Annual Report 2021 JMBC – Research Highlight

This highlight refers to the PhD Thesis by Jesse Will (2021)

Wake-induced dynamics of buoyancy-driven and anisotropic particles

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One of the classical problems in fluid dynamics is the motion of an unrestrained body rising (bubbles in your favourite beverage) or settling/falling (rain, hail, or the big rock you threw in a lake) in a fluid otherwise at rest under the effect of its own effective **buoyancy**. Investigations of this problem date back at least as far as Leonardo da Vinci who documented, and questioned the reason for, the non-vertical paths of small bubbles rising in water. Later on, Sir Isaac Newton dropped solid spheres and hog's bladders inside St. Paul's cathedral in London. Both found that, even when correcting for buoyancy, the particles do not always experience the same aerodynamic or hydrodynamic **drag**. Surprisingly, this deceivably simple system can behave in remarkably complex ways. For large enough Reynolds numbers, the ratio of inertial to viscous forces, the flow around the body will begin to separate resulting in periodic shedding of vortices akin to the famous von Kármán vortex street. For these cases, the periodic forcing by the flow and the particle rotation and translation will interact with each other; the particle motion affecting the flow and vice versa resulting in complex and sometimes chaotic particle motion. This coupling makes the system extremely sensitivity to both particle and fluid properties. For this reason it is, to this day, still impossible to predict the dynamics and kinematics of freely rising and settling bodies. However, understanding the fundamental origins and nature of the differences in particle drag and the observed paths is a key question in many fields of research such as meteorology, sedimentology, as well as in many practical, industrial applications where, particle induced mixing is present. Therefore, in the present work we focus on identifying key parameters or characteristics of particles by means of controlled experiments that can be used to model and predict their behaviour. We specifically focus on **body rotation,** which has been a largely overlooked but nevertheless important parameter, as we find.

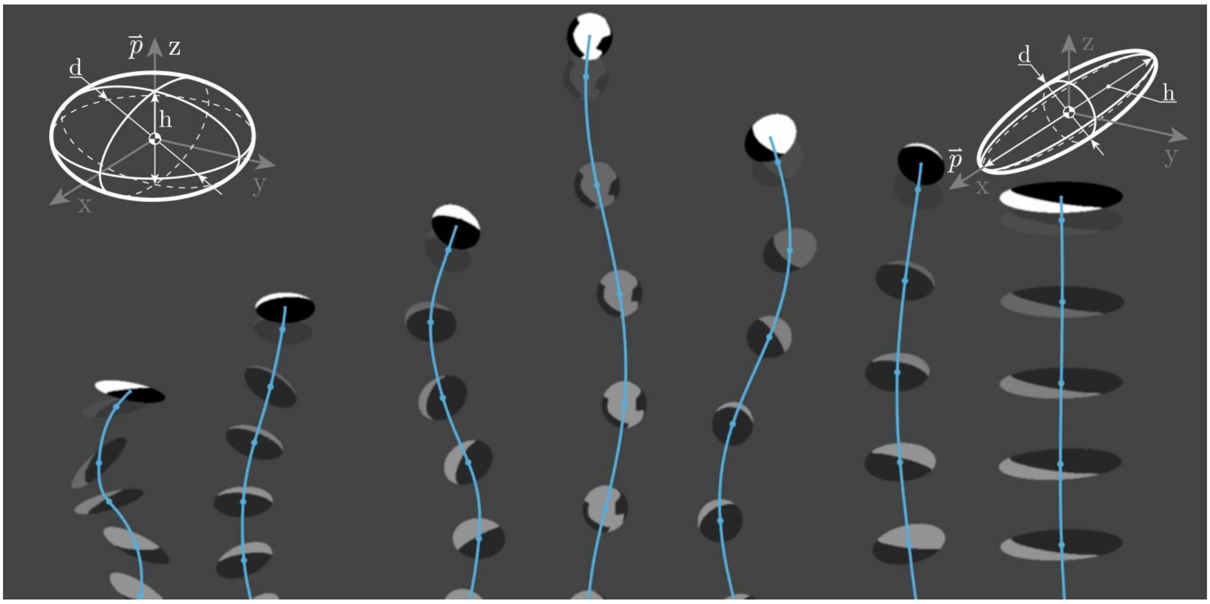

Figure 1: Seven rising particles with different geometries but identical volume and density, all released at the same moment in time. In the centre we observe the fastest (lowest drag): a rising sphere, to its left are 3 oblate (disk shaped) ellipsoids with the furthest left being the most anisotropic and to its right 3 prolate (needle shaped) ellipsoids. The black and white pattern on these bodies is used for rotational tracking.

