Drop parameter estimation from underwater noise produced by raindrop impact

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Abstract: A study is presented of the acoustic signals produced by raindrops impacting on the surface of water contained in a sensor assembly. The impact generates low frequency damped pressure waves in water. The low frequency spectrum of this signal is seen to be fairly consistent and is used for measuring the kinetic energy of the raindrops from which the drop-size distribution and the rain intensity are estimated. The proposed method is computationally efficient and can be implemented with simple DSP hardware.

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1. Introduction

Rain plays an important role in agriculture and global weather. It is the most important component of climate and it affects the ecosystem in various ways such as soil erosion, flood, drought, etc. The ability of raindrops to detach soil particles depends upon raindrop size and impact velocity or, in other words, the kinetic energy of raindrop.[1] There exist various classical ways of measurement of rain parameters.[2] Previous acoustic measurement methods rely on the fact that the raindrop falling in water traps some amount of air underwater, which forms an air bubble. The air bubble oscillates at a frequency determined by the size of the air bubble, producing noise. The size of the air bubble in turn depends on the size of the drop. Because of the unique characteristics of the underwater noise produced by the raindrop, rainfall measurements are possible from the analysis of this noise.[2,3] Various researchers have studied the acoustic spectrum of rain generated signal in the range of 500 Hz to more than 50 kHz and established the fact that rain parameters can be measured from the acoustic inversion method.[4–6] However, few studies have been reported for frequencies less than 500 Hz. More detailed results related to this phenomenon is reported in Refs. 5 and 7. One important drawback of this acoustic method is that not all the drops produce a bubble and hence some drops are "silent," introducing error in the estimation of rain rate.

In the present study it is observed that the amplitude of the low frequency signal in water at the impact site is related to the kinetic energy of the droplet producing the wave. This paper reports the investigations carried out on raindrop generated acoustic signals below 600 Hz and an algorithm to estimate the drop size and rainfall rate from the signal.

2. Methodology

A rigorous analysis of the acoustic signals generated by the impact of individual drops[4] reveals that the initial impact pulse produced by the droplet consists of two components, the first being a sharp leading edge, which is the true radiated sound that exists only for a short duration of about 10 to 40 μs, while the second component is a damped pressure wave. The pressure variation that follows the leading edge is a near field hydrodynamic effect related to the flow established near the impact site.

The true impact pressure is given by[4,8]

$$P_i \propto V_i^3, \tag{1}$$

where V_i is the impact velocity.

Consider a single drop falling into the sensor chamber. The energy delivered to the water in the chamber is given by

$$E = \frac{1}{2} m V_i^2, \tag{2}$$

where m is the mass of the drop and V_i is the velocity with which it is impinging on water.

Under stable atmospheric conditions, a raindrop of diameter D falling to the earth will attain terminal velocity before it impinges on the water surface. Several factors influence the speed of raindrops falling through the atmosphere. For very small drops, the terminal velocity exhibits a quadratic dependence on the size of the drop ($V_T \propto D^2$).[9] This proportionality is called Stokes' law and applies only to cloud droplets of up to about 40 μm in radius.

A widely used formula for the terminal velocity applicable to raindrops is

$$V_T(D) = 0.0561 D^3 - 0.912 D^2 + 5.03 D - 0.254. \tag{3}$$

In natural rain, the drop size varies from 0.1 mm to a maximum of 6 mm in diameter. The kinetic energy of a single raindrop can be calculated from Eqs. (2) and (3) that holds a ninth-order polynomial relationship with drop size. Impact of drops on water surface transfers its kinetic energy to water, and, as a result, pressure waves are set up at the impact site. Gravity waves are also generated on the water surface. Frequency of the same is very low, of the order of 4–7 Hz.[10,11] A sensor mechanism is developed to measure the acoustic signal due to the effect of drop impact. The impact causes the sensor assembly to resonate at its natural frequency. It was observed that the duration and amplitude of the signal picked up by the sensor assembly depends on the drop size. The energy of this acoustic signal is a measure of the kinetic energy of the drop impact. Hence it is assumed that the output of the sensor is related to the kinetic energy of drops.

