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Water drop collision-induced oscillations from wind-tunnel experiments

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Contributions

M.T. conducted joint data analyses and wrote the main part of the paper. M.S. conducted the wind-tunnel experiments and performed the main data analyses and contributed to the writing of the paper.

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Abstract

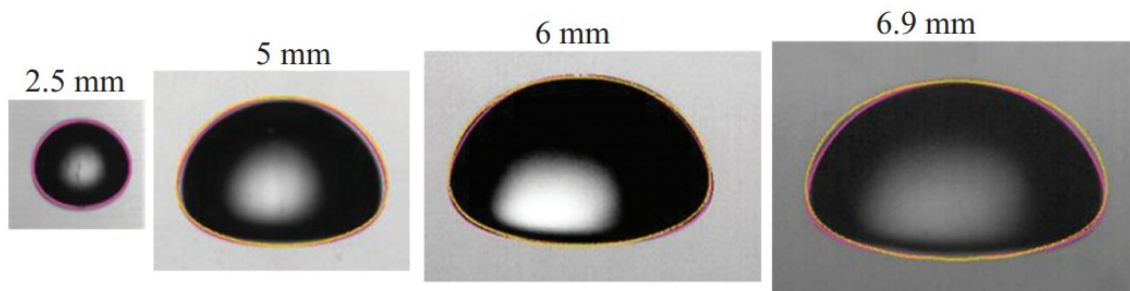
This study investigates collision-induced drop oscillations using an advanced vertical wind-tunnel facility, 40 collision events were recorded with a high-speed digital video camera. Some resulted in drop coalescence, and the others in non-coalescence collisions. The sizes of the colliding drop pairs were chosen to be typical for real-atmospheric conditions, i.e. for the collector drops, they were in the 2.4 - 3 mm drop diameter range, while the small droplets had sizes of ~500 microns. In each case, the collector drop was freely-floated inside the wind-tunnel until a small droplet (injected from below) coming from the upstream

22 side of the larger drop collided with it. Data analysis shows that the larger drop, upon collision, undergoes
23 mixed-mode oscillations with dramatically increased in oscillation amplitudes. The perturbation caused by
24 the collision lasts for over several hundred milliseconds before effectively getting damped out and reverting
25 to its usual axi-symmetric low amplitude oscillation mode. Polarimetric weather radar differential
26 reflectivities for single particles were estimated at C-band using 3D reconstructed shapes (from another
27 instrument) during intense storms and compared with those using equilibrium shapes. Results show
28 noticeable differences during a category-1 Hurricane event (where drop collision probability will be high).

Introduction

Knowledge of raindrop shapes and drop oscillations is of central importance for deriving retrieval algorithms for drop size distribution (DSD) parameters and rain rate as well as for attenuation-correction at higher frequencies (e.g. C-, X-, Ku and Ka-bands) from polarimetric radar (e.g., [1], [2], [3], [4], and references contained therein). Earlier work using 2D video disdrometer (2DVD; [5], [6]), measurements of drop shapes [7] for drop diameters larger than 2 mm had led to the derivation of the ‘most-probable’ (or most-likely) shapes as well as the shape variations due to drop oscillations. The 2DVD-based shapes had also been shown to be in good agreement with wind-tunnel measurements for $D > 2$ mm [8]. Moreover, a thorough examination of the 2DVD camera data in natural rain from several locations had shown that in the vast majority of cases, the most probable shapes conform to those arising primarily from the axisymmetric (2,0) oscillation mode [9]. The other two oscillation modes, namely, transverse mode (2,1) and horizontal mode (2,2), did not seem to be contributing to the probable shapes, at least under calm wind conditions. Fig. 1 shows the most probable/likely shapes of drops with equivalent diameters of 2.5, 5, 6 and 6.9 mm derived from the 2DVD measurements compared with the equilibrium shapes from the wind-tunnel measurements and the equilibrium shapes from the Beard-Chuang (B-C) model [10].

Fig. 1: Photos of drops in equilibrium state from wind tunnel measurements, and comparisons with the most likely shapes from 2DVD measurements shown in pink and the Beard and Chuang equilibrium shape model [10] shown in yellow. The drop diameters are shown above each panel. Taken from [8].



