Some Observations on the Joss-Waldvogel Rainfall Disdrometer

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ABSTRACT

Laboratory experiments showed that the response of the Joss-Waldvogel rainfall disdrometer, a device designed to measure raindrop size from drop impact, was influenced not only by the size and vertical velocity of the drop but also by the shape of the drop.

1. Introduction

The Joss-Waldvogel rainfall disdrometer is a device for determining the size (equivalent spherical diameter) of raindrops. Manufactured by Distromet Ltd. of Switzerland, the device was originally developed by Joss and Waldvogel (1967). The Joss-Waldvogel disdrometer does not determine drop size directly from any static attribute of the drop but provides a measure of drop size from the vertical force applied to the transducer during drop impact. Because the force applied to the transducer varies during impact, the basic ability of the device to give a measure of drop size depends on the relationships between drop size, drop velocity and drop shape. Relationships between these factors have been established previously by other workers for drops travelling at their terminal velocities under laboratory conditions. Under such conditions, devices that assess drop size from drop impact may be able to give a good estimate of drop size. However, the air movements that frequently accompany natural rainfall tend to produce variations in the shape, velocity and trajectory of raindrops. Consequently, errors are likely to exist in most drop-size spectra determined from drop impact over and above errors produced by any lack of uniformity in response that might exist over the target area. The work reported here examined some of the influences that drop size, drop shape and drop velocity have on the response of the Joss-Waldvogel disdrometer.

2. Description of the instrument

The disdrometer system is based on a transducer in which the downward displacement of a styrofoam body (target area 50 cm^2) under the influence of drop impact causes a voltage to be induced in a sensing coil. This voltage is amplified and applied to another coil within the transducer to counteract the movement of the body and return it to its rest position. This system achieves a high rate of recovery. The amplified voltage also acts as the output (U_L) of the transducer.

According to the instrument manual, U_L is proportional to the vertical momentum of the drop. On the basis of the terminal velocity values obtained by Gunn and Kinzer (1949), U_L would be expected, therefore, to be proportional to the 3.5 power of raindrop size for drops within the 0.5–5.0 mm size range. However, Waldvogel (personal communication) observed that U_L shows an approximate relationship with the 3.7 power of drop size under terminal velocity conditions. He suggests that U_L is proportional to a value which lies between the peak value of the force acting on the transducer and the time integral of the force.

In order to facilitate the electronic measurement of pulse amplitude, U_L is processed electronically by a device called the processor. In recent manuals, the processed output (U_c) is reported to be given by

$$U_c = 0.94 D^{1.47}, \qquad (1)$$

where D is the drop size (mm). This gives an estimate of drop size which the manufacturer (personal communication) claims to be accurate within 5% for all drops travelling at terminal velocity.

3. Laboratory experiments

Although Eq. (1) may enable drop size to be determined with a reasonable degree of accuracy when raindrops are falling vertically at their terminal velocities, the conditions of vertical fall and terminal velocity do not always exist under natural rainfall conditions. As mentioned earlier, air movements, both vertical and horizontal, frequently accompany rainfall. Such air movements can cause drop shape, drop velocity and drop trajectory to deviate from the conditions which existed when the relationship between U_c and D was developed. The ability of the disdrometer system to give a satisfactory measure of drop size under many natural rainfall conditions depends, to a large extent, on what effects such deviations have on U_c. Consequently, laboratory experiments were made to examine the influence on the response of the disdrometer of some of the factors which cause departures from the conditions which exist normally under terminal velocity conditions.

The laboratory experiments reported here center around a series of observations made on the response of the disdrometer to the impact of single drops which show oscillatory changes in shape during the first few meters of fall following release from a drop-forming capillary tube. This series was made to examine the influence that drop shape and drop velocity have on the response of the disdrometer. Coupled with these experiments at low impact velocities, observations were also made on the response of the disdrometer to the impact of single drops of various sizes when such drops were travelling at about their terminal velocities. There were two main reasons for the series of observations at terminal velocity. First, it was considered necessary to establish whether Eq. (1) represented satisfactorily the response of the instrument. Second, the target used for the experiment involving variations in drop shape had a flat surface as compared with the conical target surface normally supplied with the instrument. Consequently, it was necessary to test whether there was any significant difference in response between the conical and flat target surfaces.

