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Passive acoustic quantification of gas fluxes during controlled gas release experiments

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ABSTRACT

The detection and quantification of an underwater gas release are becoming increasingly important for oceanographic and industrial applications. Whilst the detection of each individual bubble injection events, with commensurate sizing from the natural frequency of the acoustic emission, has been common for decades in laboratory applications, it is impractical to do this when hundreds of bubbles are released simultaneously, as can occur with large methane seeps, or leaks from gas pipelines or undersea facilities for carbon capture and storage. This paper draws on data from two experimental studies and demonstrates the usefulness of passive acoustics to monitor gas leaks of this level. It firstly shows experimental validation tests of a recent model aimed at inverting the acoustic emissions of gas releases in a water tank. Different gas flow rates for two different nozzle types are estimated using this acoustic inversion and compared to measurements from a mass flow meter. The estimates are found to predict accurately volumes of released gas. Secondly, this paper demonstrates the use of this method at sea in the framework of the QICS project (controlled release of CO_2 gas). The results in the form of gas flow rate estimates from bubbles are presented. These track, with good agreement, the injected gas and correlate within an order of magnitude with diver measurements. Data also suggest correlation with tidal effects with a decrease of 15.1 kg d^{-1} gas flow for every 1 m increase in tidal height (equivalent to 5.9 L/min when converted to standard ambient temperature [25 °C] and absolute pressure [100 kPa] conditions, SATP).

1. Introduction

The acoustic remote sensing of subsea gas leaks from anthropogenic and natural sources is becoming increasingly important. This applies not only to the detection of gas emissions (e.g. in order to alert pipeline users to a leak) but also its quantification in order to assess gas fluxes (e.g. in order to assess the growth rate of a leak and inform judgement of when to deploy costly intervention). Gas escaping underwater frequently takes the form of bubbles and leads to specific acoustic pressure fluctuations (Leighton, 1994). The size and structure of those releases vary from small bubble streams to larger bubble clouds and are potentially strong sources of sound.

There are several reasons for the increasing study of such releases, such as the need to better understand gas release mechanisms from natural sources, or the endeavour to put more control on leaks from industrial facilities. These are expanded on in the following.

Firstly as the oil and gas industry is facing increasing regulation with respect to marine environmental pollution, consequently there is a need for increased monitoring and control in the industrial processes (Teal, 2007; Det Norske Veritas, 2010). Secondly concern regarding climate change has lead oceanographers to endeavour to better understand hydrocarbon gas releases as they play an important role in the carbon cycle (Westbrook et al., 2009; Judd, 2003). Following several decades of interest in gas flux from the atmosphere into the upper ocean layer, and vice versa (Woolf and Thorpe, 1991; Brooks et al., 2009), in recent years there has been growing interest in the climate importance of gas flux into the ocean from the sediment. For example, long term monitoring of methane seepage in west Svalbard is needed to assess methane hydrate dissociation in this region (Berndt et al., 2014). Active acoustic techniques have frequently been used to locate and produce sonar images of, say, methane plumes (Westbrook et al., 2009). In addition, sonar systems (e.g. scientific echosounders) hold the potential to produce quantification of gas flux (Hornafius et al., 1999; Caudron et al., 2012; Greinert and Nutzel, 2004; Schneider von Deimling et al., 2010; Ostrovsky, 2003; Ostrovsky et al., 2008;

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Nikolovska and Schanze, 2007; Shakhova et al., 2014). For the purpose of long term monitoring (e.g. for early warning of leaks or monitoring of changes in leaks), the power requirement of a technology is critical. Active acoustic techniques tend to have higher power requirements (Det Norske Veritas, 2010) than passive acoustic systems, meaning that passive systems tend to be better suited to long term monitoring applications.

In the 1980s it was established that bubble size distributions and gas fluxes associated with natural processes could be quantified by identifying the natural frequency emitted by each gas bubble upon entrainment in the water (Leighton and Walton, 1987), and this has subsequently been tested as a means for studying methane seeps (Greene and Wilson, 2012; Nikolovska and Waldmann, 2006; Leifer and Tang, 2007). However this technique can only be applied at flow rates that are sufficiently low to identify the acoustic 'signature' of each injection event. When the flow rate is high, the acoustic emissions of bubbles overlap and one is unable to distinguish individual bubble injection events (Leighton et al., 1991). Whilst signal processing methods (such as the Gabor transform, Leighton et al., 1998, 1997) can be helpful to isolate individual acoustic emissions from each bubble, they do not provide a complete solution. An alternative approach is needed to quantify high volumes of natural and industrial gas emissions. In industrial applications these are usually the releases which it is most imperative to correct, since they represent gas losses so great that they can lead to structural failure, as well as potential major economic and pollutionary impacts. Leighton and White (2012) describe a scheme for quantifying the gas flux and bubble size distribution injected into liquid from high flux leaks. They test the applicability and robustness of their method against simulated data.

This work first tests the accuracy and applicability of the method (Leighton and White, 2012) against experimental data. Clouds of bubbles were generated in a water tank using different bubble generation systems fed with nitrogen gas. The amount of gas injected in the system was controlled using a mass flow meter and the passive emissions were recorded with a calibrated hydrophone. Those results were processed and then compared to assess the accuracy in the various situations. This includes cases with constant or varying flow rates.

