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UNDERWATER RAIN NOISE— THE INITIAL IMPACT COMPONENT.

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1. INTRODUCTION

1.1 History

The sound made by rain falling onto water has been a much-investigated subject recently. There are two main reasons for this, one is simply the general desire to understand ambient noise in the ocean because of its detrimental effects on sonar. The other reason is the hope that the sound could be used as a method of measuring the amount of rain which falls onto the worlds oceans. This is matter of interest to climate modellers, but is very difficult to measure by traditional methods such as rain gauges.

Progress has been made in two distinct and complementary fronts, the first being studies of the sound produced by real rain falling onto lakes or the sea, the second being laboratory experiments on the sounds of single water drops. The first discoveries of any real importance were made by Franz [1], who showed that an impacting water drop can produce sound in two distinct ways. The first sound is generated by a "water hammer" effect at the moment of impact, while the second is radiated by a bubble, which is entrained in the water by the splash. Franz considered bubbles to be unimportant because they are only produced occasionally, while the initial impact sound occurs for every drop. He also made measurements of the sound of a spray of drops, and attempted to predict the sound of rain from the results. His predicted spectra were not like those obtained with real rain, but as no good real-rain data was available at the time, he had no way of making this comparison

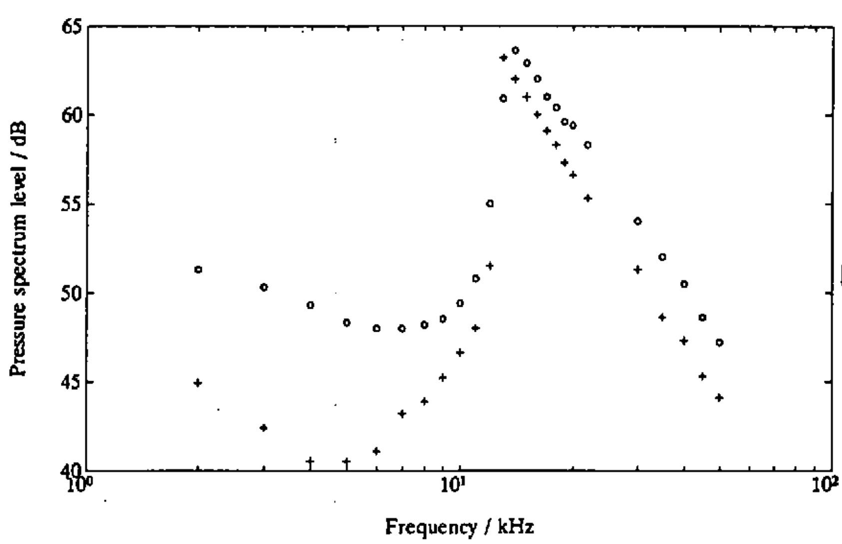

Fig. 1. Sound power spectra of the noise made by light rain falling onto a lake. The data was taken by Scrimger et al. [4] in a lake in British Columbia. The circles represent a heavier shower than the crosses, with a higher proportion of large drops. The spectrum level is in dB re $1\mu Pa^2/Hz$

The first useful data on the sound made by real rain appeared about six years ago [2–4], and provoked a great deal of interest. The spectra showed a very persistent peak at a frequency of 14 kHz, as shown in Fig. 1. The peak appeared in all types of rain, but was less obvious if the rain was heavy.

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At least one attempt [3] was made to explain this peak in terms of the initial impact sound alone; Franz's conclusion that the bubbles were sporadic and therefore unimportant was almost taken as read. However, I have shown that for certain sizes of drop, impacting at certain velocities, a bubble is entrained predictably, every time. This remarkable phenomenon has been described in great detail, simulated on computers and is now considered to be reasonably well understood [5–11]. For raindrops, travelling at their terminal velocity, it occurs for drops with diameters between 0.8 and 1.1 mm. The bubbles entrained have resonance frequencies of 14 kHz and above; this accounts for the spectral peak.

The role of the initial impact sound has remained relatively poorly understood. This is mainly because it is not at all easy to deal with, either experimentally or theoretically. In this paper, I shall describe some experiments in which I attempted to measure the pulse shape of the initial impact sound and how the pulse parameters depend on the drop size and impact velocity. The experimental problems will be discussed, and I shall also examine how they relate to previous work.

