PASSIVE ACOUSTIC QUANTICATION OF GAS RELEASES

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Abstract: *The assessment of undersea gas leakages from anthropogenic and natural sources is becoming increasingly important. This includes the detection of gas leaks and the quantification of gas flux. This has applications within oceanography (e.g. natural methane seeps) and the oil and gas industry (e.g. leaks from undersea gas pipelines, carbon capture and storage facilities). Gas escaping underwater can result in the formation of gas bubbles, and this leads to specific acoustic pressure fluctuations (sound) which can be analysed using passive acoustic systems. Such a technique offers the advantage of lower electrical power requirements for long term monitoring. It is common practice for researchers to identify single bubble injection events from time histories or time frequency representations of hydrophone data, and infer bubble sizes from the centre frequency of the emission. Such a technique is well suited for gas releases that represent low flow rates, and involving solitary bubble release. However, for larger events, with the overlapping of bubble acoustic emissions, the inability to discriminate each individual bubble injection event makes this approach inappropriate. In this study, an inverse method to quantify such release is used. The model is first outlined and following this its accuracy at different flow rate regimes is tested against experimental data collected from tests which took place in a large water tank. The direct measurements are compared to estimates inferred from acoustics.*

Keywords: *methane seeps, inverse problem, passive acoustic*

1. INTRODUCTION

Assessing levels of underwater gas leaks from anthropogenic sources (pipelines, Carbon Capture and Storage facilities, etc.) or natural sources (hydrocarbon gas release) is of importance because of their economic and polluting impacts. These releases can take the form of bubbles that present specific acoustic emissions [1,2]. For the purpose of quantification of gas release, passive acoustics are applicable and it presents advantages in term of cost and electrical power consumption. Leighton and Walton were the first to use such emissions to quantify gas bubble formation in the natural world [3], and now it is common practice to determine gas volumes by relating the centre frequency of the acoustic traces to the bubble sizes [4–6]. However, this approach requires distinguishing each bubble emissions and although signal processing techniques can help as the flow rate increases [7], in essence it is limited to releases representing low flow rates [8]. The inversion scheme proposed by Leighton and White [9] is aimed at quantifying higher volume gas discharges, especially in the case where the acoustic emission of each single bubble overlaps with other bubbles. This paper draws on experimental data to assess the accuracy and applicability of the model.

An experiment, which was carried out in a large water tank facility, is presented here. Metered amounts of gas were released from an arrangement of needles and the acoustic emissions were recorded. Gas was injected in two ways: 1) with a stationary flow rate at different regimes, and 2) with varying flow rates. In each case, based on the inverse model [9], gas flow rates are estimated and compared to direct measurements.

2. EXPERIMENTAL PROCEDURES

In a large water tank (8 m x 8 m x 5m deep) of volume $V = 320\ \mathrm{m}^3$, bubbles were released from an arrangement of needles (1.2 mm nozzle diameter) at the bottom of the enclosure. The bubble generation system was placed at large enough distances from the side walls so the reverberation has no effect on the damping and resonance frequency of the bubbles [10]. The gas used was nitrogen and the amount injected was controlled and metered by a mass flow meter (Bronkhorst high-tech in-flow F-111BI). The gas was injected with flow rates kept steady at 15 discrete regimes and also with varying flow rates over a period of 200 seconds.

The acoustic emissions of the bubbles were recorded using a SM2M+ hydrophone unit (wildlife acoustics). This acoustic recorder consists of a buoyant body containing an embedded data acquisition board connected to a calibrated hydrophone and is powered by internal batteries. A schematic of the experiment is presented in Fig. 1. First, similarly to Bergès et al. [11], flow rates were kept steady at 15 regimes for 30 seconds. From the spectra of the acoustic emissions at different regimes, gas fluxes are estimated. In addition, in this gas injection case, at all regimes, signals were acquired at different distances from the bubble release site in order to investigate the effect reverberation has on the results. Second, a scenario is considered where the amount of gas is varied over a period of 200 seconds. In this case, flow rate rates are estimated every second. Signals are acquired at a sample frequency of 48 kHz.