This quantification scheme is then used on data collected during the release phase of the QICS (Quantifying Impacts of Carbon Storage) project (Blackford and Kita, 2013; Blackford et al., 2014) that aimed at evaluating the impact of potential leaks from CCS (Carbon Capture and Storage) facilities. In May/June 2012, controlled CO_2 gas release was performed in Ardmucknish Bay (near Oban, west coast of Scotland). During this period, gas leaked from the seafloor in the form of bubbles and acoustic emissions were recorded using a hydrophone. The behaviour of the measured gas flux is investigated and compared with the amount of gas injected through the system and the tidal levels. The results are also compared to independent flow rate measurements from divers collecting gas directly from all the observed bubble streams.

2. Model

The method used in this study is aimed at determining bubble generation rate distributions from sound emissions from bubble plumes as proposed by Leighton and White (2012). Part of this theory will be outlined in this section to provide the background for the calculations that are presented in this study.

The starting point is the acoustic waveform received on a sensor which is close enough to a cloud of bubbles (whilst remaining in the acoustic far field) to record its emissions at an acceptable SNR (signal to noise ratio). The output of the inversion process is the bubble generation rates from which the gas flow rate (the experimental quantity measured here) is estimated.

As a bubble is released into the water column, it undergoes fluctuations in its volume which efficiently radiates sound (Leighton, 1994). These oscillations decay with time and so the detectable acoustic emission has a finite duration. The bubbles will be assumed to be spherical and volume changes result from oscillations of the bubble radius R about the equilibrium radius R_0. The oscillations occur close to the natural frequency of the bubble and decay exponentially. The natural frequency relates to the radius R_0 which has been used for decades to count and size bubbles in laboratories, and even in the natural world for studies of waterfalls (Leighton and Walton, 1987), wave-breaking and rain at sea (Updegraff and Anderson, 1991; Leighton et al., 1998), and methane seeps (Leifer and Tang, 2007). When rapid gas releases occur, the bubble signatures overlap and the size distribution of the bubbles being produced can be characterized by the spectrum of the acoustic signal (Loewen and Melville, 1991). In obtaining absolute gas fluxes from such a spectrum, Leighton and White (2012) suggest that the most important unknown is the acoustic energy released by an individual bubble. For want of a full description, a pragmatic solution can be adopted (Leighton and White, 2012), specifically that each bubble is excited only once (Leighton et al., 1991), generating an initial amplitude of bubble wall pulsation for the breathing mode ($R_{\epsilon 0\mathrm{i}}$), a quantity that, for want of further information (Leighton and White, 2012), could be treated as being broadly invariant with depth and the nature of the gas-emitting orifice, an assumption that this paper will examine. Assumptions about the correct value of $R_{\epsilon 0\mathrm{i}}$ to use constitute the main source of uncertainty for the model and the estimated flow rates inferred using it. The parameter characterizing this effect in the model is the dimensionless ratio $R_{\epsilon 0\mathrm{i}}/R_0$. To date, only few studies provide measurements for this quantity (Leighton, 1994; Leighton and Walton, 1987; Pumphrey and Walton, 1988; Medwin and Beaky, 1989; Pumphrey and Crum, 1990; Deane and Stokes, 2006, 2008). In order to better predict this factor for different bubble sizes and nozzle types, more experimental and theoretical work is needed. For now, the most recent and complete estimate of this ratio comes from Deane and Stokes (2008), who calculated $R_{\epsilon 0\mathrm{i}}/R_0$ for fragmented bubbles in sheared flow. Using these data (kindly provided by Grant Deane) and employing the assumption that $R_{\epsilon 0\mathrm{i}}/R_0$ is invariant with depth and bubble size, a confidence interval is determined based on the 25th and 75th percentiles of the Deane and Stokes data (Deane and Stokes, 2008), respectively $R_{\epsilon 0\mathrm{i}}/R_0 = 1.4 \times 10^{-4}$ and $R_{\epsilon 0\mathrm{i}}/R_0 = 5.6 \times 10^{-4}$ (the fixed value of 3.7×10^{-4} used by Leighton and White (Leighton and White, 2012) lies within this range). Moreover, calculation of the contribution of each bubble to the spectral magnitude of the acoustic emission at frequency $f (\omega = 2\pi f)$ is (Leighton and White, 2012):

$$|X_\mathrm{b}(\omega, R_0)|^2 = \left[\omega_0 R_0^3 \frac{\rho_\mathrm{w} R_{\epsilon 0\mathrm{i}}}{r R_0}\right]^2 \times \frac{4[(\omega_0\delta_\mathrm{tot})^2 + 4\omega^2]}{[(\delta_\mathrm{tot}\omega_0)^2 + 4(\omega_0 - \omega)^2][(\delta_\mathrm{tot}\omega_0)^2 + 4(\omega_0 + \omega)^2]}, \quad (1)$$

where r defines the distance from the hydrophone to the bubble cloud, ρ_w the water density and ω_0 is the angular natural frequency of the gas bubble (Leighton, 1994). Eq. (1) is derived analytically by Leighton and White (2012) by taking the Fourier transform of the temporal pressure fluctuations of a gas bubble after injection. The dimensionless damping factor δ_tot is calculated using the revisited bubble damping theory (Ainslie and Leighton, 2009, 2011)