The Use of Vibrating Quartz Forks in Cryogenic Helium Research - On Their Ability to Detect an Externally Applied Flow in Superfluid $^4$He

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Abstract. Quartz tuning forks mass-produced as frequency standards for watches proved to serve as very useful tools for generating and probing flows of gaseous and liquid helium. Their cryogenic use as thermometers, pressure- and viscometers as well as generators and detectors of cavitation and turbulence has been recently widely discussed in the literature [JLTP 136, 1 (2004); 146, 537 (2007); 150, 525 (2008)]. Here we report our preliminary experiments where the vibrating fork is used to detect the externally applied flow in superfluid $^4$He.

1. Introduction
Oscillating structures such as discs, piles of discs, spheres, grids and wires have been widely used as multipurpose tools in cryogenic fluid dynamics and in quantum fluids research since the discovery of superfluidity (see, e.g., recent review [1] and references therein). A most recent addition to this family of oscillating objects is represented by several types of widely commercially available quartz tuning forks, which are mass-produced as frequency standards for digital watches. They can be used as multipurpose cryogenic tools, via their ability to probe

Figure 1. Schematics (left) and photograph (right) of the experimental arrangement used to test the ability of the quartz fork to detect the externally applied flow, generated in He II thermally, using the fountain pump heater. The fork is placed about 2 mm above the top of the capillary.
the flow of surrounding cryogenic helium. They are cheap, highly sensitive, robust and easy to install and use for most applications. Only two shielded wires are needed to drive and readout these piezoelectric sensors: no magnetic field (to which they are highly insensitive) is required to drive them. Relatively simple electronic scheme allows detection of their resonant response over up to eight orders of magnitude of the driving force. Our own experience as well as results from a number of other low temperature laboratories show that vibrating quartz forks can be used as generators and detectors of turbulence and cavitation, secondary thermometers, pressuremeters, viscometers in helium gas, normal liquid $^3$He and He I, in superfluid He II, $^3$He-$^4$He mixtures as well as in superfluid $^3$He phases at submillikelvin temperatures [2-9].

It is therefore of considerable interest to learn about their potential to be used as sensors in physical and technical projects on cryogenic flows and turbulence, both classical and quantum.

2. Experiment and results
Our cryogenic experiments schematically shown in Fig. 1 have been motivated by a qualitative room temperature test, when the resonant response of a bare fork vibrating at low amplitude becomes noticeably affected by a stream of compressed air. We used a typical commercially available fork (DT26 type, produced by Fronter Electronics, China) tuned for $2^{15}$ Hz at room temperature, removed its metal can and soft-soldered it via original legs. Its resonant response is measured using our standard electrical circuitry [7]. The fork is placed in front of the capillary of inner diameter $2R = 0.6$ mm, about 2 mm above its top. The capillary is an outlet of the fountain pump, allowing a smooth adjustment of the mean velocity of a submerged jet acting on this weakly driven fork. The entire setup is placed in the glass helium cryostat. We use technical helium directly from our liquefier, the helium bath using the rotary and roots pumps brought down to the desired temperature and stabilized on the level of few mK either manually, by adjusting the pumping speed, or using the temperature controller.

The typical results obtained at $T \approx 1.6$ K (during this experimental run the helium vapour pressure measured right above the bath level by the MKS Baratron was stabilized within $5.62 \pm 0.02$ mm) are shown in Fig. 2. The resonant characteristics of the fork are plotted against the mean normal fluid velocity in the capillary $v_N = \dot{Q}/(\pi R^2 \rho ST)$, where $\dot{Q}$ is the heat power applied to the fountain pump heater, $\rho$ and $S$ are the total density and entropy of He II.

Each experimental point represents an average from a set of 20-25 increasing frequency sweeps over four linewidths across the resonance. Each individual sweep (consisting of 50 data points) produced strongly varying results and the shown error bars originate from statistical averaging. Sweeps in the opposite frequency direction have been performed several times with no appreciable difference in obtained results. The experimental protocol was to start from zero applied heat power, which was subsequently, roughly in logarithmic steps, increased.

Fig. 2 represents the typical behaviour of the fork as measured in several runs at three various temperatures: 1.5, 1.6 and 1.7 K. Within a single experimental run, the results are reproducible, at least within the accuracy given by the error bars. At higher $T$, it is more difficult to control the temperature with sufficient accuracy, due to steeper $\Delta f(T)$ dependence. At lower $T$, the control is difficult due to limited efficiency of the pumping system.

