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Analysis of motion of solid hydrogen tracer particles in oscillating superfluid flows.

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Abstract. We have developed a relatively simple cryostat which allows us to image turbulent flows in superfluid helium at temperatures below 2 K, using frozen H₂ particles. We analyze the statistics of the velocities of these solid tracers, which follow the turbulent flow generated by oscillating bodies. We have also studied one of the oscillators working in air at room temperature, and traced the flow with solid talcum particles for comparison. Images were recorded by a digital camera at 240 frames per second, while frequencies of the oscillators are between 20 to 45 Hz. The flow is characterized by a modified Reynolds number Re_δ based on the viscous penetration depth δ . Software in a dedicated particle tracking velocimetry code allows us to compute the trajectories and velocities of tens of thousands of particles. We have obtained the number of particles for equally spaced intervals of the velocity modulus. For the oscillators in the superfluid, the probability of finding particles at higher velocities has an exponential decay. Within our resolution the statistics in the superfluid for oscillating objects with sharp borders is largely independent of Re_δ , while the logarithmic decay at low velocities seems faster than for high velocities for rounded objects. On the other hand, for data taken in air the result is closer to a classical Gaussian distribution of velocities.

1. Introduction

Quantum Turbulence studies have a long history[1, 2] and the subject is far from being exhausted [3]. Similarities and differences have been found between classical and quantum turbulence giving rise to a continuing interest in the subject[4–9]. New experimental techniques for flow visualization[10–12] have been developed and adapted to quantum fluids.

Micron and sub-micron solid particles can trace in detail the dynamics of quantum flows. They have been used to image situations of possible dissipation mechanisms such as reconnections and Kelvin waves[13]. Other experiments image thermal counterflow and flow in channels[11, 12, 14–17]. Unsteady and oscillatory flows that have a classical analogue can also be studied by this technique and Vinen[9] has pointed out that tracer imaging of oscillatory flows in Quantum turbulence could provide valuable information.

We have been able to film H₂ solid particles flowing around oscillating objects of different shapes, which generate turbulence when submerged in superfluid helium. By analyzing video images of the particle motion, we can obtain the statistics of the particle velocities and we report the results in the present paper.



2. Experimental Details

The apparatus has been described in more detail in a previous publication[18], and here we give a brief description of the main points. We used a glass dewar with a window to allow filming from outside, images were obtained with a camera[19] at a rate of 240 frames per second. Experiments were performed between 1.7 and 2 K. Dissipation in the superfluid component in this range of temperatures is mainly produced by mutual friction between the quantized vortices and normal fluid[20].

The oscillators studied consist of a body attached to a flexible stem which moves in flexure producing a translation of the rigid body. Different shapes were tried. The first one consisted of a sphere of radius 4.5 mm with a stem in the shape of a beam of BeCu alloy 5 mm wide and 0.05 mm thick. As the wide beam modified the flow substantially, we made a second experiment with the 5 mm wide laminar beam only. A third oscillator consisting of a sphere of 5 mm radius and a cylindrical wire stem of 0.7 mm radius was also used in order to study the spherical geometry with a smaller perturbation. For comparison, we took videos of this last oscillator in air at room temperature using solid talcum particles as tracers.

Solid particles in helium are formed when a hydrogen-helium gas mixture is injected into the liquid following the procedure outlined by Bewley and co-authors[21–23]. We filmed each injection to detect the movement of particles in the fluid. We use a Hydrogen-Helium mixture with a 1/50 ratio at a pressure of 500 Torr, around a hundred cubic centimeters of gas are injected each time. We wait until the perturbations caused by the injection die out before using the video footage of particle motion.

To illuminate the tracer particles we used a green laser beam fed into the cryostat through an optical fibre. The frozen H₂ particles are not expected to absorb significant energy in the visible[24]. The illumination forms a three dimensional cone of light, which also partly diffuses in the oscillators. Other reflections were minimized by using a black screen in the background.

The time interval is 4.17 ms between frames and we use this quantity as our time reference to calculate velocities. The distances in the images are calibrated with respect to the measured dimensions of the optical fiber. The particles analyzed here occupy one or just a few pixels in the image obtained. The size of a pixel corresponds to around 70 microns in the image but the light could be scattered from a particle which is smaller than this size. It is hard to evaluate the minimum observable dimension, but we estimate our particles to be distributed from well below 70 microns to 200 microns in size.