3. Experimental setup

The experimental setup of the type described in Ref. 12 was used to measure and analyze the drop-generated signal. A sensitive hydrophone is mounted inside the chamber made of PVC and fixed rigidly in the upright position. The mounting of the chamber is so made that the acoustic coupling between the chamber and the mounting attachments is adjustable. This coupling mechanism is used for controlling the damping of the signal produced by drops. Fresh water is poured into the chamber such that the transducer is fully immersed in water. Provision is made in the chamber to drain out excess water when drops are impinging on the sensor assembly. A drop generating mechanism made of hypodermic needles and syringes are used to generate drops of different diameters. Diameter of drops produced by each needle is found out from the number of drops produced for 10 ml of water in the syringe. Drops from various heights are allowed to fall on the surface of the water in the chamber and the signal captured by the hydrophone is fed to the sound card of the PC through a precision conditioning amplifier. Data capturing is done at 48 000 samples per second with 16-bit resolution. The experiment is repeated by allowing the drops of various sizes to fall into the sensor with terminal velocity. Acoustic signals produced by drops of different diameters falling from various heights are captured and analyzed. The results of this investigation were already published.[13] The acoustic-energy-of-drops-generated signal seems to be correlated with the kinetic energy of the drops.

For measuring the rain, the sensor assembly is exposed to the rain and the captured signal is analyzed to find the rainfall rate from the signal energy. A tipping bucket rain gauge is used to measure the rainfall rate and to compare with computed measurement.

4. Results and discussions

It was observed that the spectrum of the signal captured has a predominant low frequency component. Figure 1 shows the signal captured and its spectrum for a single drop falling in water. The time domain plot shows that the amplitude of the signal shoots up at the instance of impact followed by a slowly damping sinusoidal wave. The frequency spectrum for the signal

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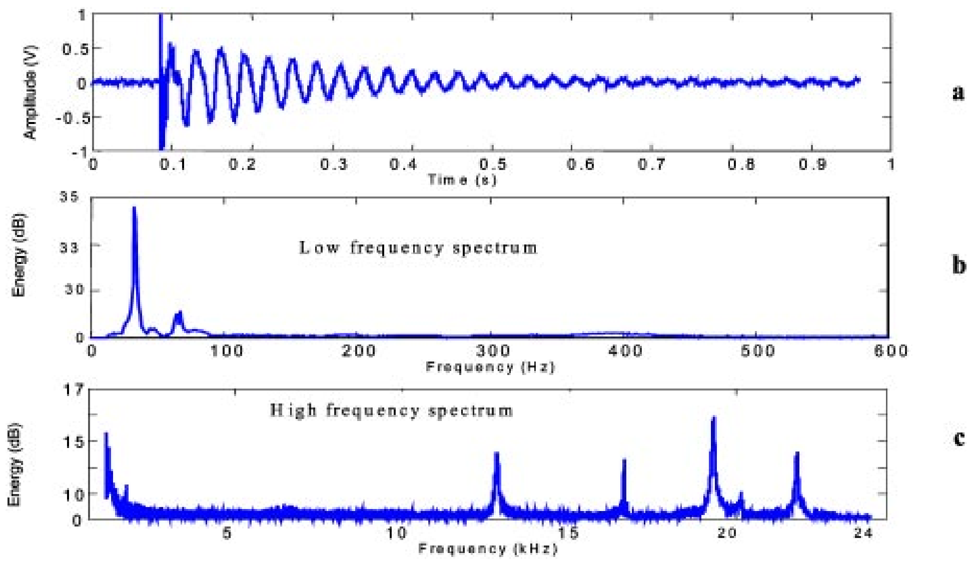

Fig. 1. (a) Rain generated noise. (b) Low frequency spectrum over the range of 0 to 600 Hz. (c) Spectrum beyond 600 Hz.

shows a sharp peak at a frequency of about 32 Hz, which might be the resonant frequency of the sensor assembly. This frequency is found to vary with the dimensions of the chamber of the sensor assembly. The spectral peak around 64 Hz is a harmonic of mechanical resonance frequency. It is also observed that maximum spectral energy lies below 600 Hz. Spectral peaks in the frequency range 13 to 15 kHz due to bubble[14] are negligibly low compared to the low frequency spectrum as evident from Fig. 1.