1.2 Preliminary theory

The water surface is effectively a pressure release surface, so any sound field which is generated at a point close to it has to be a dipole field. This means that the pressure perturbation must be of the form

$$p = p_0 \cos\theta \frac{\partial}{\partial r}\left\{\frac{-\psi(t-r/c)}{r}\right\}, \tag{1}$$

where r is distance from the source, θ is the polar angle, measured from vertically downwards, c is the speed of sound, t is time and ψ is any function [12]. The − sign is included for convenience, as the equation reduces to:

$$p = p_0 \cos\theta \left\{\frac{\psi(\tau)}{r^2} + \frac{\phi(\tau)}{r}\right\}, \tag{2}$$

where τ is the retarded time $t - r/c$ and ϕ is given by $\phi = (1/c)(d\psi/d\tau)$. Note that the pressure consists of a near-field component ψ and a far-field component ϕ, it is only the latter which is of interest to us as the near-field is only detectable close to the splash and does not consist of energy being radiated away from the source region.

The form of ϕ is not easy to deduce by theoretical means. We suppose that the process is basically a water hammer, and hence the pressure in the source region should be proportional to $\rho c v$, where ρ is the density of the water and v is the drop impact velocity. The problem is complicated greatly by the geometry, a recent attempt [13] succeeded mainly in showing exactly how difficult it is. Most of the real progress has therefore been made by experimental or computational means, but a number of theoretical guidelines have been suggested, usually on dimensional grounds. In particular, both Franz [1] and Oğuz and Prosperetti [10] have said that the far-field pulse should be of the form

$$p \propto \frac{\rho v^3 d \cos\theta}{r} u\left(\frac{\tau v}{d}\right), \tag{3}$$

where d is the drop's diameter, and u is a universal function. This tells us how we should expect the pulse length and amplitude to scale with d and v; we shall see how well it agrees with experiment. It does not, however, give us any help as to the shape of the pulse; it is therefore necessary to resort to experiments, some of which are described below.

2. EXPERIMENTAL METHOD

Impact sounds were studied in a large water tank (4.5 m × 1.3 m × 1.3 m deep); the tank was not anechoic, but was large enough to ensure that reflections were not a problem. The drops were produced by allowing water to flow slowly through hypodermic needles of various sizes. The velocity, v, was calculated from the drop diameter d and the height h from which the drop fell; v is given by [6]

$$v = v_T(1 - e^{-2gh/v_T^2})^{1/2} \tag{4}$$

In this equation, v_T is the terminal velocity of the drop, calculated by a power law fit to the drop diameter [14]. The sounds were detected by a miniature hydrophone (Bruel and Kjaer 8103), which was placed vertically below the splash. They were then amplified by a suitable charge amplifier (Bruel and Kjaer 2635); the resultant signals were analysed on a Macintosh IIci computer, using a National Instruments digitising card (model NB-A2000) and LabView software.

3. RESULTS

A typical drop impact pulse is shown in Fig. 2; this is the raw signal as it comes from the hydrophone and an unwary investigator might be tempted to assume that this is the form of the radiated sound pulse, ϕ. This is not actually the case, the far-field pressure must drop off as $1/r$. The pulse shown in Fig. 2 drops off as $1/r^2$ and is therefore the near-field pulse, ψ.

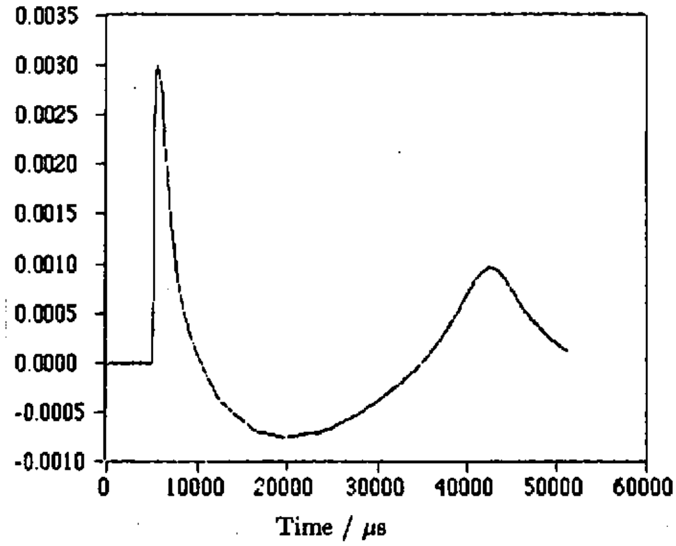

Fig. 2. The pressure pulse measured at a depth of 45mm below a drop impact. Units of pressure are arbitrary.