4. Procedure

a. Drops at terminal velocity

In the experiments made with drops travelling at about their terminal velocity, water drops were produced from a capillary tube using distilled water at 11–13°C. These drops, produced at approximately 1 drop every 10 s, were allowed to fall some 14 m before striking the target of the disdrometer. The average size of the drops was determined by weighing 10 drops that had been caught in a container of oil immediately below the drop former. By use of various sizes of capillary tube, the range of drop size (equivalent spherical diameter) covered by the experiment was 2.6–5.4 mm (9.2–82.4 mg). On the basis of the observations of Laws (1941), impact velocities would not have deviated by more than 2% from terminal velocity for any of the drop sizes used.

For each drop size and for each target, the peak amplitude of the pulse produced by the processor was measured for 20 impacts. A peak detector linked to a digital voltmeter was used for this purpose. The target was dried between each impact. The mean for the 20 impacts served as the basis for examining the response of the disdrometer to variations in drop size.

b. Low velocity drops

Drops 6.05–6.11 mm in size were allowed to fall between 0.63 and 1.39 m after release from a drop former before impacting at the center of a dry, flat transducer target. Drops approximately 6 mm in size were chosen because large drops show considerable changes in shape during the first few meters of fall after release from a drop-forming capillary tube. Impact at the center of a flat target was used so that impact force was at right angles to the surface and acting along the line of displacement of the target. The flat target used in the experiment was prepared by modifying a standard (conical) transducer target. This involved grinding the cone flat and covering the resulting surface with a hard plastic sheet affixed to the styrofoam by a resin glue. This increased the weight of the target by 1.9 g over the 6.1 g of the standard target. The vertical extents of the drops at the position of drop impact were recorded from photographs of the drops obtained by the technique described by Pfeiffer (1963). For each impact condition, the amplitudes produced by 20 sequential impacts were measured—10 for each of the outputs U_L and U_c. The mean for each set of 10 amplitudes served as the basis for the analysis of the data. For each impact condition, the average drop size was determined in the manner described previously for the terminal velocity experiments. The impact velocity for each impact condition was determined from the observations of Laws (1941).

5. Result and discussion

Fig. 1 shows the plot for the mean values of U_c (processed output) against average drop size for drops within the 2.6–5.4 mm size range travelling at about their terminal velocities. Variations in impact position on the target frequently caused the standard deviations associated with these means to be quite large. This was especially true for the flat target where the standard deviations ranged from a maximum of 0.74 V for a mean of 9.27 V (4.7 mm drop) to a minimum of 0.35 V for a mean of 3.81 V (2.6 mm drop). However, by least-squares regression analysis and covariance analysis, linear regressions between mean U_c and average drop size (D) accounted for about 99% of the variances in mean U_c with no significant difference between the regressions for the conical and flat targets. Consequently, no significant difference can be considered to exist between the average responses of the two target types to variations in drop size under terminal velocity conditions.

Despite the apparent linearity observed in the relationship between U_c and D for drops within the 2.6–5.4 mm size range, the data showed reasonable agreement with the calibration curve of the manufacturer [Eq. (1)]. Eq. (1) also accounts for about 99% of the observed variance in mean U_c and can, consequently, be considered satisfactory over this size range. However, without the specialized equipment necessary to produce uniform sized drops of less than 2.5 mm from capillary tubes, no attempt was made to establish the validity of the calibration curve for drops <2.6 mm.

The relationship between U_L and U_c was examined for some drop impact conditions. The U_L-U_c relationship was also determined when rectangular pulses (0.56 ms duration) were applied to U_L. The relationship obtained between U_L and U_c when the input pulses at U_L were rectangular in shape takes the form

$$U_c = 3.98 U_L^{0.39} \quad \text{for} \quad r = 0.9996. \qquad (2)$$

The data observed for drop impact conditions where both U_L and U_c were measured (i.e., drops <3.5 mm at terminal velocity and 6 mm drops falling from <1.4 m) show reasonable agreement with this curve (Fig. 2). Combining Eqs. (1) and (2) gives a relationship between U_L and $D^{3.8}$. It is therefore apparent that the previously mentioned approximate relationship between U_L and $D^{3.7}$ has been used as the basis by which the disdrometer system determines the size of drops travelling at terminal velocity.

Fig. 3a shows the typical variations in mean pulse amplitude produced at the U_L and U_c outputs by the impact of 6 mm drops at the center of the flat target during the first 1.4 m of drop fall. Fig. 3b shows the variation in vertical extent (e_v) and impact velocity (V) of the drops for the same impact conditions. The range of impact velocity was equivalent to 37–55% of the terminal velocity for 6 mm drops. It is apparent from these figures that variations in both outputs occurred over and above the variation that might be attributable to impact velocities and these variations were inversely related to the oscillatory changes in the vertical extent of the impacting drops.