There have been several exceptions, however. For example, Manić et al., [11] inferred that the occurrence of mixed-mode oscillations is likely within an intense organized line convection using two collocated 2DVD's and a C-band polarimetric radar. The inference was based on the fact that a significant fraction of the larger drops (e.g. drop diameters of 3 mm and larger) from the 2DVD measurements did not possess rotational symmetry when the line convection had passed over the 2DVD location. Polarimetric radar information such as the co-polar correlation coefficient, ρ_{hv} , had also supported the notion of mixed mode oscillations because of their lower values than those expected from equilibrium shapes during the passage of the line.

Beard and Johnson [12] have examined the shapes and the differential reflectivity (Z_{dr}) using a (drop) collisional probability model in heavy rain showers and found that an appreciable fraction of large raindrops (with equi-volume diameter $\gtrsim 3$ mm) undergo large amplitude oscillations which in turn can cause increasingly significant deviations in Z_{dr} from those calculated using the equilibrium shape model.

To investigate collision-induced drop oscillations, several experiments were conducted using a vertical wind-tunnel facility. Here we describe the experiments, and present the results, followed by a discussion, particularly in conjunction with the 2DVD measurements in natural rain.

Wind-tunnel measurements

The advanced vertical wind tunnel facility of the Johannes Gutenberg University, Mainz, Germany, [13], [14], (constructed based on the wind tunnel at the University of California, Los Angeles, USA, [15]) was used to conduct the collision experiments. Water drops were freely floated/suspended at their corresponding terminal velocity for a given size in an airstream (laminar flow) along the vertical. Details of the facility and related experiments conducted previously can be seen in [8]. During the collision experiments wind speed, temperature, and humidity of the tunnel air were controlled and continuously recorded. In the setup used for the experiments, it was possible to have wind-tunnel speeds from 1 to 12 m s⁻¹ so that water drops of all sizes between 100 microns and 8 mm could be investigated. Note that drop shapes and terminal

velocities are not expected to change appreciably with moderate temperature and pressure differences (see [16]).

A high-speed digital video camera capable of recording 1000 or 2000 images per second was used to capture the drop images. At its maximum resolution (1280 by 1024 pixels) it was possible to have 1000 frames per second and at half the resolution (1280 by 512) 2000 frames per second. An in-house computer program was used for the image processing. Characteristics of the recorded drop images and their time variations were used to determine the various components of the oscillation frequencies. Details of the analysis procedures can be seen in [8] and the estimation of errors can be seen, for example, in [17].

Analysis methods

A novel method was developed to identify and distinguish the axisymmetric (2,0), transverse (2,1) and horizontal (2,2) oscillation modes of freely floating raindrops. First the recorded grey level images of the oscillating raindrops were transformed to black-and-white (BW) images. Afterwards, the individual images were further analysed with the following three algorithms in order to identify the existence of the (2,0), (2,1) and (2,2) oscillation modes.

The apparent axis ratios of the drops were determined by calculating the ratio of the largest vertical and horizontal chord of the drop. The temporal variation of the axis ratio, i.e. the continuously varying oblate-prolate deformation, is primarily caused by the axisymmetric (2,0) oscillation mode. However, the other two modes also contribute to the axis ratio variation, so that in the temporal variation of the axis ratio beating can be observed. As the other two modes normally correspond to lower amplitudes and frequencies, the (2,0) mode is the primary carrier mode in the beating. Its frequency can be identified as the highest peak of the frequency spectrum of the axis ratio variation.