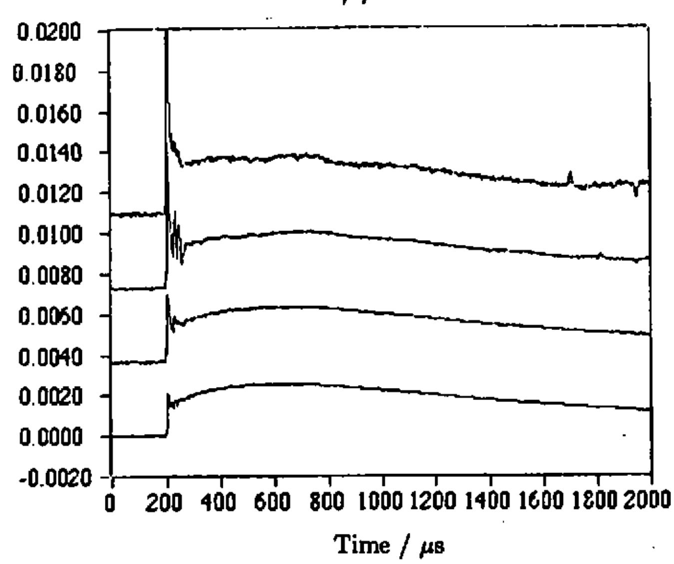

Fig. 3. The pressure perturbation below a drop impact at four depths: 30 mm (bottom), 50 mm, 100 mm and 180 mm (top), multiplied by $(\text{depth})^2$. Units are tens of Pascals multiplied by $(\text{metres})^2$. Note that as depth increases, the spike at the beginning of the pulse gets larger, but the whole trace gets noisy, and reflections are seen near the right-hand edge of the figure. The drop had a diameter of 2.9 mm and an impact velocity of 4.6 m/s.

If we look at the pulse on a smaller timescale, we can see that the first part of it does contain a significant radiated component. This is shown in Fig. 3, in which the pressure pulse multiplied by r^2 is shown for various values of r. The near-field part remains constant from one trace to another, but the spike at the beginning of the pulse becomes relatively larger as the distance increases; this spike is therefore the far-field pulse, ϕ.

The big experimental problem is that if one moved the hydrophone to a large distance, in order to eliminate the near-field component, then the signal would become so contaminated with noise and reflections as to be quite useless. The solution which I adopted was to measure the pulse shape at various depths and combine the measurements to produce the far-field pulse. Suppose that the total pressure p at retarded time τ is given by Eq. 2. If we have measurements of p for several values of r, then we can plot r^2p against r for each value of τ, obtaining a straight line of slope $\phi(\tau)$ and an intercept on the r^2p axis of $\psi(\tau)$.

If this is done for the data of Fig. 3, we obtain a collection of graphs like Fig. 4; if the slopes of these graphs are calculated and plotted against time, we obtain the required far-field pulse as shown in Fig. 5.

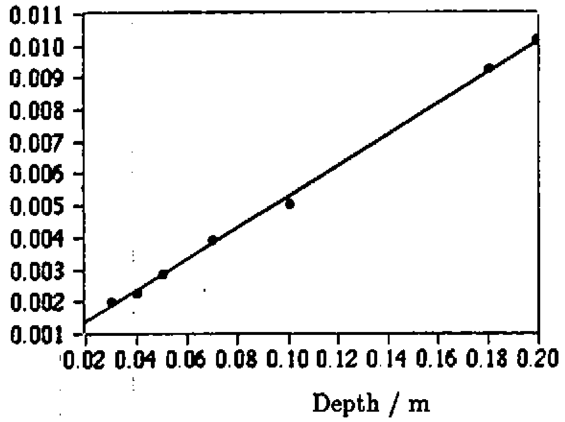

Fig. 4. Plot of r^2p against r. The slope of this graph is the value of ϕ at a time ofapproximately 4 μs after the drop impact. The intercept is the value of the near-field pulse, ψ. One of these plots is made for each point on the trace of Fig. 5.