3. Experimental Results

The images of tracer particles have to be processed and analyzed with appropriate statistical tools and we have written a particle image velocimetry code based on available MATLAB modules[25], leaving aside the non trivial question of what is really traced by the tracer particles. In each run, the oscillating body can be followed. We use this to test the program, confirming that the digital output captures the known frequency and sinusoidal motion of the oscillator. Particle detection is based on luminous contrast. In the image, spots that stand out from the background according to certain criteria (*i.e.* light intensity and diameter) are identified and their coordinates estimated in every frame of the video sequence. Digitizing the positions manually we have checked some of the data obtained from the program, both to find the best parameter settings and to assess the program performance. Trajectories and velocities of tens of thousands of particles have been computed.

At first, we must choose the region near the oscillator to be studied. The area is generally a square, approximately 10 mm in size, where illumination is higher. The edge closer to the moving body is around 1 mm away of the rest position of the oscillator to avoid including it in the images. Therefore the flow is studied up to distances of about twice the diameter of the spherical oscillators but not closer than 1 mm.

We use only one camera, therefore our image analysis can only evaluate the two dimensional velocity vector projected on the screen and is an underestimate which does not include motion parallel to the line of sight. We have evaluated the absolute value (modulus) of the velocity vector obtained and this dynamic parameter will be treated in the following. We have observed erratic velocities for our particles, and we evaluate the probability that a given one has an instantaneous velocity for a set of oscillation amplitudes in the different oscillating geometries measured.

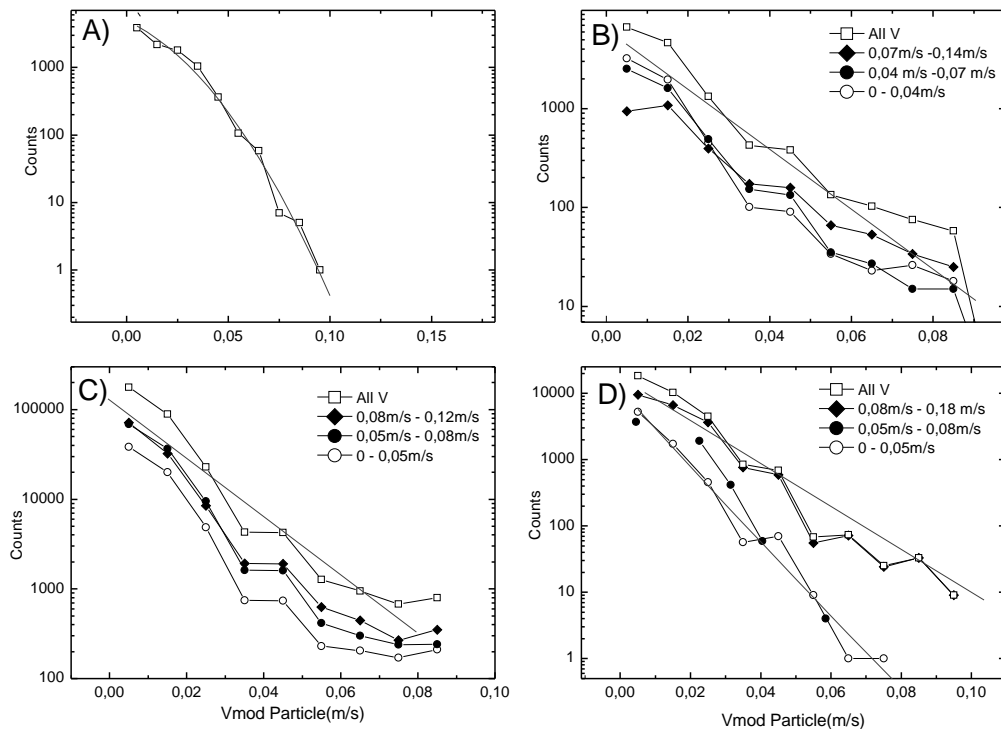


Figure 1. Un-normalized probability distribution function for the oscillating bodies; A) sphere in air with wire stem; B) sphere attached with wide flexible beam in helium; C) sphere with wire stem in helium; D) Flexible beam with no attached body, in helium. We have divided the data into groups corresponding to low, medium and high velocity of the oscillator, the intervals in which we evaluate Re_δ of the flow. A group including all of the particles observed, regardless of the oscillator velocity, is shown in open squares (labelled "All V"). It can be seen that the graphs are straight lines for the superfluid, where we have included straight lines as guides to the eye. This implies an exponentially falling probability of finding particles with higher velocities. For the sphere in air, the data can be represented by a parabola, as shown by the fitted line in the corresponding graph. The data are not normalized, so the numbers in each velocity interval are different, proportional to the number of particles captured in each measurement.

