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Excitation and Relaxation of Film Flow Induced by Third Sound

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High amplitude third sound waves are observed to create and to destroy persistent flow states within a circular resonator. These changes are necessarily a result modifying the underlying distribution of pinned vortices responsible for the flow. At low temperatures, large oscillatory flows associated with the third sound wave agitation are required to both increase and decrease the flow. At higher temperatures, thermally assisted de-pinning enhances the destructive aspects of lower amplitude third sound agitation. The constructive, or swirling tendency of the third sound agitation is also enhanced, but only in the presence of the wave excitation. At the higher temperatures, the ability of the induced flow to be trapped as a persistent current is diminished.

1. INTRODUCTION

The presence of a persistent current in a film requires some form of circulation, either as a circulation trapped about a topological feature, or a concentration of pinned vortices. Recent experiments have shown that high amplitude third sound is capable of creating the latter by polarizing either a pre-existing density of pinned vortices or nucleated vortex pairs.[1] In this paper, we discuss some of the aspects of the interaction of third sound with the pinned vortices of such a persistent current, particularly with regard to changing the persistent current during exposure to the high amplitude third sound. We will not specifically address details of any nucleation process that might be involved.

The only way to change a DC flow is to permanently move vortices (via the oscillatory wave flow) with a displacement component perpendicular to the streamlines of the wave flow. This may result from the nucleation of vortex pairs, and subsequent lateral separation, or from the de-pinning and subsequent lateral

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motion of existing vortices. In either case the consequence is that there is a threshold for either inducing the flow or for relaxing the flow. If the wave motion is stopped, the new configuration of pinned vortices is trapped as a persistent flow.

In general, the vortex motion described above is dissipative and leads to a reduction of the instantaneous superfluid flow. At low third sound amplitudes, superposition with the DC flow results in a larger instantaneous flow - hence more dissipation - in the forward direction. This reduces the DC flow in the forward direction. As in the case of the classical wave, nonlinear wave motion is crucial for inducing, or increasing the DC flow. The instantaneous forward flow-speed in the crest of a high amplitude traveling wave is smaller than the corresponding flow-speed in the trough, as required by conservation of particle flux in the direction of the wave. If the wave amplitude is large enough, the greater reverse flow dissipation of the trough will dominate the dissipation in the forward flow of the crest, possibly even in the presence of a forward DC flow, and result in an increase of the DC flow.

What distinguishes the superfluid case from the classical case is the threshold. This is really an activation behavior for the required vortex motion: the nucleation or de-pinning events generally have exponential dependence on flow, due to either thermal fluctuations or tunneling. In a small enough (or zero) third sound wave flow at low temperatures the vortices lock into a glass-like existence maintaining the corresponding persistent current. The third sound agitation can either reduce the DC flow (at intermediate amplitudes) or increase the DC flow (at high amplitudes), both with an effectiveness that increases exponentially with amplitude, always ultimately dominated by the increase in flow (swirling).

A simplified model for this activation process[2] illustrates the qualitative features of the flow induction and relaxation. Assume a dissipation proportional to the superfluid flow speed, v_s, and the number of free vortices of either circulation direction, n_f. Thermal activation of the vortices is also assumed with a barrier that decreases to zero as the superfluid flow approaches a critical speed, v_c.

$$\frac{dv_s}{dt} = -\gamma v_s n_f \qquad n_f = n_0 \exp\left(-\frac{p(v_c - |v_s|)}{kT}\right) \tag{1}$$

Here, n_0 encompasses some combination of pinned density, attempt frequency, and free state multiplicity, and pv_c is a measure of the pinning or creation energy. Finally, the DC drift, v_d, and nonlinear wave flow can be approximated by

$$v_s = v_d + \frac{v_p \cos(\phi)}{1 + \frac{v_p}{c_3}\cos(\phi)} \tag{2}$$

with the mean peak flow velocity given by v_p, and ϕ the phase of the wave. This form for the nonlinear wave field is chosen to explicitly have zero film averaged mass flux to second order in the wave amplitude.[3] Combining these relations back into the first and taking an average over the phase of the wave leads to a rate of change (acceleration) for the drift which is a function of v_d and v_p.

This acceleration has several features of note that are common to all similar variations of the component relations. First, the exponential in Eq. (1) results in the freezing out of the acceleration to zero for small, but not necessarily zero, v_d and v_p. This is the persistent current, which technically has asymptotic ln(t) behavior characteristic of glassy systems. Second, for any positive drift flow ($v_d>0$) with an increasing wave amplitude (v_p increasing), the drift flow initially decays as the vortices activate. As the wave amplitude increases further, the nonlinear wave components turn the acceleration around as a result of the asymmetry between the activation within the crest and trough of the wave cycle.