Effects of geometry

A very fundamental but from a fluid dynamic perspective crucially important distinction is that between a sphere (isotropic) and any shape besides that (anisotropic). We experimentally investigated the effect of **geometry** by studying ellipsoids ranging from oblate (disk shaped) to prolate (needle shaped) (Will et al., 2021). The reason for this distinction is rotation and the driving thereof. For a sphere, any body rotation is induced by the thin layer of fluid close to the surface **shearing** the surface resulting in a torque and rotation, however for any other shape the fluid will also ‘push’ against the surface resulting in a **pressure** induced torque. We found that for anisotropic bodies the vortex shedding, which results in significant pressure asymmetries on the body’s surface, will in general result in large torques resulting in a more rotationally active particle. More importantly, even a small amount of anisotropy was enough to induce a tumbling mode, where the body continuously flips (for visualization particle motion see supplementary videos to Will et al., 2021) accompanied by a significant increase in drag compared to the sphere. Surprisingly, this flipping behaviour does not persist as anisotropy increases, in fact for the explored parameter range six unique regimes of motion were uncovered. A number of these regimes are visualised in Figure 1, where path and orientation are shown from left-to-right for 3 oblate, one spherical, and 3 prolate geometries of identical volume and weight which are released simultaneously. For oblate bodies the motion becomes extremely regular and periodic, this is accompanied by a strong increase in drag. For prolate bodies on the other hand the two cross-flow dimensions result in more chaotic and surprising behaviour. In general, the drag tends to increase the further the geometry deviates from spherical, however for some prolate particles the trend was the opposite due to a reduction in body rotation and the absence of path-oscillation under certain conditions, see the right most particle in Figure 1. The differences between oblate and prolate clearly show that a simple measure of ‘sphericity’ as often employed in literature and modelling can never be sufficient to predict behaviour in any sensible way.

Effects of moment of inertia

Besides changing the shape of a body, it is also possible that there is an **internal inhomogeneity**, a small pocket of air inside the material or a body made up of two or more materials. This can result in changes in the **rotational inertia** of the body without affecting what the flow ‘sees’. In the past, many experiments with rising bodies used hollow shells; not too dissimilar from a ping-pong ball. It was recently suggested that resulting changes in the rotational inertia could explain the large variation of the measured drag coefficients in literature (see black dots in Figure 2d). To test this, we systematically varied the moment of inertia for spherical bodies of several particle-to-fluid density ratios (Will and Krug, 2021a,b). The idea again relies on body rotation, the coupling to the particle path, and vortex shedding being important aspects of the measured drag coefficient. While we did observe that the mean rotation rate reduces for increased inertia and this did result in a gradual increase in the drag no variations were observed to the extend as those found in literature, thus rotational inertia alone cannot explain these aberrant findings. The reason for this is that, although the body responds more strongly to the fluid induced torques when the inertia is lower, it still only gets rotated by **shearing** forces on the particle shell, which at higher Reynolds numbers are relatively weak compared to the pressure forces that rotate the previously described anisotropic bodies. We did however show the direct correlation between moment of inertia and drag and amplitude of the path oscillations of rising particles which is a valuable fundamental insight in the coupled dynamics of rising spheres as well as in interpreting previous work.