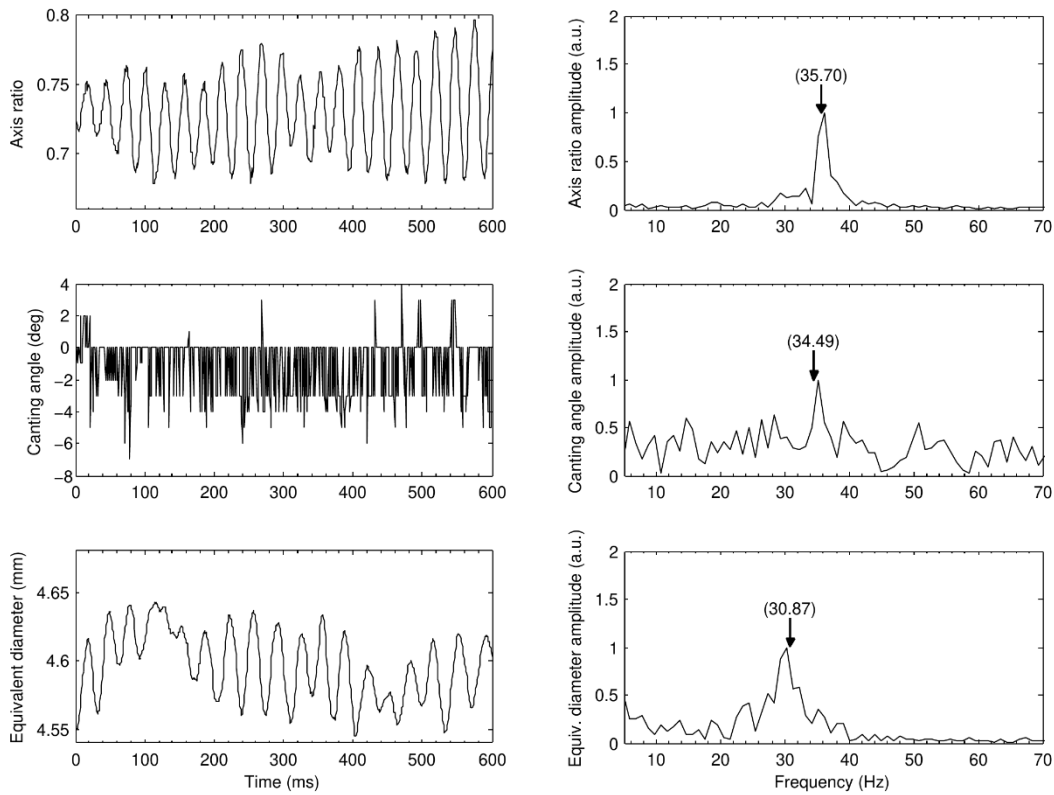
The frequency of the (2,1) transverse oscillation mode can eventually also be determined from the frequency analysis of the axis ratio variation. This procedure requires, however, that the frequency resolution of the measurement is high enough to be able to distinguish between the (2,0) and (2,1) frequencies. In other words, the observation time should exceed the time period of beating resulted by the oscillation modes.

This requirement can be fulfilled if the drops are levitating in the field of view of the camera for time periods of a few seconds which is essentially rare. If a drop would oscillate exclusively in the (2,1) mode (which has never been observed in our wind tunnel measurements), its shape would be changed in a way like the drop as a whole would be canted around a horizontal axis. The maximum of this apparent canting is only a few degrees. The canting angle variations of the oscillating drops in the present experiments were determined as follows: First, a horizontally oriented rectangle fitted to the drop image, and the axis ratio of the rectangle was calculated. Next, the BW image was rotated by 1° , and the former process was repeated. Rotating the BW image to 180° in 1° steps and calculating the corresponding axis ratios of the best-fit rectangles, the orientation of the one with the minimum axis ratio gave the “apparent canting angle” of the drop. Repeating this algorithm for all images, the “apparent canting angle” variation of the drop during oscillation was determined. The frequency of the (2,1) mode was obtained by frequency analysing the temporal variation of the “apparent canting angle”.

The frequency of the (2,2) horizontal mode of an oscillating raindrop was determined from the temporal variation of its projected area. First the volume equivalent diameters were determined from the BW images using the integration method as follows. In the recorded digital images, the drops were composed of 1-pixel thick horizontal slices. Hence, the volume of the drop could be determined as the sum of the volumes of discs with a thickness of one pixel and with a diameter equal to the width of one slice. Since a drop oscillating in the (2,2) mode is not rotationally symmetric around the vertical axis at any phase, the volume calculated from the side projected area of the drop, i.e. not the true drop volume but a pseudo volume assuming vertical axis-symmetry, is not constant during the oscillation. Hence, a periodic change in the calculated drop volume could be observed. The other fundamental oscillation modes, i.e. the (2,0) and the (2,1) do not contribute to the variation of the calculated drop diameter, so that the frequency of the (2,2) mode could exclusively be determined from the frequency analysis of the periodic change of the calculated drop volume.