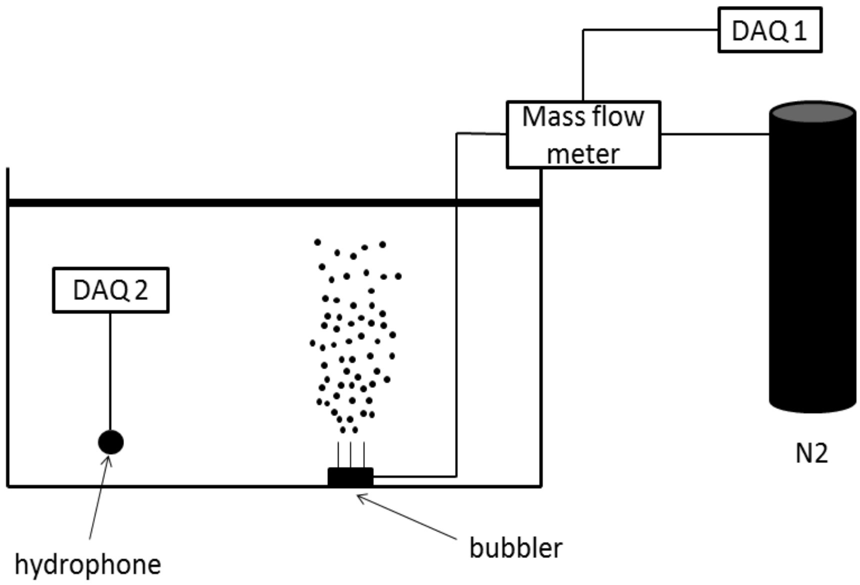

Fig. 1: Schematic of the experimental apparatus deployed in the water tank. It consisted on the acquisition of acoustic emissions of bubble release from controlled nitrogen gas injection using a calibrated hydrophone.

Using the method of Leighton and White [9], from the acoustic traces of the release of bubbles, the power spectral density $S(\omega)$ is calculated. At frequency ω this relates to the distribution of bubble sizes in the form of bubble generation rates $D(R_0)$ as:

$$S(\omega) = \int_0^{+\infty} D(R_0)|X_b(\omega, R_0)|^2 dR_0, \tag{1}$$

with $|X_b(\omega, R_0)|^2$ the predicted magnitude of the Fourier transform for a bubble of radius R_0 at a frequency ω [9]:

$$|X_b(\omega, R_0)|^2 = \left(\omega_0^2 R_0^3 \frac{\rho_0}{r}\frac{R_{\epsilon 0i}}{R_0}\right)^2 \times \left(\frac{4[(\omega_0\delta_{\text{tot}})^2 + 4\omega^2]}{[(\omega_0\delta_{\text{tot}})^2 + 4(\omega_0 - \omega)^2][(\omega_0\delta_{\text{tot}})^2 + 4(\omega_0 + \omega)^2]}\right). \tag{2}$$

The quantity ρ_0 is the density of the water, r the range from the bubble to the sensor, ω_0 the bubble natural frequency [1] and δ_{tot} the total bubble damping coefficient [12,13]. One important unknown to consider is the initial amplitude of the bubble wall at the start of the emission $R_{\epsilon 0i}$. This quantity can differ for example with different type of nozzles of bubble sizes. This is expressed relative to the equilibrium bubble radius and in this paper, $R_{\epsilon 0i}/R_0 = 3.7 \times 10^{-4}$ is used following the procedure of reference [9]. This factor constitutes the biggest source of uncertainty and its relevance has for example been discussed by Deane and Stokes [14] or Leighton and White [9]. In this study, focus is given to the effect due to the relative change in flow rates. From Eq. (1), the problem can be approximated at discrete frequencies and bubble radii and expressed in matrix form [15]. The function $D(R_0)$ can then be determined in different bubble size bins. Furthermore, as the problem tends to be ill-posed because of measurement errors, regularization in the form a Tikhonov regularisation is introduced. In matrix form, the regularised solution is as:

$$\mathbf{D} = (\boldsymbol{X_b^t X_b} + \alpha^2 \mathbf{I}) \boldsymbol{X_b^t S}, \tag{3}$$

with the regularisation factor α chosen by the mean of a Generalised Cross Validation function including a positivity constraint on the distribution of bubble sizes $D(R_0) > 0$ [15]. The inversion gives a bubble count in terms of the radius the bubble would have if it was spherical (R_0), since this is the parameter that governs the frequency of the sound emission [1,2]. Thus, it can be easily converted into flow rates assuming individual bubble volumes of $4\pi R_0^3/3$. This gives direct comparison to the measurements from the mass flow meter.