It is also noticed that the signal due to bubble frequency[15] is not always present in the signal, which confirms that not all the drops produce air bubbles underwater. The low frequency spectrum is found to retain its shape with drop sizes while the signal energy of each frequency component varies with drop size. A plot in Fig. 2 shows the correlation between the kinetic energy of the drops and the spectral energy of the signal.

We also performed outdoor experiments in which the sensor assembly was exposed to natural rain. A typical rain generated signal captured by the sensor is as shown in Fig. 3. It is seen that each drop impact produces a clearly defined shape with a sharp rise in signal level at the impact instant that can be easily detected.

Since it is essential to compute the drop size distribution for estimating the rain intensity, an algorithm has been developed for detecting individual drops. One important parameter for drop detection is the threshold value. A drop is detected when there is fast change in signal level that is greater than the threshold value from its neighboring samples. This threshold value helps to avoid false drop detection in the presence of noise. A higher threshold value will eliminate the possibility of false detection. When the threshold value is increased, it leads to certain undesirable effects, as smaller droplets will escape the observation of the drop detection system. Such a situation can be handled amicably by setting the threshold value adaptively depending on the average value or median value of the signal level over a selected period of time. In doing so, small droplets will be ignored during heavy rain. The error introduced is negligible as the rain intensity in heavy rain is mainly due to larger drops. However, for light rain, small drops will be detected as the threshold is proportionately lowered. Drop sizes as low as 0.5 mm in light rainfall (less than 14.1 $\mathrm{mm\,h^{-1}}$) were detected with this algorithm. Drops of sizes less than 0.5 mm were missed from heavy rain (greater than 120 $\mathrm{mm\,h^{-1}}$) signal.

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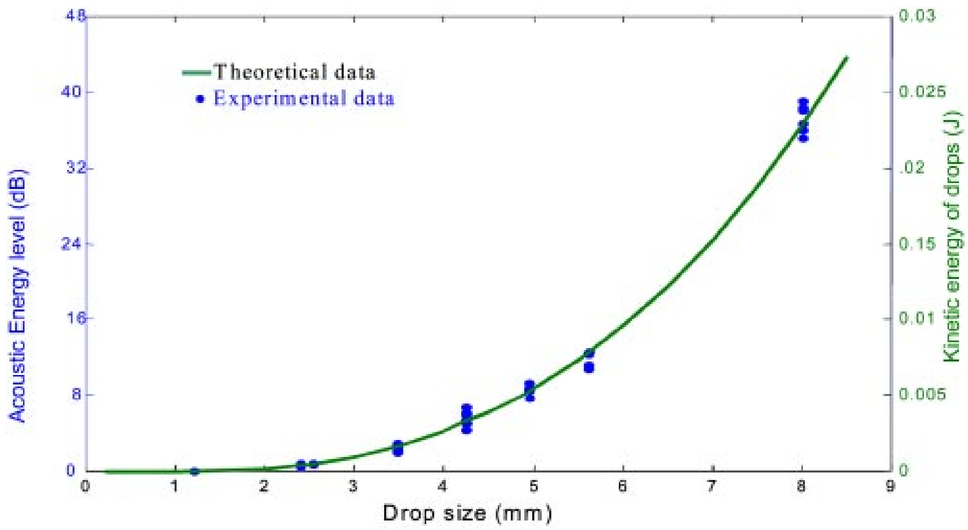

Fig. 2. Variation in energy of low frequency pressure wave with drop size.

After identifying the start of the drop signal, the energy of the signal contributed by this drop is computed using the samples of the signal lying within a response window. Response window width is set by trial and error. If the window is too wide, there is a possibility of overlapping of the window with that for the neighboring drops, which may cause measurement error. In this scheme, simultaneous drops or multiple drops within a single window were detected as a single larger drop. It is assumed that this detected drop size is equivalent to the drop size that produces the sum of the kinetic energy of the simultaneous drops. The experimental verification of this inference is being taken up separately. A lookup table has been prepared to determine the size of the drop from its kinetic energy.