Figure 2 shows results of the above-described algorithms for identifying the different oscillation modes in case of a 4.6 mm diameter water drop freely floating in the vertical wind tunnel. The time series and the corresponding frequency spectra of the axis ratio (a and b), the canting angle (c and d), and the volume-equivalent drop diameter (e and f) are presented. The arrows and the numbers are marking the frequencies computed using the formulas given in [18].

Fig. 2: Variation of axis ratio, ‘apparent’ tilt angle and the ‘apparent’ volume with time (left panels) and their frequency components.



Collision experiments

More than 200 collision experiments were carried in the Mainz vertical wind tunnel, from which 130 were recorded with a high-speed digital video camera. Many of the recorded collision events had to be abandoned because the drops were not in the focal plane of the camera. Finally, we were able to analyse around 40

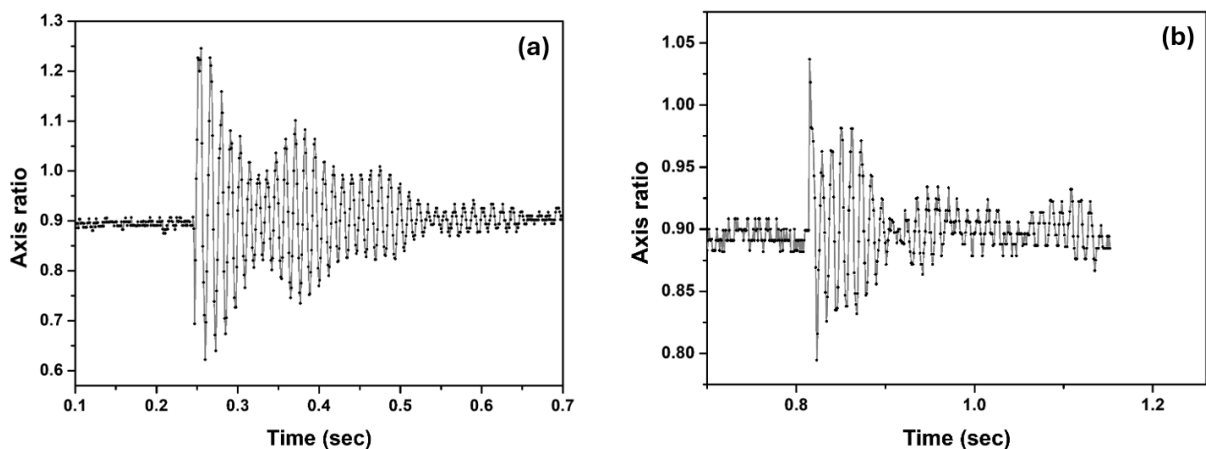
collision events; among them were 27 which ended with coalescence and the remaining with non-coalescence collision.

The sizes of the colliding drop pairs were chosen to be typical for real-atmospheric conditions, i.e. for the collector drops, they were in the 2.4 mm - 3 mm drop diameter range, while the small droplets had sizes of around 500 microns. In each case, the collector drop was freely-floated inside the wind-tunnel until a small droplet (injected from below) coming from the upstream side of the larger drop collided with it.

A typical example of the axis ratio variation of a drop during a collision-coalescence process is presented in Figure 3a. The collector drop was freely floating in the wind tunnel until a small droplet coming from the upstream side of the drop collided with it at 250 milliseconds. The time moment of the collision is coupled with a large axis ratio variation. The multimode oscillation of the drops is obvious from the beating in the time series. Around 450 milliseconds after collision the perturbation caused by the collision is effectively damped out and the drop is oscillating with the same amplitude as before collision.

Figure 3b represents the time evolution of the axis ratio during a collision of two drops where no coalescence occurred. In this case the axis ratio variation is not so pronounced as in the former case but beating can again be recognized.

Fig. 3: Axis ratio variation with time before, during and after collision.