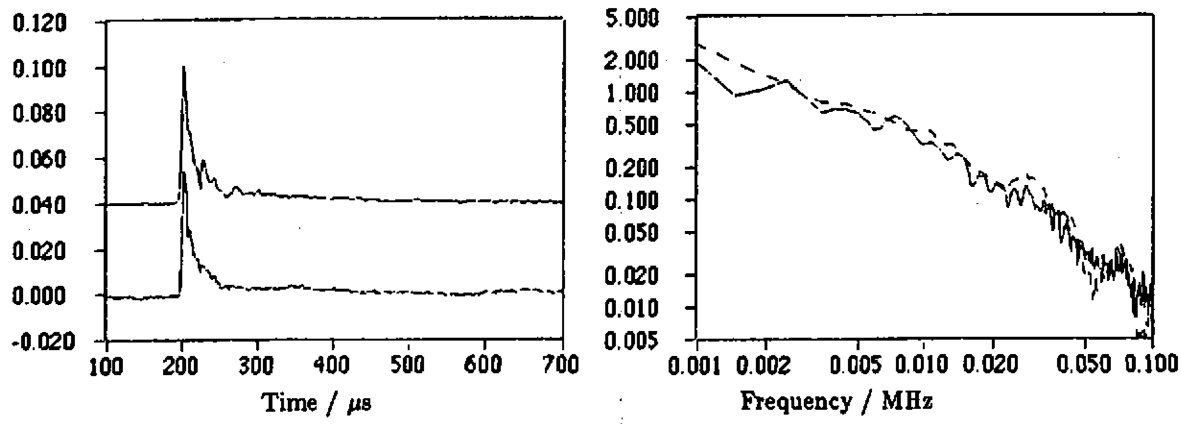

Fig. 5. Left: this shows the far-field pulse, ϕ, extracted from data taken at various depths (bottom) and by Franz's filter method from data taken at a depth of 50 mm (top). Units are (tens of Pascals)(metres). Right: the energy spectra of these two traces in arbitrary units; the dashed line corresponds to the filter method.

Franz describes another way to extract the far-field pulse, which does not require data to be taken at several depths. It relies on the fact that $\phi = (1/c)(d\psi/d\tau)$. Consider a simple high-pass RC filter as shown in Fig. 6, and for which

$$\frac{d}{dt}(v_i - v_o) = \frac{v_o}{RC}. \tag{5}$$

If v_i happens to be of the form $\psi + (r/c)(d\psi/d\tau)$ and r/c happens to be equal to RC, then we have

$$\frac{d\psi}{d\tau} + \frac{d}{dt}\left(\frac{r}{c}\frac{d\psi}{d\tau}\right) = \frac{cv_o}{r} + \frac{r}{c}\frac{d}{dt}\frac{cv_o}{r}, \quad (6)$$

and therefore

$$v_o = \frac{r}{c}\frac{d\psi}{d\tau} = r\phi. \quad (7)$$

The filter can be implemented digitally and applied to the data of Fig. 3, a typical result is shown in Fig. 5; it compares well with that of the multi-depth method.

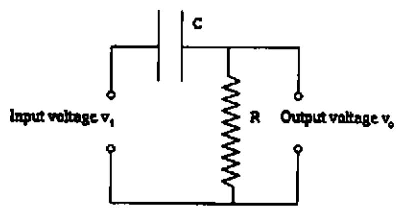

Fig. 6. The filter suggested by Franz [1].

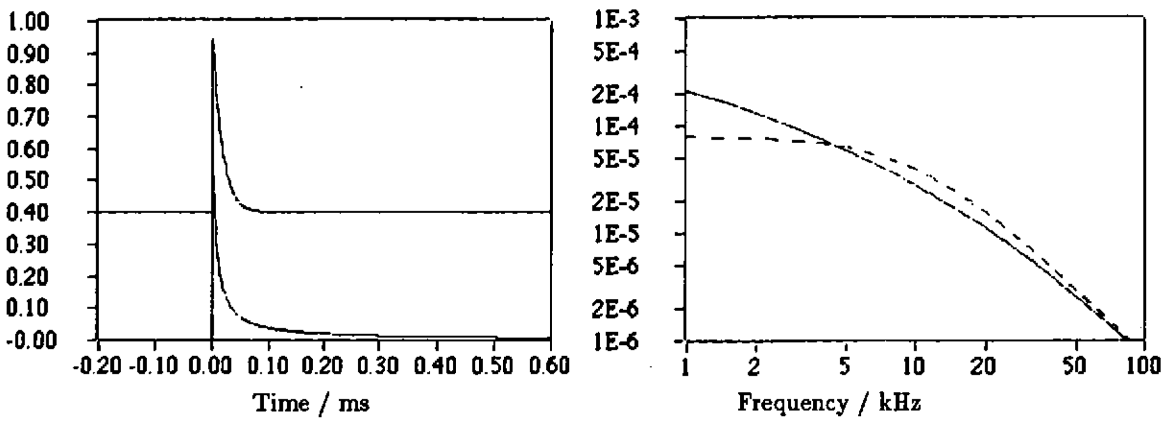

Fig. 7. Possible approximations to the pulse shape and their spectra. Left: pulse shapes of Eqs. 8 (below) and 9 (above); Right: Spectra of Eqs. 10 (solid) and 11 (dashed).