2. EXPERIMENTAL

A persistent current in a real experiment must involve a closed circuit of flow. In this case the persistent current flows azimuthally around the axis of a circular third sound resonator, and the third sound waves are rotating waves instead of the traveling, one dimensional waves discussed above.

The modes, driven and detected electrostatically, resonate with frequencies centered about $\omega=c_3 x_{m,n}/a$ where a is the radius, c_3 is the third sound speed, and the $x_{m,n}$ are the zeros of the derivative of the Bessel function $J_m(x)$. Each mode (m,n) has a double degeneracy lifted by the Doppler shift of any persistent current circulating within the resonator. By observing the splitting of several modes, a filtered image of $v_d(r)$, the DC drift, can be deduced.[1] Measurement of the resonance amplitude can converted into v_p using the properties of the modes.

Under certain circumstances, this information is available simultaneously. If the dissipation processes acting within the film are independent of amplitude and drift flow (a fixed Q), the resonance frequency can be identified by the drive frequency and phase through

$$f_{res} = f_{drive} + 2Qf_{drive}\tan(\phi - \phi_{res}) \tag{3}$$

so that changes in the drift can be monitored during the application of variable third sound amplitudes. A correction for a hydrodynamic frequency shift must also be applied.[3]

Two methods for observing the drift acceleration are reported where the condition of constant Q happened to be satisfied. This is *not* generally the case for amplitudes high enough to induce are drift.

3. RESULTS

The preliminary results reported here are limited to only one film thickness (h=2.4 nm, c_3=23.7 m/s) and one mode (m=2, n=1, $x_{m,n}$=3.054). Figure 1 shows the amplitude vs. frequency for a 24 V drive scanned down with 2 mHz steps every 10 s. The drift speed was initially v_d=0.25 m/s. The phase information (not shown) along with Eq. 3 has been used to extract the acceleration of the drift flow shown in Fig.2. As the wave amplitude, and consequently v_p, increases, the resonance appears distorted. This is not a consequence of dissipation, but due to

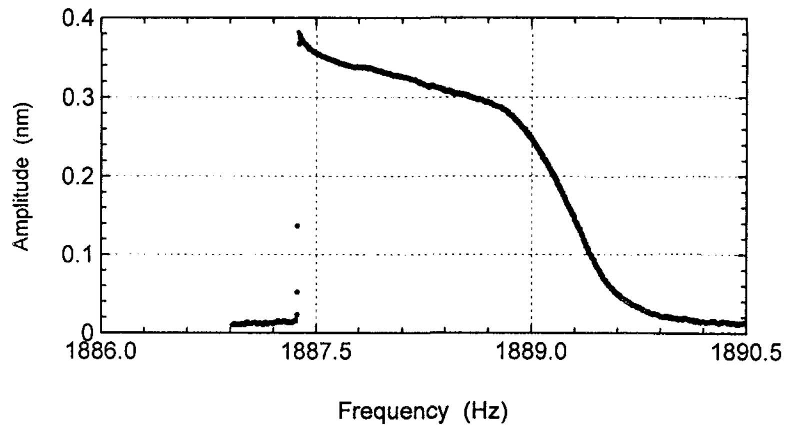

Fig. 1. Third sound resonance scanned down at a high amplitude

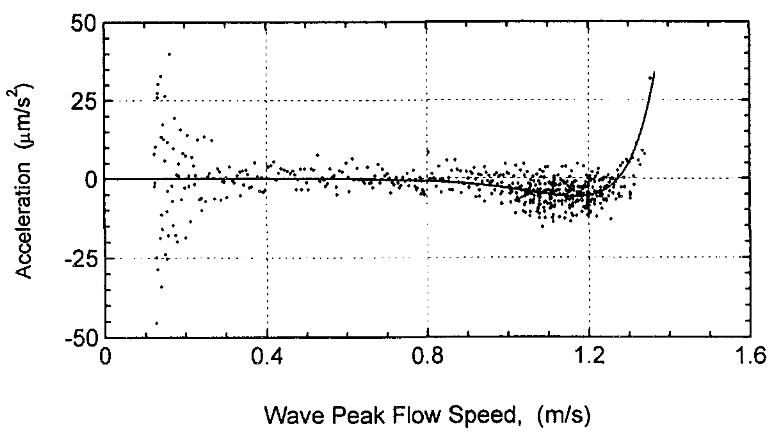

Fig. 2. Extracted drift flow acceleration and fit to simple model. Above 1.4 m/s the drift is catastrophically increased as the resonance moves toward the drive.

the deceleration of drift flow - the resonant frequency is shifting down along with the scanning drive. At the highest amplitudes, the v_d increases and then catastrophically shifts itself up, moving the resonance completely away from the drive. The up-turn near the top signals the beginning of this increase as the resonance moves itself back through the drive. Figure 2, though noisy, captures the turn-around. A fit to Eqs. 1-2 is also shown from which a critical velocity of 1.4 m/s is obtained. Figure 2 does not show the behavior after the highest amplitude point (its faster than the detector response) where the acceleration is estimated to be greater than 200 times the full scale shown, deduced after relocating the resonance.