Data analyses

The frequency spectra of the oscillations of drops before (left panels) and after the collision processes (right panels) are shown in Figure 4. The following pre-collision and post-collision periods:

I. Pre-collision period is the whole-time interval before the collision when the large drop floated in the view of the camera. Analysing this time interval was important for characterizing the large colliding drop before collision in regard to its size, active oscillation modes, frequencies and axis ratio. Since the small colliding drops used in the experiments with diameters between 0.33 and 0.67 mm are not suspected to influence significantly the air stream behind them, this time period was actually corresponding to a freely floating drop.

II. Post-collision period has three parts:

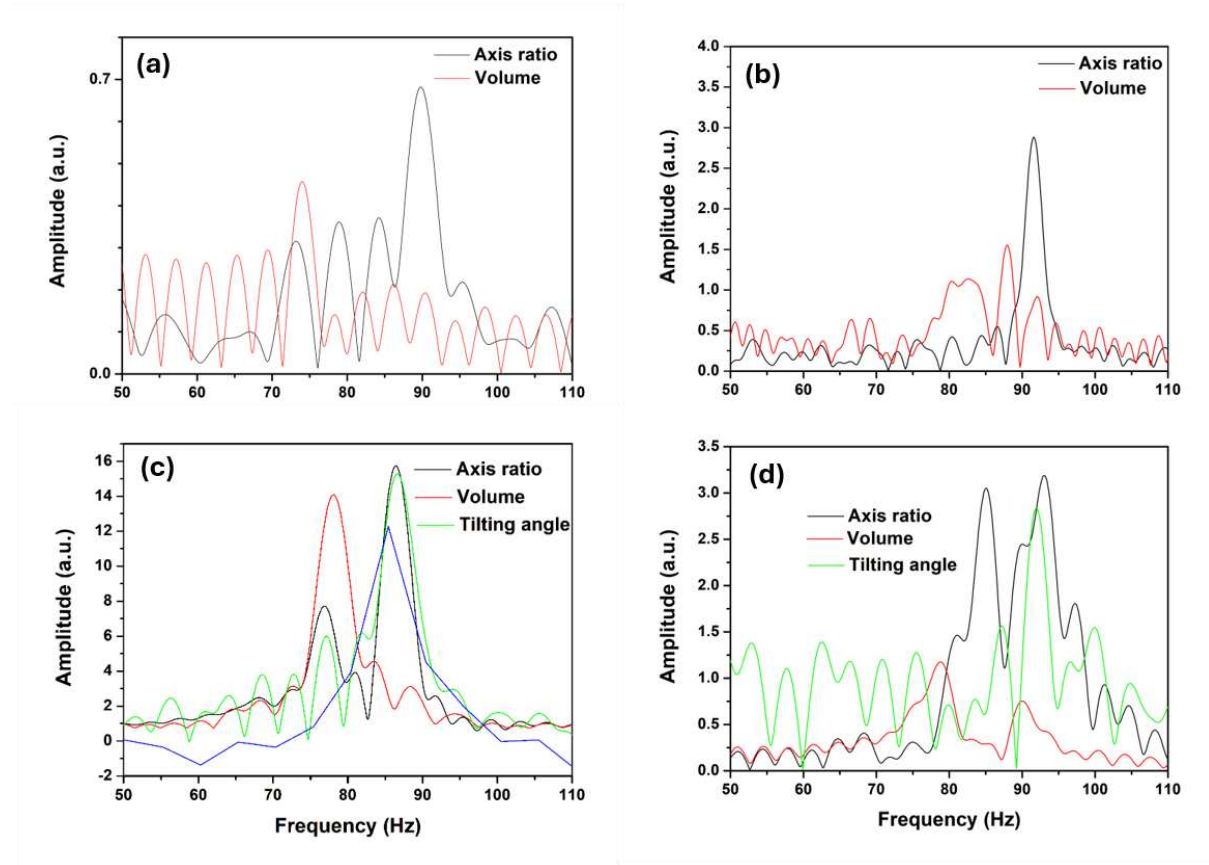
- a) Instantaneous - after collision the large drop is significantly deformed. No oscillation modes are identifiable. After this very short transition time (typically a few milliseconds) the transverse (2,1) mode is the strongest developed oscillation mode and the shape of the largest drop after collision is determined primarily by this mode.
- b) The axisymmetric (2,0) mode is getting dominant, but in most of the cases the (2,1) mode still exists. The shape of the drop is qualitatively similar to that in time period I. The amplitude of the shape variation attenuates.
- c) The amplitude of the axis ratio variation decays down to its value in time period I.