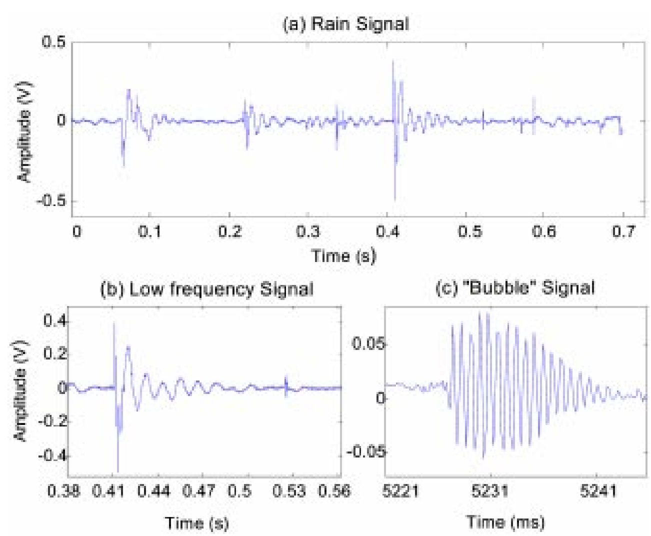

Fig. 3. (a) Rain signal captured by the sensor assembly. (b) Zoomed low frequency pressure signal after impact. (c) Bubble generated signal.

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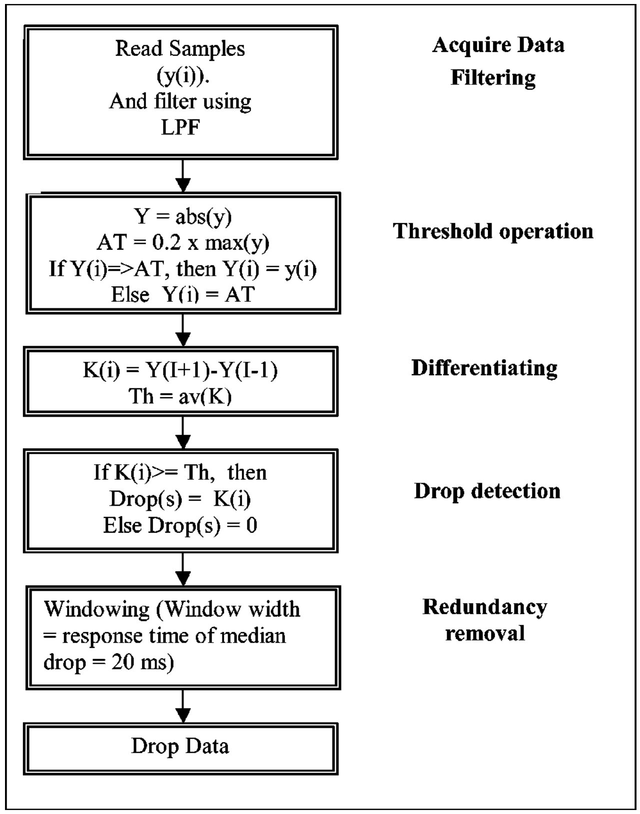

Fig. 4. Drop detection algorithm.

The drop detection algorithm shown in Fig. 4 has been implemented in MATLAB 5.3. Figure 5 shows the MATLAB plot showing the detection of raindrops and the rain generated noise amplitude. False drop detection due to noise has been reduced here by taking the derivative of the signal as suggested in the paper by Friesen *et al.*[16]