The second method for observing the drift change is much less susceptible to interpretation errors, since tracking a fixed phase point of the resonance will mirror any resonant frequency shifts. Figure 3 shows the data for both v_p and v_d vs. time where the drive level was started at 6 V and incremented every hour by 0.6 V. Data was recorded only when the frequency crossed 10 mHz increments, so the paucity of data early on only reflects the absence of drift changes. As before, higher wave amplitudes result in a faster decay, which is tracked for

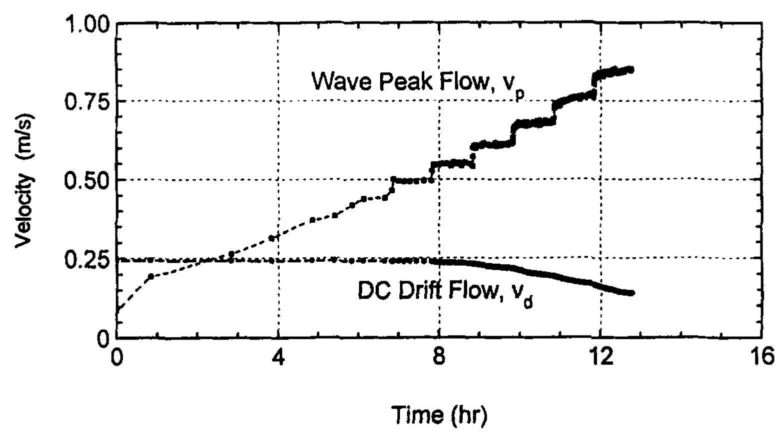

Fig. 3. Wave peak flow (v_p) and induced DC drift flow (v_d) as the drive is increased at hourly intervals. The resonance phase is kept fixed.

longer times and to lower drift flows. Note that in this data there is a significant variability in both v_d and v_p. In searching for Arrhenius like behavior it was found that a combination peak velocity, $v^* = v_p + \frac{T_0}{T} v_d$ with T_0=0.95 K, did a reasonable job at collapsing all of the data onto lines with the same slope, shown in Fig. 4. An independent linear combination for each temperature does not do significantly better. This is surprising given the scattered nature of the original measurements, prohibiting any other meaningful presentation of all results.

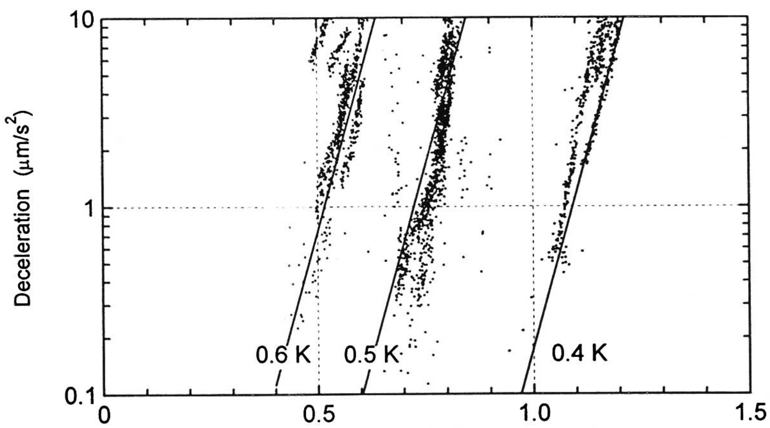

Fig. 4. Deceleration rate of the drift flow for many runs collapsed onto bands of similar slope. Wave peak and drift velocity are combined as described in the text.

Although this is just an empirical combination, it is tempting to associate decay of the drift flow, which requires the 1/T term, with thermal activation, and that of the wave peak flow with tunneling. However, there is no obvious reason for why such a separation should survive when the two flows superpose. Attempts to identify a critical velocity consistent for subsets of the data by forcing the exponential of Eq. 1 result in excessive dependence on v_p.

As a qualitative note with relevance to the behavior of Fig. 2, the high amplitude catastrophic increase in induced flow occurs at all temperatures, but was only temporary at the higher temperatures studied: apparently the high amplitudes necessary for inducing the flow end up destroying any gains during the subsequent ringdown of the resonance. The decelerations in Fig. 4 are consistent with this observation and the general observation (for this film thickness) that the induction of persistent currents was only possible at low temperatures. There, the decay taking place while wave action is turned off, and passes through the intermediate amplitudes, is negligible.

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