We have plotted the number of particles for equally spaced intervals of the velocity modulus, (*i.e.* an un-normalized probability distribution function (pdf)) and we show the results in Figure 1. We group our data according to the velocity amplitude of the sinusoidal motion of

the oscillator as low, medium and high velocities. We have considered as well a group including all of the particles observed and calculated the statistics of these lumped data.

For oscillating flow due to vibrating objects, moving with velocity amplitude U frequency ω and with amplitude l in the limit $U/\omega \ll l \gg \delta$, the characteristic length is not the size of the object, but the viscous penetration depth $\delta = (2\nu/\omega)^{1/2}$, where ν stands for the kinematic viscosity. The flow therefore is characterized by a modified Reynolds number[26] $Re_\delta = U\delta/\nu$. The values of Re_δ for the oscillators are shown in Table 1. In our case the limit $U/\omega \ll l$ is not fully realized, the oscillator is closer to $U/\omega \sim l$, however Re_δ is still more appropriate than Re because the displacement is small compared to the dimensions of the oscillators.

Oscillator	T(K)	$f = \omega/2\pi$ Hz	δ (mm)	Re_δ High	Re_δ Medium	Re_δ Low
sphere & beam	1.8	40	0.014	74	36	20
beam	1.8	37	0.014	65	43	27
sphere & wire	1.8	23	0.018	124	55	35
sphere in air	300	23	.47	4.5	-	-

Table 1. Frequency, viscous penetration depth and values for Re_δ corresponding to the maximum value for each velocity range of the different oscillators.

The pdf observed in Figure 1, for the oscillating systems studied show two slightly different types of behavior. In this graph with a logarithmic y-axis a straight line fit adjusts the results in the superfluid, implying an exponential decay in the observed velocity distribution. In the objects with sharp edges (the beam and sphere plus beam) the exponential behavior is not greatly dependent on the velocity of the oscillating object, and the straight lines corresponding to different velocities all have the same slope, within experimental error. Thus, almost independent of the velocity of the oscillating object, the number of particles whose modulus velocity acquires greater values decreases exponentially. In the sphere attached by a thin wire, the adjustment to be made is dependent on the amplitude of oscillation of the sphere. At different speeds it shows different exponential behaviors in the velocities. For values of lower Re_δ the slope is higher, meaning that the decay is faster, whereas the exponential decay is slower for high Re_δ .

In order to compare with a classical case, with no superfluid, we have tested the sphere with thin wire oscillating in air at room temperature. We have used particles of talcum powder as tracers. The values of Re_δ and δ attainable in air are different than those of liquid helium. In this case, we have plotted the higher values of Re_δ , and we find a decay in the form of a parabola in a graph with a logarithmic y-axis, as would be expected for a Gaussian distribution of zero mean.

4. Discussion

Following the analysis found e.g. in Landau-Lifshitz[27], it can be assumed that the vorticity produced by a rounded body oscillating with small amplitude is annulled to a great extent when the body changes the direction of motion. If sharp edges are present, the cancellation is much less, so it is possible that the observed differences in the pdf may be related to the presence of sharp edges in the beam, and the sphere attached by a beam, and the more rounded geometry of the sphere attached by a wire. The fact that a (classically expected) Gaussian distribution with no exponential tails was found in the sphere in air may be significant and could be due to the absence of superfluid. Some caution is necessary in this conclusion however, because of the difference in Re_δ between liquid helium and air.

Non-Gaussian velocity distributions have been reported in other experiments in superfluid visualization[28–30] and for example in thermal counterflow a non-Gaussian tail in the pdf, proportional to v^{-3} was found[28, 29]. These measurements are not in the type of flow observed

here. In this sense our data are difficult to compare with other experiments in quantum turbulence since to the best of our knowledge there are no published data on statistics of tracers in oscillating superfluid flows.

In conclusion, we present data on the visualization of turbulent flows around oscillating objects, which possibly show a different overall behavior than in classical fluids. Other observations of filamentary structures, which might be produced by quantum vortices are not numerous enough to be treated statistically and will be reported elsewhere.

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