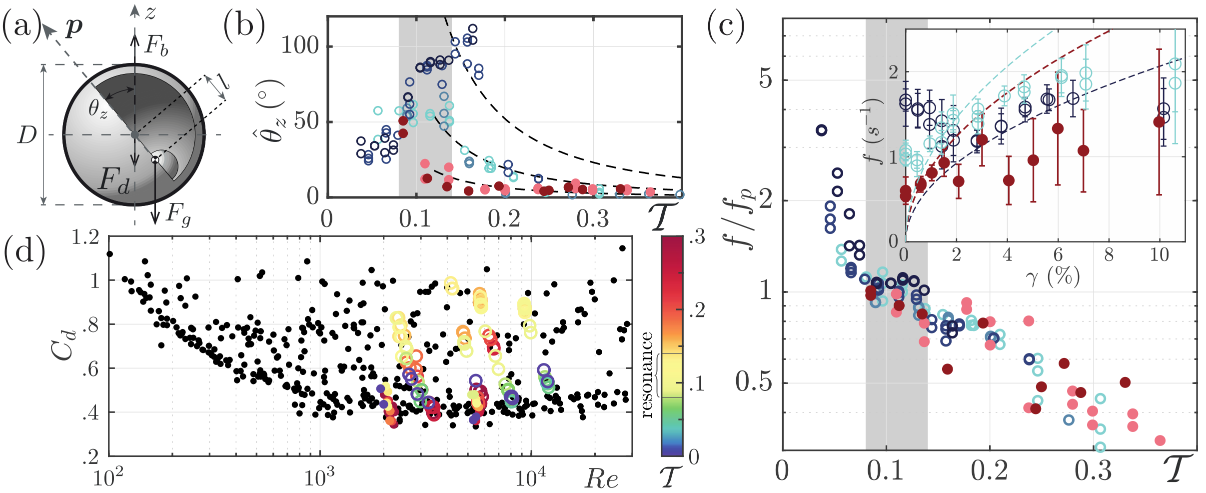

Figure 2: (a) Schematic of a sphere used in the experiments, by moving an internal metal ball radially outwards inside the shell the COM is displaced from the geometric centre. (b) Amplitude of the rotational oscillations of the sphere as a function of the dimensionless COM offset. (c) Inset: Frequency of the path oscillations vs. COM offset, the dashed lines show the pendulum frequency of the system. Main panel: frequency ratio vs. dimensionless offset. (d) Drag coefficient vs. Reynolds number, the coloured markers indicate the present results, compared to the spread in literature (black dots).

Effects of centre of mass offset

Another, completely unexplored, way to affect the internal mass distribution is by changing the location of the **centre of mass** (COM) with respect to the geometric centre, see Figure 2a. This does not affect the geometry that the flow encounters. Due to the offset, however, there is stronger coupling between the translational and rotational dynamics. In Figure 2b, where we plot the rotational amplitude versus the dimensionless offset ($\mathcal{T}$) we find that the rotational amplitude increases for a subset of offsets, the so-called **resonance** phenomenon. To explain this behaviour, we considered the rotational equation of motion as a driven harmonic oscillator with a pendulum frequency (f_p). When the driving (vortex shedding/path oscillation) frequency (f) is equal to this pendulum frequency, as is shown in Figure 2c, then the system is in resonance and we observe a maximum enhancement of rotational dynamics as well as of the drag. The change of the resonance frequency with COM offset is shown for different particle densities by the coloured dashed lines in the inset of Figure 2c, for a subset of offsets the observed path oscillation frequency is found to ‘lock-in’ with this pendulum frequency and the as a consequence the frequency ratio in the main panel of Figure 2c equals one. This region is indicated by the grey area in the figure. Note, that this is indeed the range where the rotational amplitude is at its peak in Figure 2b. Notably, this resonance behaviour only works for rising particles due to an asymmetry in the equations of motion, this can be seen in Figure 2b where the blue markers indicate rising and red settling particles and the rotational amplitude is only increased for the blue cases. Finally, in Figure 2d we show the drag coefficient versus the Reynolds number and compare these results to those from literature, the black markers. The range of drag coefficients observed with COM offset appears to match that observed in literature and offers a plausible explanation for previous findings that do not match more recent attempts to reproduce them; a small offset might have been present during the original experiment that might have gone unnoticed. The effects of offset on rising bodies are very significant, causing drag to more than double for small offsets of a couple of percent of the radius making this parameter one that should be carefully considered.

Conclusion

The dynamics and kinematics of rising and settling particles are complex, many parameters affect what will happen when you throw that rock into a pond. The shape of the rock will matter a lot, if it is perfectly ellipsoidal based on this work you can more accurately predict what will happen but if it deviates a little, things might already begin to vary. If the rock is hollow, we have learned that this will have marginal effect, rotations will be enhanced a little and so with the path oscillations and drag, but no significant regime changes are expected. If the centre of mass of the rock is different than its geometric centre rotational resonance with the vortex shedding might occur greatly increasing the rotational amplitude and drag, but this is only if the rock is rising instead of sinking!

References

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