The starting point of the inversion scheme is the acoustic trace of bubbles in free field condition. Because here the acoustic measurements were acquired in a water tank, the reverberation of the chamber results in increased acoustic energy. It is important to investigate the effect this has on the inversion scheme. In an enclosure, there is a combination of the direct and reverberant field and the averaged total rms pressure is given by [16,17]:

$$\overline{p_{\mathrm{t}}^2}(r) = S^2 \left[\frac{1}{r^2} + \frac{1}{r_0^2} \right], \tag{4}$$

with $S = p_{\mathrm{d}} \times r$ the source output, the product of the range and the direct field pressure p_{d}. The quantity r_0 is the radius of reverberation, corresponding to the distance where the reverberant and direct fields have equal contribution. This is given by [16,17]:

$$r_0 = \sqrt{\frac{A Q_\theta}{16\pi}}, \tag{5}$$

with $A = 55.3 \times V/T_{60}c$ the Sabine coefficient being dependent on the sound speed in water c. The reverberation time in the enclosure is $T_{60} = 181$ ms between 0.8 kHz and 8 kHz (frequency band of interest in this study) and the directivity factor Q_θ is taken equal to 2, corresponding to an omnidirectional source lying on a reflective flat surface [16]. The radius of reverberation is $r_0 = 1.62$ m in the conditions considered here.

For the case of steady flow rates, measurements at 10 distances were repeated and the Sound Pressure Levels (SPL) were determined. The 10 data points at each regime are plotted against the distance from the source and a fitting based on Eq. (4) is performed. This is shown in Fig. 2 for regimes 10 and 15. The direct field decay can be observed at short ranges while the contribution of the reverberant field is noticeable at largest r (level stabilizing). Because it is needed to apply the inversion to data in free field, it is important to account for the effect of the reverberation field. To that purpose, the measurements at the shortest range (1 m) are used because at this distance, the direct field dominates over the reverberant field.

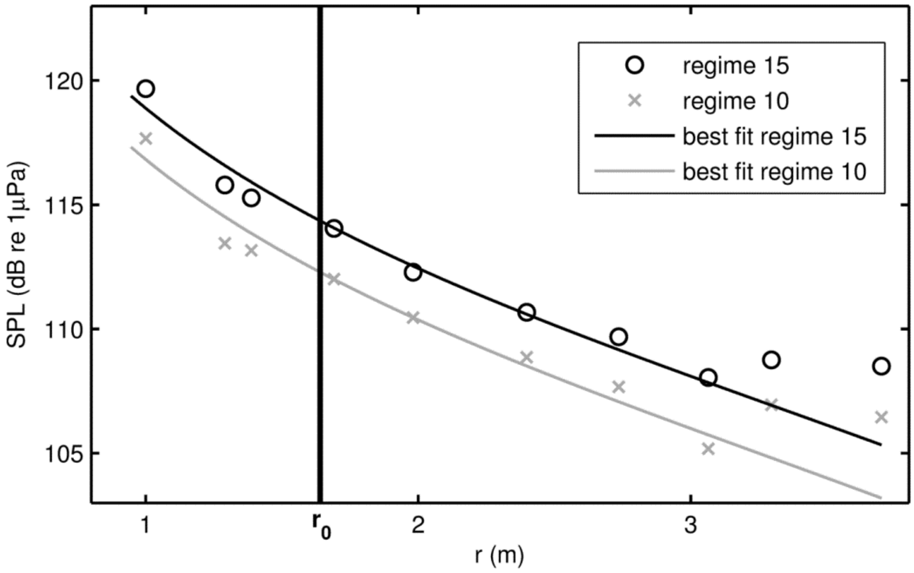

Fig. 2: Acoustic emissions from bubbles at different regimes recorded at 10 different distances. Black circle (regime 15) and grey cross (regime 10) markers are the measurements. Black (regime 15) and grey (regime 10) lines are the best fits using Eq. (4)

3. RESULTS

First, results for steady flow rates are presented in Fig. 3 (left axis). At the 15 regimes, the spectra from the bubble emissions are inverted to obtain bubble emission size distributions at discrete size bins. From these distributions, assuming spherical bubbles, flow rates can be inferred and compared to measurements from the mass flow meter. At the highest regimes, the results from the inversion scheme correlate with the metered flow rates. Between regimes 15 and 10, the flow rates are underestimated by 1.5 dB to 3.7 dB. Because the model described in Sec. 2 relies on the quantity $R_{\epsilon 0i}/R_0$ the agreement in absolute level could be improved by using a value that account for this specific bubble injection system. However, independently from the absolute level of the flow rate estimates, it can be noticed that there is an agreement with the relative decrease. Between regimes 15 and 10, flow rates decrease by 35% and this is estimated to 57% from the acoustic emissions.

The inversion method is sensitive to noise and the signal to noise ratio (SNR) is shown in Fig. 3 (right axis, dashed line). Noise floor was measured when no gas was being injected and the ratio of measurements at each flow rates gives the SNR. The agreement of the acoustically inferred flow rates is seen to decrease with decreasing SNR. As SNR diminishes, the estimates fail to track the change in flow rate, this corresponds to regimes where the SNR is too low for the inversion to perform accurately.