From Figure 4, we see that in both the coalescing and non-coalescing cases, the (2,0) mode is the most pronounced oscillation mode before collision (plotted as black line). The (2,2) mode (red line, calculated from the virtual volume variation as described above) is also active in both cases though its amplitude is very low. The (2,1) mode was not present before collision.

After collision the (2,1) mode, which is shown as the green line and calculated from the apparent tilting angle of the drop, becomes active, and in fact it becomes the dominating oscillation mode, i.e. the mode which determines the axis ratio variation. The apparent axis ratio after collision was increased by 0.9% in

case of coalescence and by 0.44% in cases of breakup, as a consequence of the dominance of the (2,1) mode. Furthermore, in the coalescing case the amplitude of the (2,2) mode is also significantly large and appears in the frequency spectrum of the axis ratio variation, and seemingly in the spectrum of the tilting angle variation. The small deviation of the peak frequencies in the (2,0) and (2,1) spectra from the peak of the (2,2) mode (at 78 Hz) is most probably a result of the applied frequency analysis (discrete time Fourier-transformation).

Fig. 4: Oscillation amplitudes before (panels (a) and (b)) and after collisions (panels (c) and (d)) for coalescence (panels (a) and (c)) and for non-coalescence (panels (b) and (d)) cases.



The oscillation modes in the non-coalescing case are not so pronounced as in the coalescing case. This results in noisier frequency spectra. In spite of this, the existence of the (2,0), (2,1) and (2,2) modes is obvious, though the origin of the large secondary peaks appearing in the spectra has to be further analysed.

Discussion

Data analysis clearly shows that the larger drop - upon collision - undergoes mixed-mode oscillations, with (2,1) and (2,2) modes dramatically increasing in oscillation amplitudes. The perturbation caused by the collision is seen to last for over several hundred milliseconds before effectively getting damped out and reverting to its usual (2,0) oscillation mode as the dominant mode. Typical time constants for the decay after collision were measured to be between 0.145 and 0.2 s for coalescence, and between 0.3 and 0.4 s for breakup.

The coalescence cases show somewhat more pronounced mixed mode oscillations compared with the non-coalescence cases. Note, the decay time constant is considerably larger than those used in the collision model given in [19].

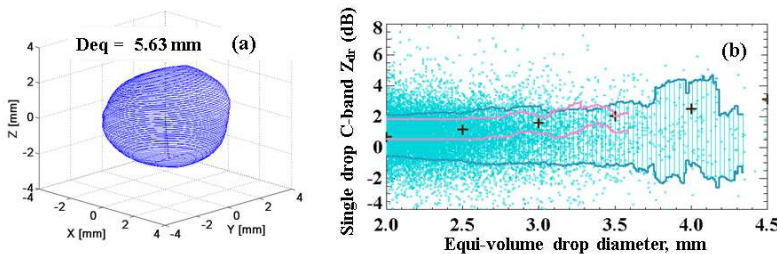
The fact that the damping time constant for the mixed mode oscillations to decay is of the order of several hundred milliseconds must mean that if in real-atmospheric conditions the collision frequency has similar time constant, then sustained drop collisions can cause significant fraction of the drops at any instant in time to be in mixed mode oscillation state (and not have rotational axis symmetry). Referring back to the event analysed in [11] using 2DVD data and the C-band ARMOR observations in Huntsville, Alabama, the most probable explanation is that drops are undergoing mixed mode oscillations within the line convection region, and that these are probably due to drop collisions, e.g. 3 mm with tiny drops (probable scenario according to literature). If such collisions occur typically at a rate of 0.2 s^{-1} (for 3 mm drops in a 55 dBZ reflectivity rain column, from [20]), then it is conceivable that collisions can sustain drop oscillations (against viscous dissipation) for a significant fraction of the 3 mm drops. This has also been hypothesized in [21] from airborne measurements of co-polar and cross-polar backscatter from tropical storms.

