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Noise reduction in acoustic disdrometry

Phil Winder,
Michiel Postema,
Kevin Paulson

Department of Engineering,
The University of Hull,
Kingston upon Hull,
East Riding of Yorkshire,
HU6 7RX
United Kingdom

ABSTRACT

This paper reports progress on the development of a novel rain disdrometer and the methods of noise reduction. The proposed instrument will measure the raindrop size distribution using the sound generated by raindrops landing in a tank of water.

When an incident hydrometeor impacts on the surface of a liquid, two processes create an acoustic signal. The first is a broadband impact pulse which is related to the impact size and velocity. The second is created when pockets of air are trapped underneath the water's surface; this is termed entrainment. One particular solution to disdrometry is to use the acoustic signature of the impacts to classify the parameters of the rain event.

To an extent, entrainment can be predicted, since fluid dynamics dictates that a bubble will oscillate and emit an acoustic signal as a damped sinusoid. In a rain event however, the bubbles can occupy a wide area in both temporal and spectral regions, overpowering the comparably small impact pulse.

We present three methods to remove bubble related noise within acoustic disdrometry. These include the addition of a driving signal to force a bubble to oscillate in a non-resonant way, liquid additives to suppress the formation of bubbles and signal processing methods to filter any remaining bubble noise.

It was found from simulation that driving a bubble does not reduce the entrainment signal. Experimental conditions can hardly be kept constant. Adding an oil film prevented bubble formation, but the maintenance required makes it less suitable to be used in the field. Using signal processing methods proved to be the most sustainable and flexible way of suppressing bubble noise.

1. INTRODUCTION

Common rainfall gauges measure the rate at which rain falls over a specified period, known as the integration period. More advanced forms of rain gauges have been developed that provide data regarding distribution of the rain. The rain drop size distribution (DSD) describes the distribution function of raindrop sizes; i.e., $N(D)dD$ is the number of drops per unit volume in the diameter range D to $D+dD$. The DSD is linked to the rain rate by the drop fall-speed distribution. Instruments generally yield the number of drops measured in diameter bins.

Many applications exist where the effects of rain are highly non-linear with respect to drop size, for example: radio communications and geomorphology. An economically important example is in determining the link between rain rate and microwave specific attenuation or radar reflectivity. Understanding these relationships is vital in the optimisation and regulation of microwave telecommunications links and in the interpretation of meteorological radar measurements.

Current disdrometers are limited by their catchment area, the area over which droplets can be detected and added to the distribution, and therefore cannot reproduce the large drop diameter tail of the DSD accurately. Furthermore, depending on the technology used within the disdrometer there are further limitations; for example, when two drops overlap in a laser disdrometer's sensing beam. The Acoustic Disdrometer provides an accurate description of the large diameter DSD by being physically large. Other experiments[1-7] have attempted to perform a similar function, but this project will improve their work by isolating the tank to remove the sources of oceanic noise and apply more advanced processing techniques to improve the DSD data.

Raindrops impacting on a liquid surface have been studied for many years[8]. Underwater sound produced is created in the following way. Initially, when a water droplet impacts on the surface of a liquid it creates a short, sharp impulse signal. This is proportional to size, velocity and the type of impacting hydrometeor. After a duration ranging from a few milliseconds to hundreds of milliseconds, a damped sinusoidal signal is created from a process of air being trapped within the liquid. From these signals it is possible to determine the size of the impacting droplet, assuming it is a liquid and it is at terminal velocity. Figure 1 shows an example impact and bubble. Note that there is a pause between the impact and the bubble. Typical durations are between 1 and 500 ms.