Note that the pulse is positive-going; the pressure does not cross the axis and go negative. This means that the power spectrum of the pulse will be monotonically decreasing; it will not have any peaks; this is shown in Fig. 5. The exact form of the pulse is rather difficult to infer, but we might model it with one of the following functions:

$$\phi = A\left(\frac{\delta}{\tau + \delta}\right) \quad (8)$$

or

$$\phi = Ae^{-b\tau}. \quad (9)$$

These functions have the following power spectra:

$$|\tilde{\phi}(f)|^2 = A\delta\left(\mathrm{ci}(f\delta)^2 + \mathrm{si}(f\delta)^2\right) \quad (10)$$

and

$$|\tilde{\phi}(f)|^2 = \frac{1}{b^2 + 4\pi^2 f}, \quad (11)$$

where ci and si are the sine-integral and cosine-integral functions [15]. These are also shown in Fig. 7; equations 8 and 10 seem to give a better agreement with the experimental results of Fig. 5, at the expense of being more of a nuisance to calculate.

We now consider how the pulse amplitude A and timescale δ depend on the drop size and impact velocity. There is no experimental data on this in the literature; but my own experiments suggest that $A \propto v^\alpha d^\beta$, where $\alpha = 2.8 \pm 0.2$ and $\beta = 1.5 \pm 0.2$. This is in tolerable, agreement with the suggestion of Franz and Prosperetti (Eq. 3), that $\alpha = 3$ and $\beta = 1$. We shall therefore compare amplitudes by calculating the dimensionless peak pressure p_d, given by

$$p_d = \frac{2 p_p r c}{\rho d v^3 \cos\theta}, \tag{12}$$

where p_p is the peak pressure By using drops with sizes between 2.93 and 4.13 mm, and impact velocities between 2.5 and 4.5 m/s, I obtain an average value for p_d of about 7 with an error of about ± 2.

The timescale proved rather difficult to determine experimentally; some rather crude attempts to measure the time taken for the pressure to drop to a quarter of its peak value suggest that δ decreases with v and increases with d, in line with the requirement that $\delta \propto d/v$.

4. COMPARISON WITH PREVIOUS RESULTS

There have been several previous attempts to measure or calculate the form of the initial impact pulse, in this section the results are compared to those presented above. The graphs in this section have been copied by hand into a computer, and their energy spectra calculated. Some inaccuracy is therefore inevitable, but the main features are certainly preserved.

4.1 Franz [1]

This was the first study of the sound of drop impacts; Franz recognised from the beginning that the near-field sound was likely to be a problem, and he devised a cunning method to remove it, as described above. He presents the pulse in a dimensionless form which I have converted to real units of time for a drop of 3 mm diameter impacting at 4 m/s (Fig. 8). There are two major differences between this and my own result: Franz's pulse goes negative by a substantial amount, and it occurs over a much longer timescale. This would give a spectral peak at 600 Hz. The dimensionless peak pressure is 1.8, only a quarter of the value which I obtained. One is forced to conclude that Franz's equipment let him down, somehow.