When the influences of the mass (M), velocity (V) and vertical extent (e_v) of the drops on U_L were examined by least-squares regression analysis, the parameter $MV^{3.03}e_v^{-2.04}$ was found to account for the greatest proportion (96.5%) of the variance in U_L. Because the duration of drop collapse (t) is equal to $e_v V^{-1}$ (Kinnell, 1972), it is apparent that, under these low-impact velocity conditions, the response of the transducer output (U_L) could be related to the average rate of change of the vertical force of drop impact (MVt^{-2}). On the basis of the observations of drop shape at terminal velocity observed by Pruppacher and Pitter (1971), MVt^{-2} is related to $D^{2.8}$ under terminal velocity conditions. This exponent of D differs considerably from the value of 3.7 used as the basis by which the disdrometer determines the size of drops travelling at terminal velocity. An apparent discontinuity therefore exists in the response of the transducer to drop impact between drops travelling at terminal velocity and drops travelling at a relatively low velocity. Discontinuity in response was also evident in oscilloscope observations of the pulses produced by the transducer. Although the duration of the pulses produced by drops in the low-velocity experiment showed a variation related to t, the peak amplitudes were developed at about 240 μs irrespective of the value of t. On the other hand, the same sized drops travelling at terminal velocity produced pulses with peak amplitudes which occurred well within 240 μs without any apparent restriction to the time of development. This indicates that the response of the transducer changes when t exceeds some critical value.

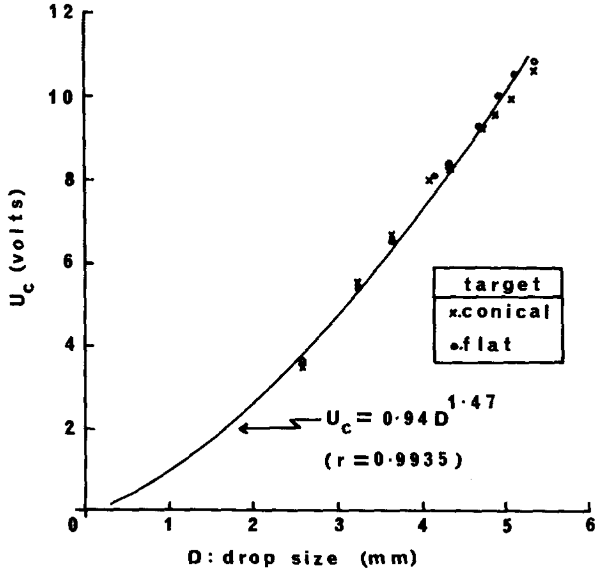

Fig. 1. The relationship between drop size (D) and processed output (U_c) for single drops travelling at about terminal velocity.

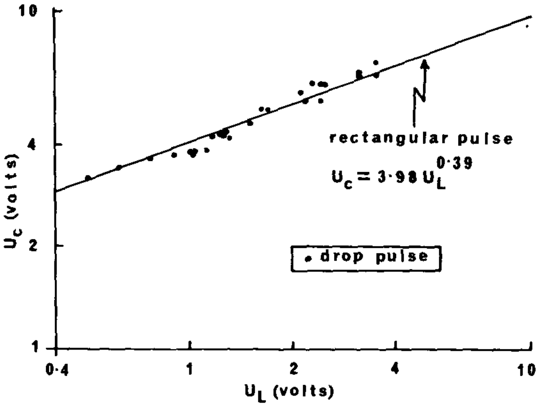

Fig. 2. The relationship between transducer output (U_L) and processed output (U_c).

Although a change in the response of the transducer is evident, it is difficult at this stage to trace the phenomena with which such a change might be associated. The consistency with which the peak amplitudes were developed at 240 μs at low drop velocity suggests that the transducer may restrict the peak amplitude when t exceeds some critical value. It might, therefore, be suggested that there is an interaction between the duration of drop collapse and the electromechanical mechanisms involved in determining the response of the transducer when t is less than this critical value. Unfortunately, there are physical difficulties which prevent the present study from being extended to the intermediate velocities in order to trace the critical phenomena.