3. Discussion
As expected, the externally induced flow influences the resonant response of the weakly driven fork. All measured quantities - the relative amplitude, resonant frequency and linewidth change with the applied heat power to the fountain pump in a consistent way, however, rather large mean normal fluid velocity $v_N$ in the capillary of order 50 cm/s was needed to observe any appreciable change in these quantities, beyond statistical scatter. On first approximation, these changes vary linearly with the the applied heat power. A very rough estimate of the Reynolds number for the flow inside the capillary based on its diameter, $v_N = 50$ cm/s
and kinematic viscosity based on the total density of He II of order \( \nu \approx 10^{-4} \text{ cm}^2/\text{s} \) gives \( Re \) of order \( 10^4 \). We therefore assume a turbulent pipe flow and a submerged turbulent jet outside the capillary, of the form of a cone with angle \( 2\alpha \approx 25 \) degrees [10]. Thus the prongs of the fork are vibrating within the area of turbulent jet (that 2 mm away from the capillary without the fork disturbing the flow would be spread over a circle of \( \approx 1.5 \text{ mm in diameter} \), assuming that the He II jet behaves in analogy with a classical one.

Let us compare the behaviour of the strongly driven fork vibrating in quiescent liquid [1, 6, 7] with the behaviour of the weakly driven fork vibrating in a jet. In a quiescent liquid, on increasing the drive the Lorentzian shape of the absorption becomes distorted and the resonant frequency (the point of maximum response) shifts towards the lower frequency. At \( T = 1.6 \text{ K} \) the observed transition from laminar to turbulent drag is not sharp and occurs when prongs move with velocities 5-10 times lower than \( v_N^{th} \).

On increasing \( Q \), Fig. 2 shows similar behaviour of the relative amplitude and linewidth of the weakly driven fork in the vicinity of \( v_N^{th} \). As the mean velocity in a jet decreases inversely proportionally with the distance from the capillary [10], the behaviour of the relative amplitude and linewidth seems consistent with the transition from laminar to turbulent drag force exerted on vibrating prongs of the fork. However, the resonant frequency shifts up, i.e., in the opposite direction than in the case of strongly driven fork. The reason might be slightly lower density of flowing helium due to the Bernoulli equation, but at present we cannot offer any quantitative explanation of this experimental fact.

Fig. 3 shows the quantity amplitude times linewidth of the resonant response of the fork plotted versus \( v_N \). Both linear and logarithmic plots show that the mean value of this quantity remains constant up to higher \( v_N \), of about 200 cm/s, which suggests that up to here the response of the fork remains of Lorentzian form. On the other hand, the statistical error drops significantly. We speculate that this fact results from strong intermittent features.

Figure 2. Plots of relative amplitude (upper panel), resonant frequency (middle panel) and linewidth (lower panel) as a function of the mean velocity of the normal fluid in the capillary. The main panels are plotted in logarithmic axes, while the insets show the same data in linear axes. The solid lines represent linear fits to the data.
taking place until fully developed turbulent flow in the jet establishes at higher flow velocities. Although the discussed data clearly demonstrate the ability of the weakly driven fork to sense the applied flow in superfluid $^4$He, the observed threshold seems rather high in order to use it as a sensitive sensor for obtaining detailed statistical properties of turbulent flows. Let us mention in passing that (without any special care such as accurate temperature stabilization) we so far failed to sense the thermal counterflow up to 20 cm/s using a similar fork placed inside a counterflow channel 1 cm in diameter. Moreover, if technical helium is used, the characteristics of the fork are not reproducible from run to run. For example, the undisturbed linewidth measured in several runs on different days at 1.7 K and 1.6 K, although the observed data obtained for each run are within given error bars reproducible, do not display the correct temperature dependence as established in our earlier work inside a pressure cell, where care was taken to purify the incoming helium. We believe that this is caused by gathering frozen particles on the prongs of the fork. We did not obtain fully reproducible data even when the fork was shielded by paper housing and/or cotton wool from the top, at least partially preventing the fork from gathering frozen particles on its prongs.

In summary, our preliminary experiment shows that the vibrating quartz fork is capable of probing externally applied flows in superfluid $^4$He. On the other hand, for its possible use as a useful flow sensor better understanding of its behaviour in external flows (both classical and quantum) is needed. An important issue is reproducibility of the data in technical applications, when the response of the fork might be affected by frozen air or other impurities.

3.1. Acknowledgments
The authors appreciate technical help during the measurements and data processing and discussions with M. Blažková - Králová, M. Rotter and V. Pilcová. This research is supported by research plan MS 0021620834, by GAUK 7953/2007 and by GAČR 202/08/0276.

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