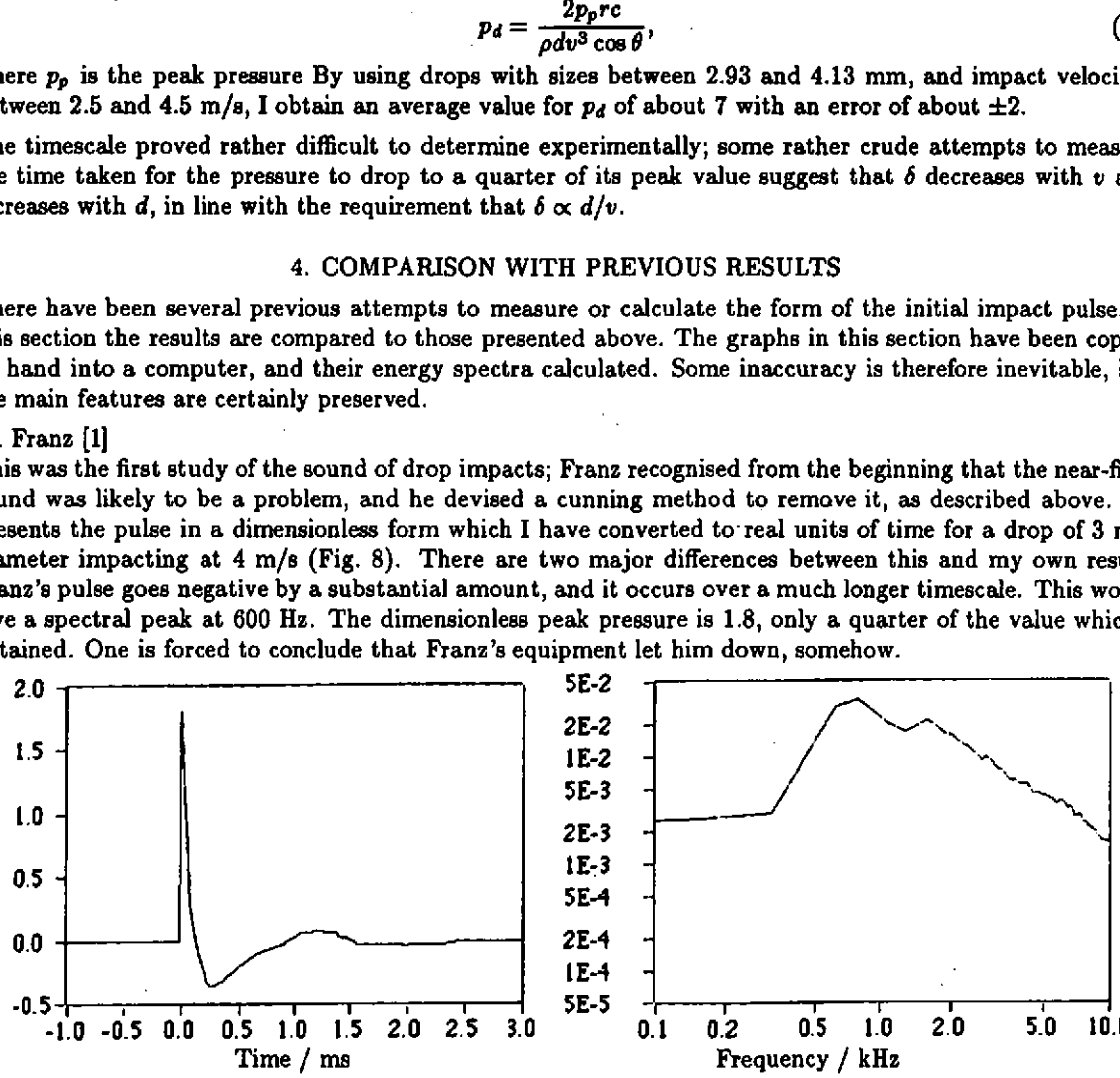

Fig. 8. Franz's pulse, and its power spectrum, calculated for a drop of 3 mm diameter, impacting at 4 m/s, for comparison with Fig. 5 Pressure is in the dimensionless units of Eq. 12.

4.2 Nystuen [3], Nystuen and Farmer [16]

In these papers, a remarkable computer simulation of the drop impact is described. In the first paper, only the near-field pulse is shown, together with a power spectrum which shows a very small (3 dB) peak at 10 kHz. As they were unaware of the bubble mechanism, the authors then attempted to use their result to explain the spectral peak (which is 30 dB high, at 14 kHz). The second paper is similar, but includes a far-field pulse, shown in Fig. 9, note that this too goes negative, and that it is on a somewhat shorter timescale than my own results. Its power spectrum has a peak at 10 kHz, again this is too small and at the wrong frequeny to explain the spectral peak. The value of p_d is 35, five times larger than my own result.

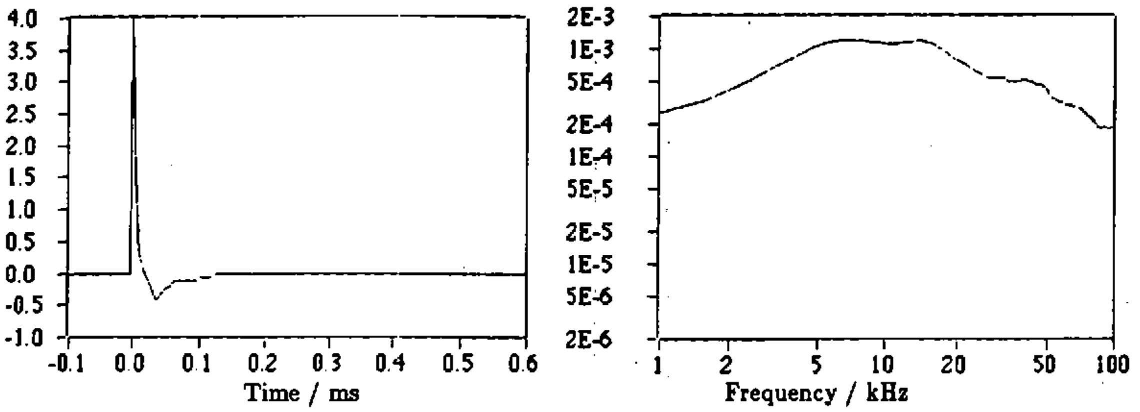

Fig. 9. This is the pulse described by Nystuen and Farmer in Ref. [16]. drop diameter is3 mm, velocity is 4 m/s, as in Fig. 8

4.3 Nystuen and Farmer [17]

This paper shows a drop impact pulse, but gives no detail on the equipment with which it was measured. The pulse and its spectrum are shown in Fig. 10; note the peak, at 20 kHz this time, and that the overall timescale of the pulse is reasonably similar to my own results. No units are given on the pressure axis.