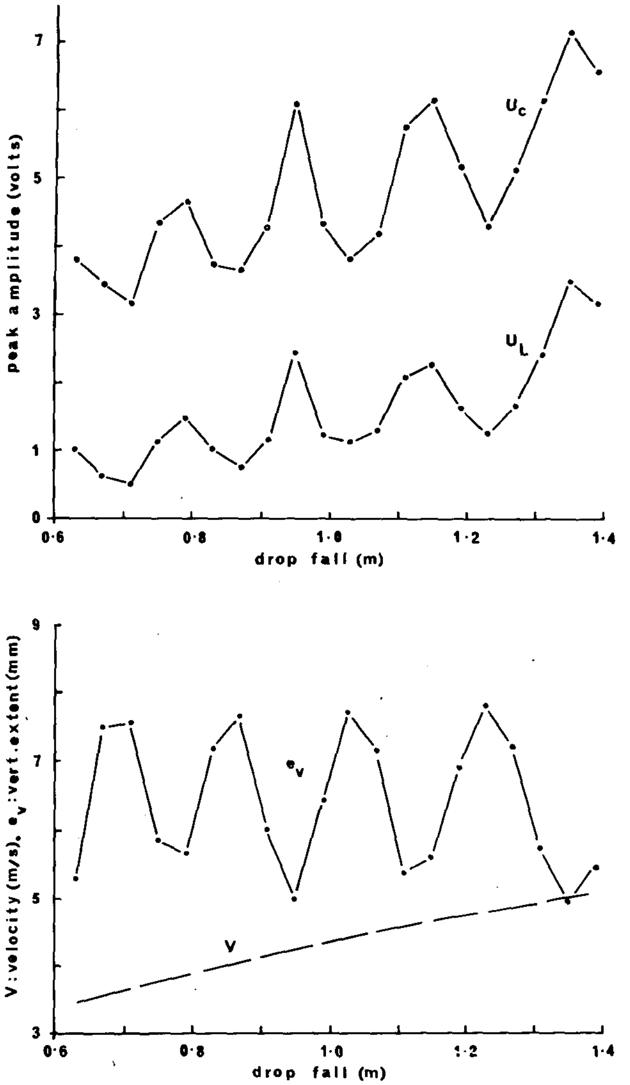

FIG. 3. Response of the disdrometer (a) to variations in drop velocity and (b) to drop vertical extent for approximately 6 mm drops falling between 0.63 and 1.39 m: U_L=transducer output, U_c=processed output.

The discontinuity in the response of the transducer associated with drop velocity does not enable the effects of variations in drop shape and drop velocity on the measurement of raindrop size to be predicted directly from observations at low impact velocities. However, it is probable that variations in the shape and velocity of drops do influence the measurement of raindrop size in a way that is not accounted for by the total vertical momentum of each drop. Considering that the relationship between U_L and $D^{3.7}$ appears to describe approximately the response of the transducer under conditions of terminal drop velocity in still air, the mechanical power expended during drop impact might be more satisfactory than total momentum in describing the response of the transducer to raindrop impact. The mechanical power [equivalent to the average rate of change of kinetic energy, $MV^2\,(2t)^{-1}$] under terminal velocity conditions also shows an approximate relationship with $D^{3.7}$. The processed output (U_c) might then be expected to vary with $V^{1.17}$ and $e_v^{-0.39}$. Under such circumstances, 1% changes in V and e_v for a given drop size could produce errors of 0.80% and 0.27%, respectively, in the measurement of drop size when drops are travelling near their terminal velocities. If the response of the transducer is not wholly a function of the vertical momentum of the drop, variations in factors such as raindrop velocity (Shupatsky, 1959; Disrud *et al.*, 1969) and raindrop shape (Blanchard, 1948; Disrud *et al.*, 1969) generated by air movements might produce unacceptable errors in the measurement of drop size by the disdrometer under some rainfall conditions.

6. Conclusions

The experiments reported here suggest that the response of the Joss-Waldvogel rainfall disdrometer is influenced not only by the size and velocity of the impacting drops but also by drop shape. The results also suggest that a discontinuity exists in the response of the transducer between drops travelling at terminal velocity and drop travelling at an appreciably lower velocity. This discontinuity appears to be associated with the time taken for the drop to collapse.

Under conditions where drop shape influences peak amplitude, the response of the transducer is not described adequately by the vertical momentum of the drop. Consequently, variations in factors such as raindrop velocity and raindrop shape generated by air movements might produce unacceptable errors in the measurement of raindrop size by the disdrometer under some rainfall conditions.

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