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ACOUSTIC QUALITY FACTOR OF AN ALUMINIUM ALLOY
FOR GRAVITATIONAL WAVE ANTENNAE BELOW 1 K

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ABSTRACT

We report the measurements of the acoustic Q factor of an Al-5056 bar at the 35 kHz frequency of its first longitudinal resonance, in the temperature range 0.1-300 K. The data is characterized by a plateau below 10 K at $Q = 4.1 \times 10^7$. The interest of this result for a gravitational radiation experiment is discussed.

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In a Weber-type gravitational radiation (g.r.) experiment [1] the energy absorbed from a g.r. burst by a solid-body antenna has to be large compared with the thermal noise in the antenna and in the electronic equipment. The thermal fluctuation ΔE of the energy in a given mode of oscillation is $\Delta E = kT(\omega/Q)\Delta t$, where Δt is the sampling time interval and Q the acoustic quality factor in the particular mode of oscillation with angular frequency ω . The ratio Q/ω represents the characteristic time for the loss of energy.

The interest in reducing this noise has stimulated the use of low-temperature techniques and the search for low acoustic loss materials. The discovery of the increasing Q factor of the aluminium alloys at low temperatures [2,3] was very important, and in particular the remarkable Q factor at 4 K of the aluminium alloy 5056 (5.2% Mg, 0.1% Mn, 0.1% Cr) [3] now used by several g.r. groups.

Since the next generation of antennae are already planned to operate at temperatures well below 1 K, we have considered it important to investigate the Q factor of this alloy in the temperature range accessible with dilution refrigerators. We report here the measurements of the Q factor of the first longitudinal mode of a small Al-5056 bar at $\omega/2\pi = 35$ kHz in the temperature range 0.1-300 K.

The dimensions and consequently the frequency of the mode were determined by the available volume of our ^3He - ^4He dilution refrigerator. Previous measurements [4], however, show that the Q factor of this alloy should not depend on the frequency in the range 10 - 10^5 Hz down to 4 K temperature.

The sample, shown in Fig. 1, is a cylindrical bar machined with a narrow ring in the central section. The sample is supported by three beams clamping the ring; the knife-shaped contact areas are shown in the inset of Fig. 1. The sample and the support have been cut from the bulk of the 2.3 t Al-5056 antenna material of the Rome g.r. group [5].

The support is the most delicate point in such experiments, because it can have a definite effect on the Q factor of the sample. Our support is machined from a single block of Al-5056. In order to minimize the loss of the acoustic energy through the support, the beams have been designed in such a way as to have their transversal eigenfrequencies far from the frequency of the sample. The support is made rigid in order to have a stable position of the sample during the assembly and operation of the dilution refrigerator.

An electrode of area $\pi(9)^2\text{mm}^2$ at a distance of about 100 μm from the end face of the bar, and at a potential of about 100 V, was used

as an electrostatic capacitive transducer. The electromechanical coupling coefficient β of the transducer was kept deliberately low ($<10^{-8}$) in order to have a minimal electrical loading on the mode during the measurements. By means of a vibrometer [6] and a frequency synthesizer the transducer was used for both the build-up of the oscillation of interest and for the measurements of the free decay of the amplitude.

The pressure of the ^4He heat exchange gas was below 10^{-4} Torr before final cooldown from 20 K. During the experiment there is no way of measuring the pressure in the sample area. The cryopumped layer of the residual ^4He on the sample, however, is much thinner than the limit of mobility, and therefore cannot cause residual damping.

Because no thermometer could be fixed directly to the bar, the temperature of the sample was estimated from that of the support, measured with calibrated carbon and germanium resistors. The sample equilibrium time above 0.5 K temperature was determined using the bar frequency as a thermometer; extrapolation to lower temperatures was done using the diffusivity of Al-5056 from our earlier measurements [7].

The results of the Q measurements are presented in Fig. 2. The value of Q is 3.6×10^5 at room temperature, 5.0×10^6 at liquid nitrogen temperature and reaches a plateau at about 4.1×10^7 below 10 K.

Before the second run we annealed the sample at 340°C in vacuum for 12 h. The Q factor at low temperature is 15% higher than in the first run.

We do not observe any variation in the Q factor passing through the superconducting transition temperature $T_c = 0.925$ K of this alloy [7].

Fig. 3 shows the frequency of the sample as a function of temperature. The frequency increases by about 6% when going from room temperature to 40 K. This behaviour follows the expected temperature dependence of the Young modulus.

We have observed, using different supports, that the suspension system may strongly influence the Q factor. The results reported here are the best obtained, and we note that they agree down to 4 K with those of ref. 3, performed on this material with a different sample geometry, mode of oscillation, and support.

Assuming that only the effect of the internal friction in the material has been measured, we think that our results may be interesting also from the point of view of the solid-state physics and

metallurgy, as the frequency investigated here is below the usual ultrasound region, and an explanation of the observed behaviour of the Q factor below 10 K in terms of the usual sources of internal friction, such as defect scattering or anharmonicity, seems unsatisfactory. Dislocation resonances have been recently suggested [8] as the possible acoustic-loss mechanism responsible for the temperature-independent behaviour of the Q factor at low temperatures. This mechanism could be influenced, and the effect on the Q factor possibly reduced, by suitable thermal treatments of the material.

From the point of view of the g.r. experiment a temperature-independent Q factor leads to a thermal fluctuation decreasing only linearly with the temperature. Then, on the basis of current estimates, in order to make the energy noise smaller than the energy absorbed from g.r. bursts produced in the galaxies of the Virgo Cluster, which would ensure a reasonable rate of a few events per month, one has to reduce the temperature of an Al-5056 multi-ton bar below 0.1 K.

Although the measured thermal properties [7] of Al-5056 show that cooling below 0.1 K is possible, it seems opportune to investigate the Q factor of other commercial materials at very low temperatures. A high Q steel or copper alloy, for instance, will give a nearly 3 times higher cross-section for g.r. than an Al bar of the same dimensions, because of the larger mass.

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FIGURE CAPTIONS

Fig. 1. Geometry of the sample and support system, which is fixed to the heat contact in the mixing chamber of a horizontal dilution refrigerator. C indicates the capacitive transducer, T_1 and T_2 are resistance thermometers, and H is a manganin wire heater. The inset shows the knife-shaped contact areas between support and sample ring.

Fig. 2. Observed quality factor Q of the first longitudinal mode of vibration of the sample versus temperature. The open points refer to the sample after annealing at 340°C.

Fig. 3. Frequency of the first longitudinal mode of vibration of the sample versus temperature below 1 K. The inset shows the frequency dependence up to room temperature.

Fig. 1

Fig. 2

Fig. 3