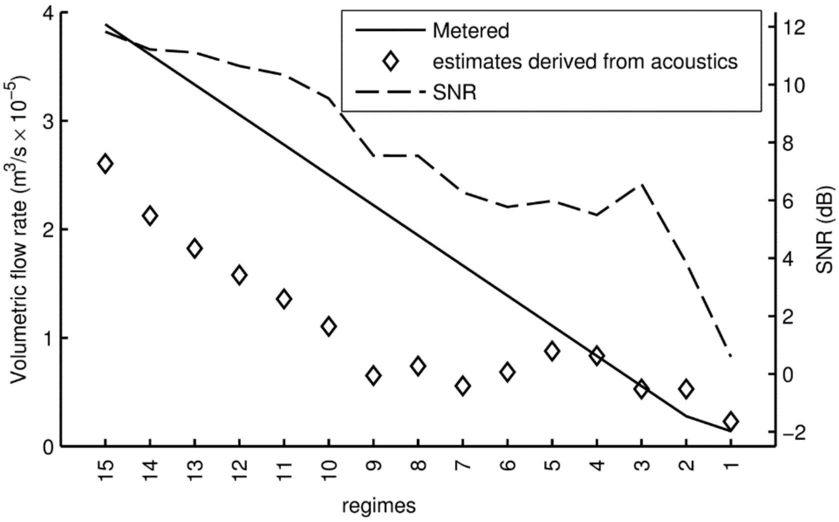

Fig. 3: metered and acoustically inferred flow rates at different regimes. Left axis: mass flow meter measurements (straight line) and acoustic estimates (diamond markers). Right axis: SNR (dashed line)

Second, results from varying flow rates are presented in Fig. 4. This compares metered and acoustically inferred flow rates when the injected gas was being varied. Estimates are computed by inverting the power spectral density of the acoustic traces for each 1 second window. It can be observed that the estimates track the changes in flow rate. Also, local fluctuations of the flow rates inferred from acoustics is noticeable and is due to the influence of the background noise that corrupts the bubble count when the signal spectra are inverted. This can be mitigated by applying a filter to smooth the results.

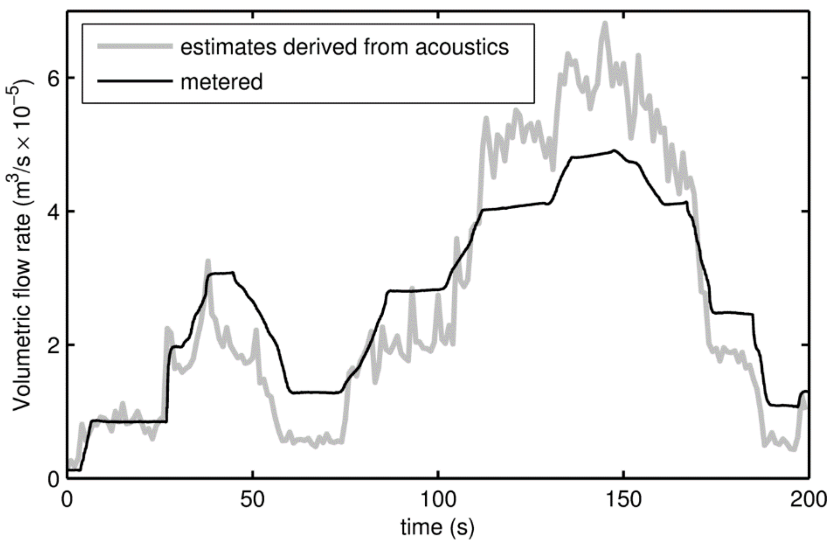

Fig. 4: Results from data collected during laboratory experiment (Fig. 1(a)). Comparison between metered (solid black line) and acoustically inferred (solid grey line) flow rates over 200 seconds of a varying release of nitrogen gas.

4. CONCLUSION

In this study, the applicability of the inversion scheme described by Leighton and White [9] to quantify "high volume" gas leaks is demonstrated by the mean of results from a gas injection experiment in a large water tank. First, gas was injected and controlled using a mass flow meter at 15 flow rates regimes. Gas releases are estimated from the acoustic emissions and compared to metered results. A good agreement is found at high flow rates. The absolute level of the estimates is dependent on the quantity $R_{\epsilon 0i}/R_0$ that needs further research. The influence this factor has on the uncertainty of the estimated flow rates will be presented in separate work. Second, gas was injected and varied over a period of 200 seconds. Applying the inversion method every second allows tracking the changes in flow rates.

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