (Yarra Valley Water, 2021). Furthermore, Prezioso et al. (2019) directly tested the differences in surface tension between distilled water and hard water (calcium carbonate higher than 120 mg/L), producing values \( \approx 72 \) mN m\(^{-1}\) in both cases. The slight differences between tap and distilled water can be attributed to the general impurities that can be...
commonly found in tap water, which can be assessed only through dedicated laboratory analysis. The SPL is highest for the water-ethanol solution, where the large reduction in surface tension is accompanied by sound emissions 1.16 dB higher than in distilled water for bubbles of 1 mm diameter up to 2.93 dB higher for bubbles of 7 mm diameter.

Figure 3(b) shows a comparison of bubble diameter versus nozzle diameter for distilled water, tap water and water-ethanol solutions. Results show that water-ethanol solution produced bubbles 25% smaller than tap and distilled water, using the smallest nozzle, and up to 11% smaller for the biggest nozzle. This could be explained by the lower surface tension of the water-ethanol solution. A surface-tension force that balances the buoyancy force of the bubble requires a smaller bubble in the ethanol solution than in the pure water. Thus, the pinch-off is triggered at a lower bubble volume. On the other hand, the difference between tap and distilled water is again minimal. No changes in neck angle values have been noticed for larger bubbles compared to the smaller ones, if generated using the same experimental setup. Distilled water results are in accordance with relationship between nozzle and bubble diameter presented in Longuet-Higgins et al. (1991b). Although the theory slightly overestimated the bubble size generated by the smallest nozzle (0.5 mm), there is good agreement between experimental results and theoretical predictions for nozzle diameters bigger than 1 mm.

4.2 Forcing functions

Figures 4(a)–4(c) shows the comparisons of experimental and modeled forcing functions (both ideal and with time-varying n), for distilled water, for the 2.24, 5.15, and 6.21 mm bubble diameters (±0.1 mm), corresponding to 0.5, 4, and 6 mm nozzles. The time axis is scaled by the period of the bubble natural frequency, \( T \). The axis extends to only \( T/20 \) because of the short time scales over which the neck retraction and forcing function operate. In distilled water, for the smallest nozzle, the model forcing functions follows closely the value calculated from the sound pulse (in particular...
including neck deceleration effects) up to the reference time $T/20$. From 0 to $T/40$, the forcing function in the ideal case matches well the experimental curve for all nozzle diameters. However, at $T/20$ the gap between the two curves becomes wider. For the smallest nozzle, the difference between experimental and model forcing functions is maximum 6% in the ideal case, while for 4 and 6 mm nozzles it increases, respectively, to 30% and 43% (37% and 49% including neck deceleration effects). Figures 4(d)–4(f) shows the comparisons of experimental and modeled forcing functions, for ethanol-water solution, for the same bubble sizes. Similar to the distilled water case, the time frame extends only up to $T/20$. The behaviour between real and model forcing functions is similar to Figs. 4(a)–4(c). At $T/20$ the difference between experimental and modeled forcing function for 0.5 mm nozzle is 7%, and the ideal case works better than the time varying model, which underpredicts the experimental curve up to 12%. The gap increases up to 36% for the intermediate nozzle and 65% for the largest nozzle (ideal curve), and 61% and 72% in the time-varying power law case. As expected, the model works well with smaller bubbles, but it shows increasing overestimation of the forcing function for larger nozzles. This gap is further amplified using the ethanol-water solution and including neck deceleration effects.

5. Conclusion

A comparison was presented between the experimental forcing function and the neck-collapsing-model forcing function of Deane and Czerski (2008) for bubbles with radii in the range 0.5 to 3.5 mm. Bubbles were generated using underwater nozzles of different dimensions and their acoustic emissions at pinch-off were recorded with an hydrophone. Sound pressure data were then used to estimate the forcing function that would need be applied to the RPNNP equation to create the measured sound. At the same time, the predicted forcing function was calculated through the neck-collapsing model of Deane and Czerski (2008) starting from the moment when pinch-off occurs. Results show that forcing functions closely match for smaller bubbles, while the neck-collapsing model predictions become more and more divergent as the diameters of the bubbles increase. This is more evident for bubbles generated in the water-ethanol solution, which recorded discrepancies up to 65% between the two functions using the ideal model and 71% including the effects of neck deceleration (time-varying model). One of the reasons responsible for this divergence is suspected to be change in surface tension, which also produced louder pinch-offs for bubbles of same diameter and produced smaller bubbles for the same nozzle diameter. Since such large discrepancies develop within a small fraction (1/20) of an acoustic period, the amplitude of the acoustic oscillation for larger bubbles can not be well predicted by this neck-collapse model.

It is clear that further investigations are required to fully understand the mechanism governing the sound amplitude emitted by larger bubbles. This could lead to better results in estimating bubble properties using passive acoustic emissions only, especially in complex settings where a large number of bubbles of different sizes are created at the same time, such as breaking ocean waves.

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References and links