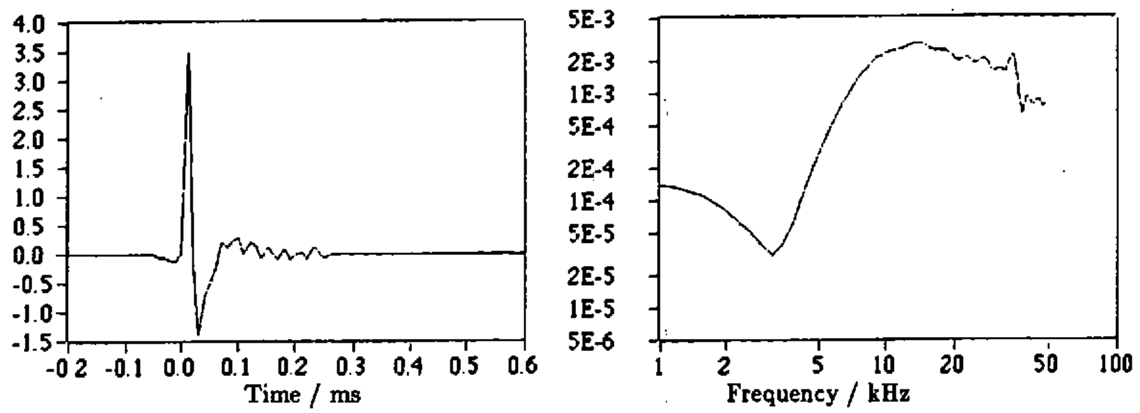

Fig. 10. From Nystuen and Farmer [17]. Drop diameter is 2 mm, velocity is 6 m/s

4.4 Medwin, Kurgan and Nystuen [18]

This paper shows a pulse and its power spectrum (Fig. 11). the authors admit that they filter their signal, removing components below 8 kHz and above 50 kHz.

Fig. 11 also shows that their result can be duplicated by feeding a raw hydrophone signal into a bandpass filter, we therefore conclude that the pulse shape shown in this paper is probably spurious and it should not be taken to mean that the impact pulse shows one or more cycles of oscillation, or that its spectrum shows any noticable peaks. In view of this, it seems possible that the pulse shape in sec. 4.3 has also been modified a certain amount. The amplitude of the peak is believable, leading to a value of p_d between 8 and 14.

These results teach us a few salutary lessons. It is clear that the pulse is very sharp, and has a very broad spectrum, which means that the observed pulse shape is very likely to be modified by by the response of the hydrophone, amplifier, and any filters which are used. In view of this, it is probably wise to treat even the present results with a certain amount of caution.