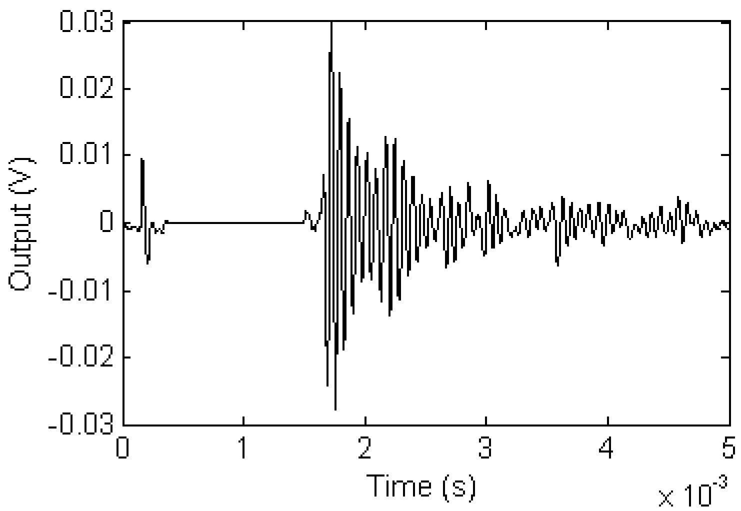


Figure 1: A typical measured droplet impact and bubble signal using the current acoustic disdrometer

The damped sinusoid produced from trapped air provides the greatest problem in acoustic disdrometry. Bubble signals have little relation to their impacting drop, do not occur on every impact event, and are determined by 3 scenarios[9]. Also, when the bubble signal is produced, it is significantly larger in amplitude than any corresponding impact signal. If another drop was to land at the same time as a bubble, this could complicate the impact extraction process.

Regular entrainment[1,10] is the name given to the process of where a bubble is created repeatedly when a droplet impacts on the surface of a liquid, usually water. A number of people developed the mechanics of entrainment[9], and found that there are a number of scenarios when entrainment can occur.

Regular entrainment occurs when a crater is formed in the water after an impact. As the liquid returns to its equilibrium, combined with the fact that the bottom part of the cavity still has momentum, the sides of the crater can collapse or *pinch-off* due to a travelling capillary wave. The resulting void at the bottom part of the crater forms a bubble.

Very large drops are affected by air resistance and tend to form an oblate, toroidal shape that produces an impact more like a water-hammer model. When a large drop impacts the preceding air is forced into the water which develops into an "azimuthal necklace[11]. This necklace then tends to form a number of stable bubbles due to their surface tension.

The third type of entrainment is formed when after an initial large impact, further smaller droplets are ejected from the impact site and create their own bubbles conforming with the first two types of entrainment. This can be due to funnel formation and separation from a crater collapse or from crown formation that is ejected into the air when a crater is formed with a very large energy impact.

Irrespective of the type of entrainment, the resultant bubble will be suspect to the comparatively large pressure of being underwater. This will compress the bubble until a point where its surface tension is greater than the force exerted on the bubble. The bubble will then expand again oscillating until the two pressures reach an equilibrium. Because the entrained air is not spherical, there will also be spherical harmonic oscillations until it regains spherical equilibrium.

2. SUPPRESSION METHODS

In order to achieve the greatest accuracy, the removal of the bubble noise is imperative. Possibilities include attempting to force the bubble into a non-resonant oscillation, altering the properties of the liquid pool so entrainment cannot occur and applying signal processing methods.

A. Driven oscillation

An analogy for an oscillating bubble can be thought of in terms of a mass on a spring. The movement of the mass is similar to the oscillation of the bubble radius when two incident pressures are straining for equilibrium. In this case, a bubble could be modelled as a harmonic oscillator which would describe the motion of the system. This would infer that the system has a resonant frequency. With a further addition, that the system was damped, this would indicate that the oscillation would tend to an equilibrium.

Noting that bubble oscillation is non-linear, it is possible to derive a model for an oscillating bubble within a liquid to form the Rayleigh-Plesset equation:

$$R\ddot{R}+\frac{3\dot{R}^2}{2}=\frac{1}{\rho}\left\{\left(p_0+\frac{2\sigma}{R_0}-p_v\right)\left(\frac{R_0}{R}\right)^{3\kappa}+p_v-\frac{2\sigma}{R}-\frac{4\eta\dot{R}}{R}-p_0-P(t)\right\} \quad (1)^8$$

where R_0 is the bubble radius at rest, ρ is the fluid density, σ is the surface tension, κ is the specific heat ratio, η is the surface tension, p_0 is the ambient pressure, p_v is the vapour pressure, $P(t)$ is a time varying external pressure and R , $\dot{R}$ and $\ddot{R}$ are derivations of the radius which are to be solved numerically.

