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Third sound interaction with pinned vortices in ^{4}He superfluid films

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Abstract

Superfluid circulation states are modified by high-amplitude third sound resonances and remain as persistent currents after the sound is removed. They are the result of pinned vortices at areal densities at on the order of tens of thousands per square centimeter interacting with the wave. A model for the flow-assisted, thermal activation of vortices has successfully reproduced both the temperature and amplitude dependence of the swirling. © 2000 Elsevier Science B.V. All rights reserved.

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High amplitude rotational waves in a circular resonator are able to create a DC circulation, or drift, of the fluid within the resonator [1]. This phenomenon is particularly interesting in the case of third sound in superfluid ^{4}He films. Not only are the circulation states produced by the waves able to remain after the waves have ceased as persistent currents, but the persistent currents so produced have been shown to involve very strongly pinned distributions of vortices. This paper reports on the success of combining several simple models, separately describing independent aspects of the third sound and vortex pinning, to reproduce some very interesting resonance line shape behavior.

The independent components of this model are summarized by the following points:

(1) Third sound resonance frequencies experience a Doppler shift in the presence of a DC film flow.
(2) Third sound resonance frequencies shift down proportional to the square of the wave amplitude due to nonlinear coupling between the normal modes [2].
(3) There is an asymmetry between the wave-flow fields associated with the crests and troughs of traveling (or rotating) third sound waves. In the absence of a DC drift, the flow speed under the wave crests (along the direction of propagation) is smaller than the flow speed under the wave troughs (opposite to the propagation direction). This asymmetry grows linearly with the wave amplitude, but is also a result of second-order nonlinear terms.
(4) The dissipation of resonance energy is not significantly effected by amplitude. This is not generally the case with third sound, but holds true for the film conditions discussed in this report.
(5) Free vortices are depinned (or created) with an energy barrier that diminishes to zero in the presence of critical flow. The number of free vortices can then be described in terms of a flow assisted thermal activation.
(6) The drag force opposing film flow is proportional to the density of free vortices and the flow speed. The flow has both a wave and DC drift components.

All of these are combined to simulate the behavior of a driven third sound resonator that includes a slowly changing DC drift flow. The first four can be simultaneously solved for wave-flow amplitude, v_w, as a function of the drive conditions (frequency and amplitude) and drift flow, v_d. These are then used to determine the rate of change of the drift flow according to the average of the vortex dissipation over the wave cycle. The rate,

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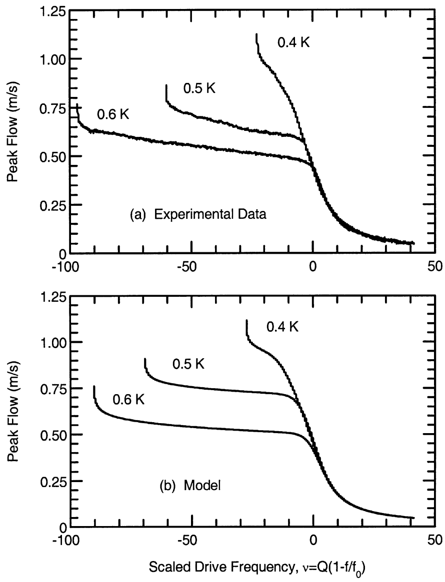

Fig. 1. Data (a) and model (b) for the third sound resonance line shape. The frequency is scaled by the Q, and scanned from above to below resonance at $v = 0$. Amplitude is reported as the peak film flow speed.

a function of v_w and v_d, is finally iterated over time steps to simulate the response of the film to the drive prescription. The results presented in Fig. 1a are the amplitude vs. frequency responses at a third sound speed of 21 m/s, each starting with an initial drift flow of 0.1 m/s. The frequency is scanned down at a fixed drive level and is reported as a scaled frequency, $v = Q(f/f_0 - 1)$, where f_0 is the initial low amplitude resonance position. This initial position is itself already shifted up by 310 frequency units by the drift flow. Fig. 1b shows the same situation simulated as described above. Although the model is based on Cartesian traveling waves, we adapt it to our circular resonator by applying the model to an azimuthal strip.

There are three features common to each temperature. There is a tail region, where the three temperatures behave similarly, responding only to the nonlinear frequency shift with amplitude. Note that $v = 0$ would have been "resonance" and the FWHM would be $\Delta v = 2$ at a low drive amplitude. As the scan proceeds down, there is a shelf region where the amplitude is sufficient to activate free vortices. The resonance effectively tracks the drive frequency down as the drift decays back toward zero. As the drift diminishes, higher amplitudes are required to activate the vortices (determined by the sum of the wave flow and the drift flow speeds). Eventually, the wave flow asymmetry (at the highest amplitudes) results in more flow dissipation in the reverse flow of the wave trough. A higher dissipation in the reverse flow relative to the forward flow results in a net forward acceleration of the film drift. Since this moves the resonance toward the drive, resulting in a run-away condition. The resonance catastrophically moves itself through the drive, giving in the hooks at the lowest frequencies of each curve. After this hook, the resonance ends up at a significantly higher frequency, leaving the response to the now way-below-resonance drive at some small amplitude, not shown in Fig. 1.

The behavior is well represented by the model, which has been used to simultaneously fit multiple data sets involving different temperatures and drive levels.

References

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