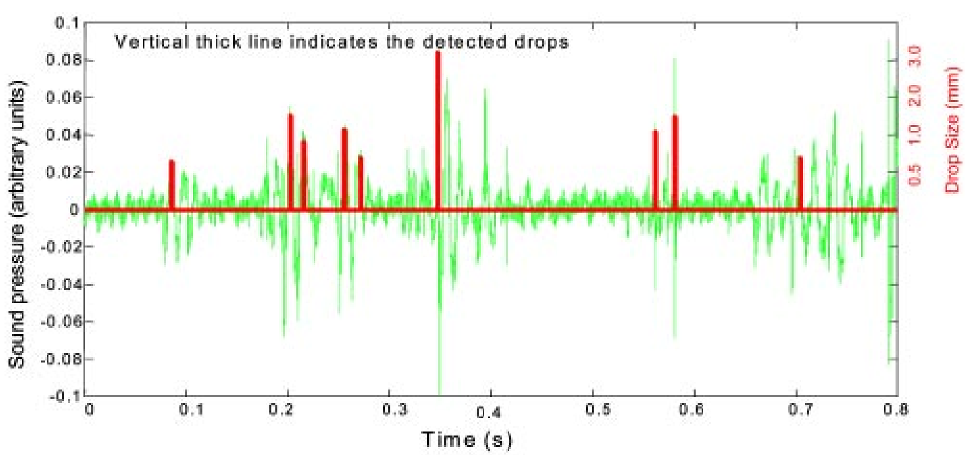

Fig. 5. Drop detection.

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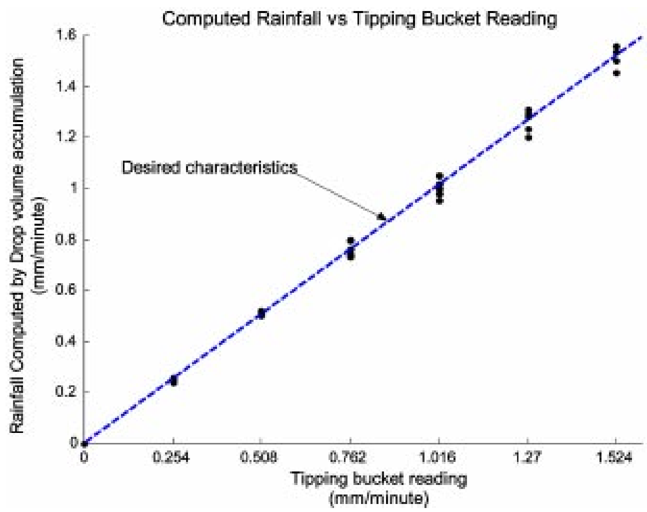

Fig. 6. Computed rainfall versus tipping bucket rain gauge reading.

Once drops are estimated, the rainfall rate can be determined from the equation

$$R = \frac{\pi}{6} \sum_i \frac{n_i D_i^3}{At}, \tag{4}$$

where D_i is the raindrop diameter, n_i is the number of drops in a given diameter interval ΔD_i, A is the area of the water surface of the sensor assembly and t is the time of observation. Rainfall is computed after detecting drops, by using Eq. (4) for various rain intensities. Figure 6 compares the rainfall rate computed from the drop accumulation with the tipping bucket rain gauge reading for rainfall rates up to 100 mm h^{-1}.

Since the signal is low pass filtered, the high frequency bubble signal can be eliminated. Moreover, the low pass filtering helps to reduce the signal bandwidth and the processing module can be implemented with cost effective hardware for real time computation. The proposed algorithm can be easily implemented in digital hardware or in general purpose field programmable gate array (FPGA) chips.

5. Conclusions

An acoustic technique offers a promising procedure for measuring the rainfall. Contrary to the conventional methods, a novel approach using the low frequency region of the rain generated noise spectrum for rain parameter extraction is suggested in this paper. The observation that the frequency of the signal remains constant while the amplitude is a function of the drop size and its terminal velocity is beneficial in extracting the rain parameters. As the band of frequencies of interest in the rain generated signal is less than 1 kHz, a sampling rate of the order of a few thousands samples per second is sufficient for the proposed system. This demands less storage space and makes the system computationally efficient compared to other systems, which are in use for rain measurement utilizing the bubble noise. This simple, reliable and cost effective method can replace the existing costly rain measurement systems. It can find applications in land based rain gauges also. Several factors such as wind, temperature, local pressure, etc. that affect the accuracy of the measurement need to be studied in detail and necessary corrections are to be applied in estimating the rainfall.

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