From (1)[8] it can be seen that an external pressure, $P(t)$, can be applied to force the bubble into another oscillation other than its resonance. This occurs naturally when the bubble is formed and creates the damped sinusoid (Figure 1). From a modified version the Rayleigh-Plesset equation to include a empirically derived damping factor, we can model this process as in Figure 2. Image a) simulates the bubble formation event and image b) shows the response in terms of, R, its radius of the created bubble.

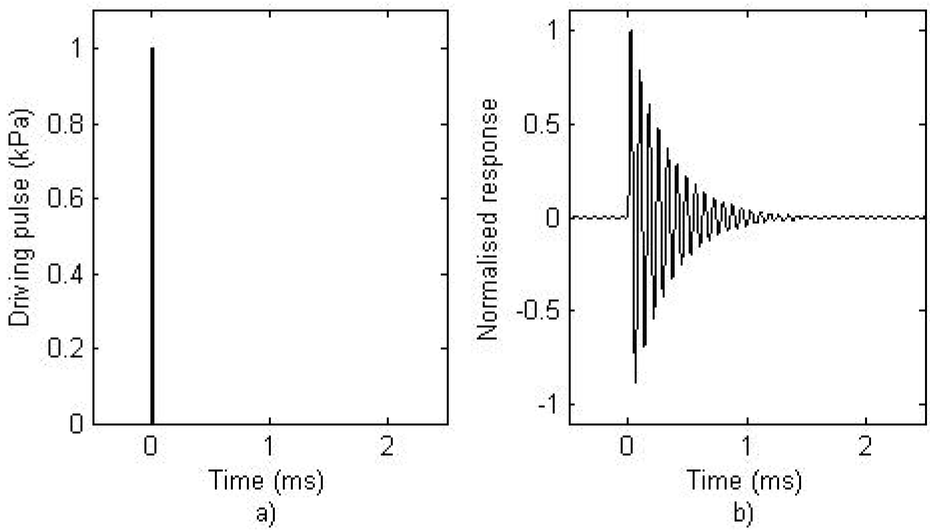


Figure 2: Numerical solution to the Rayleigh-Plesset Equation (1)

Figure 3 Shows a similar simulation where the bubble is now developed inside an external driving pressure. Image a) is the driving signal added to the bubble event and b) shows the response of the bubble. Initially, it was expected that the bubble should first go through a transient region before aligning itself to the driving oscillation. However, from Figure 3 b) it can be seen that there is no significant effect, apart from a superposition of the two signals.

Further analysis of the signal (Figure 4) shows that there is no reduction in the power spectrum of the signal.