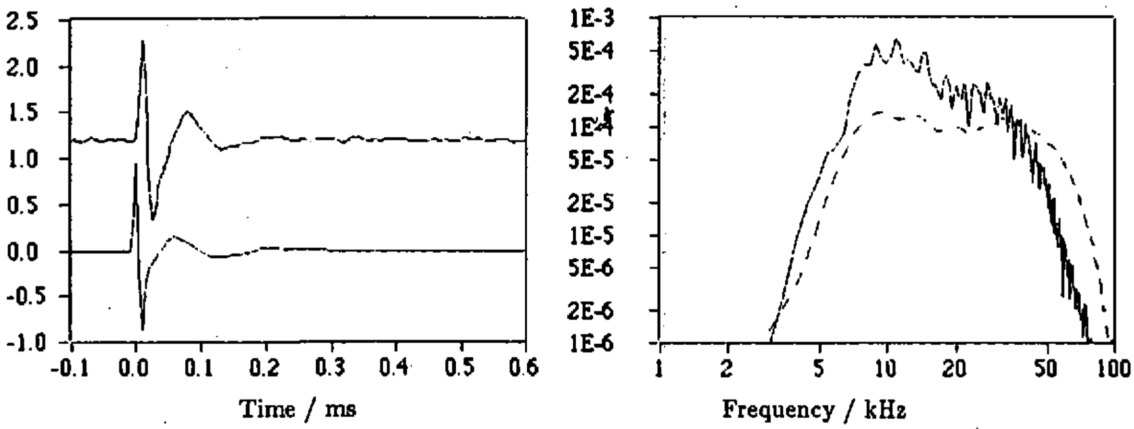

Fig. 11. This shows a pulse copied from Ref. [18] (below, left) and the power spectrum which I calculated from it (dashed line, right). It differs in some respects from the power spectrum shown in Ref. [18], for instance, the cutoff appears to be at a lower frequency here, this is probably due to inaccuracy in copying. The figure also shows the pulse obtained by passing a pressure pulse from a hydrophone situated 180 mm below a drop impact through a bandpass filter (above, left) and its spectrum (solid line, right). The drop details were as in Fig. 3; the filter was a digital 3rd-order Butterworth filter with cutoff frequencies set at 8 kHz and 50 kHz. All units of pressure are arbitrary

5. THE IMPACT CONTRIBUTION TO RAIN NOISE SPECTRA

The contribution which the observed impact pulse would make to the rain noise spectrum was calculated; there is insufficient space here to include the calculations, similar ones are presented in Ref. 10. The main input to the theory is the number of raindrops in each size range. We also make the assumptions that Eq. 3 is valid and the form of the pulse is given by Eq. 8. We use a value of 14 for p_d; this is rather at the large end of the experimental range. We let $\delta = 1.6 \times 10^{-3}(d/v)$; this is also rather larger than the majority of the experimental values. The result is shown in Fig. 12.

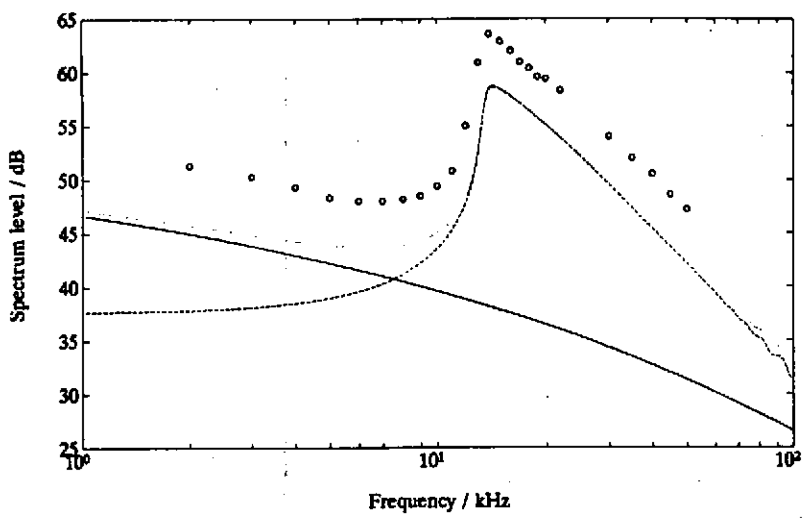

Fig. 12. The contributions of bubbles and impacts to the rain noise spectrum. The dashed line is the spectrum due to regularly entrained bubbles, as calculated in Ref. 9, the solid line is the impact spectrum described above. The dotted line is the sum of these. The circles are the relevant data from Ref. 4; they are louder than the calculated values by about 4 dB, possible reasons for this are detailed in [7-9]. The spectrum level is in dB re $1\mu Pa^2/Hz$

6. CONCLUSIONS

The acoustic pressure pulse which is emitted as a drop touches the water surface has been investigated experimentally, and has been shown to be a single pulse with a sharp front edge and a rapidly decaying tail. Its power spectrum decreases monotonically with frequency, at least above 1 kHz; the initial impact can therefore contribute nothing to the spectral peak at 14 kHz. I believe that statements to the contrary in the literature can mostly be attributed to injudicious filtering of the signal, or to the inaccuracy of computer simulations.

Superposition of the impact spectrum onto the bubble spectrum show that the impact sound is probably a significant contribution to the spectrum of rain noise at frequencies below 7 kHz, in moderately light rain. It is produced much more efficiently by large drops, which contain most of the volume of water in rain. This would explain why this part of the spectrum is better correlated to the total rainfall rate than is the 14 kHz peak. It seems likely that the impact sound may be important at higher frequencies in heavy rain, partly obscuring the bubble peak. It is true that the accuracy with which the absolute amplitude of the pulse was measured is not sufficient to enable us to state exactly how important the impact sound is, or whether it is the only important contribution in the low kHz frequency range, but we may be reasonably confident about the above description of the pulse shape; this should provide a sound basis for any further research.

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