For the event discussed in [11], high rain intensity confined within the narrow line convection would significantly increase the likelihood of drop collisions. Moreover, in the case of rain clustering (see for example [22]) which may well be the case within the embedded line convection in that event, drop collision rates can increase by a significant factor [23]. The methodology described in [24] can be used to assess the

importance of collisional-forcing of drop oscillations relative to intrinsic aerodynamic mechanisms (which for larger drops is dominated by the axisymmetric mode). The main input to the methodology is the drop size distribution, and in our case, the 1-minute DSD measurements from the 2DVD can be utilized. However, the accuracy of small drops' concentration needs to be improved, which is possible by using data from one single camera alone for drop diameters below 0.5 mm. This will be attempted in the future.

An example of a reconstructed drop using contoured images from 2DVD measurements during a category-1 Hurricane is shown in panel (a) of Figure 5. Clearly, the shape is very different from that of the equilibrium model and has no rotational symmetry. Recent studies have shown such deviations can occur for events associated with significant turbulence also. The reconstructed drops have been used to examine their effect on radar differential reflectivity, Z_{dr} , using a commercially available software package (see sections (4) and (5) in [25] for example). Figure 5(b) shows the individual drop Z_{dr} at C-band for the reconstructed drops from the abovementioned Hurricane. Significant scatter is observed compared with those using the equilibrium shapes. The mean $\pm$ standard deviation are also included. Overall, the Z_{dr} values tend to be lower than those of the equilibrium shapes. It is likely that either collision induced and/or turbulence-induced drop oscillations were occurring for a significant percentage of the drops. Also shown is the range of Z_{dr} values calculated for reconstructed drop shapes during a tropical depression (with less turbulence). These are much closer to those of the equilibrium shapes.

Fig. 5: (a) A reconstructed drop from 2DVD measurements during a Hurricane event; (b) Computed Z_{dr} of individual drops at C-band (light blue points), their mean $\pm$ standard deviation (light blue lines) and for a tropical storm event (light pink).



Summary

Collision-induced drop oscillations have been conducted using an advanced vertical wind-tunnel facility. More than 130 cases were recorded with a high-speed digital video camera. Many of the recorded collision events had to be abandoned because the drops were not in the focal plane of the camera, however, it was possible to analyse around 40 collision events. Among these were 27 which resulted in drop coalescence, and the remaining in non-coalescence collision. The sizes of the colliding drop pairs were chosen to be typical for real-atmospheric conditions, i.e. for the collector drops, they were in the 2.4 mm - 3 mm drop diameter range, while the small droplets had sizes of around 500 microns.

Data analysis clearly shows that the larger drop - upon collision - undergoes mixed-mode oscillations, with (2,1) and (2,2) modes dramatically increasing in oscillation amplitudes. The perturbation caused by the collision lasts for over several hundred milliseconds before effectively getting damped out and reverting to its usual (2,0) oscillation mode as the dominant mode. The coalescence cases show somewhat more pronounced mixed mode oscillations compared with the non-coalescence cases.

These results have been discussed in conjunction with the previously reported 2DVD measurements during a widespread rain event with a narrow, embedded, line convection, where the 2DVD measurements had shown a lack of rotational symmetry axis for a significant fraction of moderate-to-large drops during the passage of the line convection. In view of the wind-tunnel experiment results, a likely explanation is that sustained drop collisions within the narrow convection line cause a significant fraction of the drops to be in mixed mode oscillations at any given instant in time.

An additional factor which needs to be considered is turbulence intensity, for example in tropical storms and hurricanes. Analyses of several such events have shown that in regions with high turbulence intensity the percentage of drops deviating from the equilibrium shapes increases significantly, see for example [26]. As part of our ongoing investigations, we plan to simulate such conditions within the wind-tunnel and investigate the effect of turbulence on the oscillation amplitudes of the three main modes.

Data and Code Availability

The data set used for generating the figures is available under <https://zenodo.org/uploads/23400085> using login. The raw measurement data will be provided upon request to the authors.

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Ethics declarations

Competing interests

None.