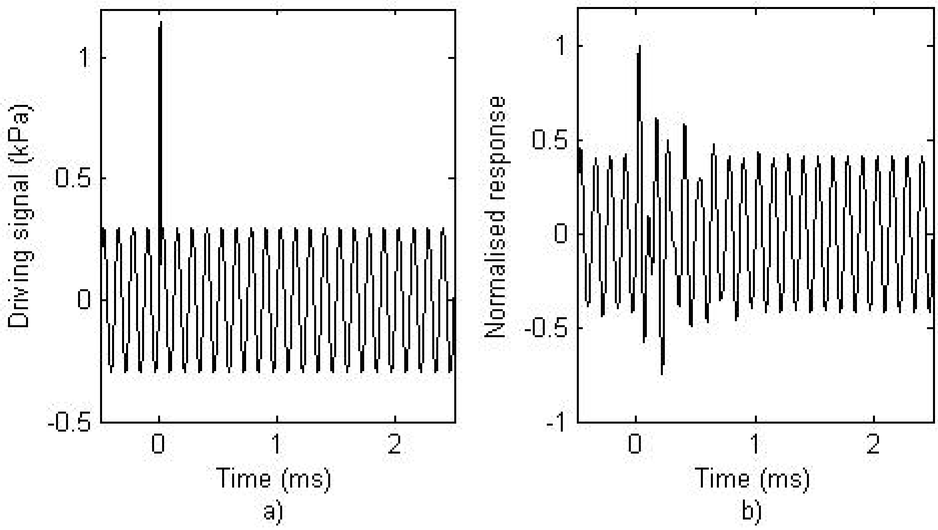


Figure 3: Simulating bubble formation within a driving sound field

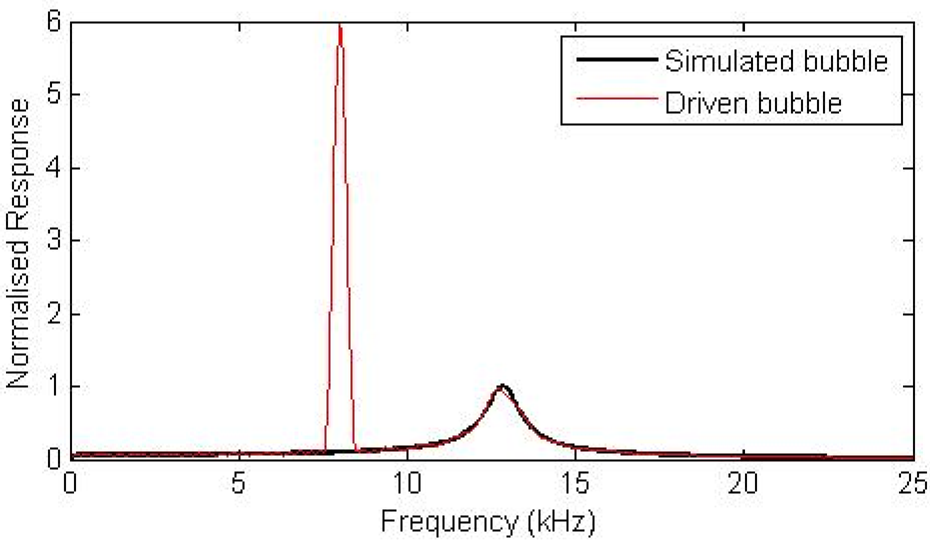


Figure 4: Example bubble forcing spectrum

Applying this principle to the acoustic disdrometer, it could be possible to emit a constant high energy sinusoidal signal into the water tank which will force any entrained bubbles to a specific frequency. This narrowband frequency can then be filtered via signal processing and the resultant will be a waveform that still holds the impact pulses, but suppresses the bubbles.

However, the simulations dictate that the principle would not be economical and this couldn't be experimentally verified due to the high dynamic range the system would require. Impact pulses commonly emit pressures in the order of tens of Pascals and after taking spherical loss into account can commonly be much less than a Pascal in a large tank. When other authors[8] performed similar experiments he used pressures of 0.24MPa. To prevent saturation in any amplifiers, a dynamic range greater than 120dB would be required.

B. Liquid Properties

It has been shown that bubbles could be suppressed by reducing the surface tension of the liquid in the tank[1]. Recent work investigated how the surface tension affects entrainment[12]. They develop the idea of the capillary number, Ca , which is the measure of the impact velocity with respect to the viscosity, μ , and the surface tension.

$$Ca = \frac{\mu V_i}{\sigma} \quad (2)$$

The viscous effects of the liquid had been neglected by most previous studies, but they found that as this ratio increases the entrained bubble size decreased until $Ca \approx 0.6$ when entrainment no longer occurred. This is partly due to both viscous damping, which decreases the angle of the crater cone, and by the surface tension, which limits the crater's ability to pinch-off.

Applying this to the Acoustic Disdrometer, it would be possible to alter the characteristics of the water in the tank to remove any bubble noise. However, the maintenance of such a system could be problematic. If a surfactant were added to the water, there would be no guarantee that the liquid would stay mixed and the addition of excess water from rain would dilute the mixture. In either case, routine maintenance would be necessary to ensure the correct surface tension. Another option is to increase the viscosity of the liquid but after experimentation it was found that when droplets landed in a similar area in a quick succession, a local pool of non-viscous water was created and entrainment resulted.

Furthermore, commonly available surfactants such as washing detergent and washing up liquid, along with substances such as glycerol tended to form foam bubbles on the surface of the liquid after a bubble had formed. This surface bubble would then form a cushion for the next droplet and attenuate the impact signal. Also when a bubble on the surface popped, it produced another large damped sinusoid.

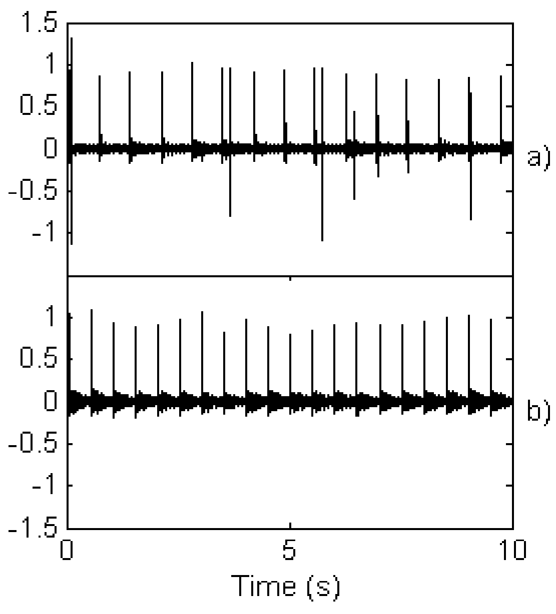


Figure 5: Surfactant addition testing. Figure a) water, figure b) with an oil film added

By experimentation, the most economical method of removing entrainment in terms of manageability and sustainability was to use an oil. One of the most helpful properties of oil is that it floats on water. This then acts like a cushion and eliminates entrainment by decreasing crater depth and increasing viscous bubble attenuation. Figure 5 depicts results from an experiment that produced impacts into a) a tank of water and b) into a tank of water with a layer engine oil floating on the top. Upward peaks correspond to the impact and dual peaks correspond to a bubble; for a zoomed version of a pulse and a bubble, refer to Figure 1.

It can be seen that the application of a layer of oil has completely removed the bubble noise from the signal and only a small loss in the impact signal was noticed due to viscous absorption. The only drawback is that over time, the oil starts to coagulate, reducing the effectiveness of the film; it would require cleaning and reapplication.

C. Software Interpretation

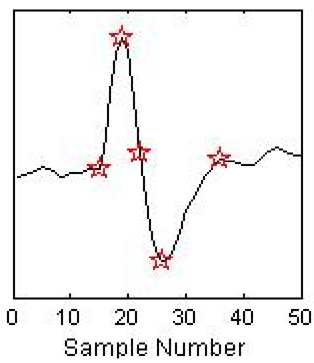
The most flexible method of bubble noise suppression is by using signal processing methods. The goal of the software is to correctly identify impact pulses with the minimum amount of error. One example of an error could be that a bubble is interpreted as an impact

As bubbles have a resonant frequency, the simplest option would be to filter out these range of frequencies: often from 8-20 kHz. Although the impact signal looks broadband in nature, it is not ideal, and a significant amount of energy lies within the 1-20 kHz band. Hence, removing this would reduce the impact signal to noise ratio, to the point where detection may not possible.

Previous work[3] attempted to use the impact signal to quantify the rain rate. They use an impact's low frequency emission, which corresponds to the crater action, as the indication of an impact. Comparing the impact's low frequency emission and the impacts pulse, the difference in size indicates that it would be more efficient to use the impact pulse. Also, as the impulse contains much of its energy in the lower part of the frequency spectrum, differentiation will suppress the impulse as well as the bubbles since the impact pulse is not ideal.

Our interpretation of the signal is empirically based; it is clear to see that the impact and bubble signals are fundamentally different. The task is to develop a series of procedural statements that clearly define what the impact *looks* like. Our current process is outlined Table 1 below:

Table 1: Signal Processing Methodology

Filtering	The frequencies from 1-50 kHZ are only of interest. Filtering also helps to remove mains and wind noise.
Thresholding	Thresholding removes redundant information if a threshold is set just above the noise floor.
Initial Peak Separation	In a local group of peaks, the first is the only one of interest since following peaks could be reflections.
Feature Masking	Impacts always look the same, independent of their size. By developing a mask, (cf. Figure 6), we can create a confidence variable to which a threshold can be applied.  Figure 6: Impact masking
Time interpolation	To get a more accurate position of the impact location, spline interpolation can be used.

Position interpolation	If we have a combination of 3 impacts, we can estimate where the fourth should be using trilateration. A pulse could then be found with less stringent constraints.

The images below in Figure 7 and 8 show an example of the current impact filtering routines. Image 8 is a zoomed version verifying that the detected second event in image 7 is an impact.

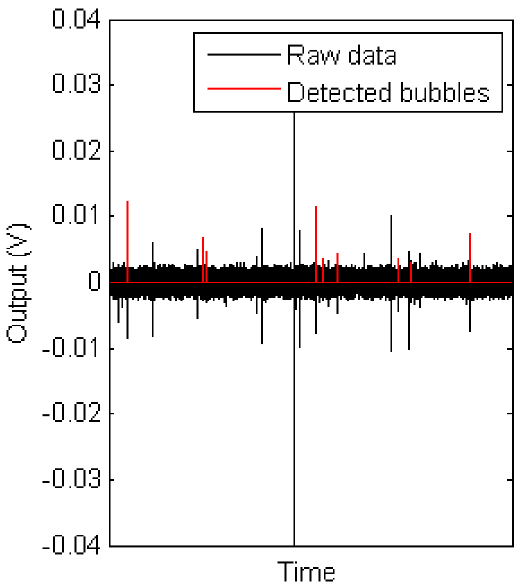


Figure 7: Example data with signal processing

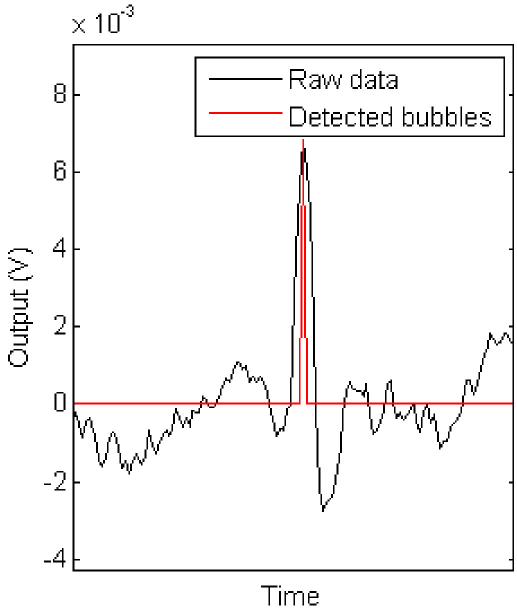


Figure 8: Example data with signal processing with zoom

3. CONCLUSIONS

The role of entrainment has been investigated when related to the Acoustic Disdrometer and how its effects can skew the data. Three methods of suppression have been suggested although only one is reasonable in terms of both quality and sustainability.

Using a driving high amplitude sinusoid, which can force a bubble to oscillate, is the most novel form of suppression. However, due to the limited dynamic range of any electronics, the large driving signal is impractical in reality. Further work includes utilising either acoustic methods or logarithmic amplifiers.

By introducing surfactants or other liquids to the catchment tank, entrainment can be mitigated completely which would greatly simplify and signal processing tasks. This included altering the surface tension or, more simply, altering the viscosity of the liquid. For the Acoustic Disdrometer, the most simple method of altering this figure is to add a film of oil to the surface of the tank. Because entrainment usually only occurs within the first centimetre of liquid, an oil thickness of this amount succeeds in removing all entrainment signals. Because the Acoustic Disdrometer is to be used in non-ideal locations, it would be difficult to sustain a maintenance schedule which would involve cleaning the tank and reapplying the oil film.

The most acceptable method of suppressing entrainment signals is via the use of signal processing; it's flexibility is unparalleled when compared to any of the other methods. A series of procedural restrictions is proposed, which were initially developed empirically. This means that the algorithm will always be open to improvement and will evolve over the time whilst the project is active.

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