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Accurate rotation and displacement in the millikelvin range: A new positioner design

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dc micromotors have been used to rotate helium 4 crystals in a pressurized cell (25 bars) at very low temperature (down to 30 mK). After slight modifications of the motors and optimization of bearings and transmission design, rotations of $\pm 6°$ were obtained with an accuracy of $\pm 0.01°$ and a dissipation of 20 μW.

During the experimental study of vicinal surfaces of ^{4}He crystals, it was necessary to rotate the crystals around two perpendicular axes with a precision of the order of 0.01°. Experiments are performed in an optical dilution refrigerator at very low temperatures ranging from 20 to 300 mK. Our cooling power being about 20 μW at 30 mK with a circulation rate $\dot{n}=7\times 10^{-4}$ mol/s, a system with very small thermal dissipation is needed. As the experimental cell was filled with superfluid ^{4}He, pressurized at 25 bars and surrounded by several vacuum chambers, the use of a mechanical transmission up to the outside at room temperature was excluded.

Hence we made the choice to use micromotors inside the experimental cell. The main problem of electrical motors at such low temperature is their thermal dissipation. Disk-magnet stepper motors are usually easy to rewind[1] with superconducting wire, thus suppressing Joule dissipation. All stepper motors commercially available are too large to be installed in the high-pressure cell of our experiments. Thus we chose dc micromotors Escap[2] model 707 because of their much smaller size (1 cm^3). It was easy to mount two of them in the small extra space of our cell. The complexity of their winding made them impossible to rewind, but we limit Joule dissipation in the motors by using pulses of well-controlled voltage, duration, and repetition rate.

Figure 1 represents a schematic view of our system. ^{4}He crystals are grown in a boat B whose dimensions are 40 mm$\times$25 mm$\times$25 mm. Two steel axles of diameter 0.8 mm are fixed to this boat along O_x. They rotate in two small bronze journal bearings mounted on a rectangular cradle C. This cradle has a similar pair of axles parallel to O_y which rotate in journals fixed to the high-pressure cell. This gives two perpendicular axes of rotation for the boat and thus for the crystal inside.

A 1.5$\times$30/100 mm screw rod with 15 mm length (S) is driven by the fixed motor ($M1$) and displaces a cubic threaded nut (N) which is linked to the cradle and rotates it. The nut (N) is freely rotating on the cradle around an axis (T) which is perpendicular to the screw (S). This axis (T) is made with another 1.5$\times$30/100 mm screw. It acts as a gimbal to allow rotations larger than a fraction of a degree. The transmission between motor and screw is a 0.15-mm-diam flexible tungsten wire (W). A second motor ($M2$) is mounted on the cradle and drives a similar screw orienting the boat versus the cradle along a perpendicular axis. The driving screws are made of brass and the cubic nuts of stainless steel. This was convenient because of the differential contraction of these materials at very low temperatures and prevents any sticking. This system has an angular range of $\pm 7°$ for the rotation along O_x and $\pm 6°$ for these along O_y.

In order to work at low temperatures, the motors must be slightly modified. One must thoroughly eliminate any trace of lubricant that would freeze and lock them. This is done by dismounting the micromotors and washing their parts in an ultrasonic cleaner with first trichloroethylene and then alcohol. As the motors have a hardened-steel shaft 0.8 mm diameter rotating in a bronze journal, we must ream out the inner journal diameter slightly (0.85 mm) to prevent locking at cryogenic temperatures where bronze contracts more than steel. For the same reasons, the inner plastic journal diameter (0.8 mm) is increased to 0.9 mm.

The disassembly of the motors is a relatively delicate operation. Firstly, one needs to remove the 0.8 mm$\times$1.6 mm steel tube spot welded on the 0.8 mm motor shaft: for that we used a small diamond saw and worked under a binocular microscope. Secondly, to open the motor after this operation, we cut the four small plastic pieces of its frame. After cleaning, epoxy resin was used to glue the plastic pieces back in place and thus reassemble the motors.

Prior to their final mounting, the motors are tested at 4.2 K temperature in a liquid helium storage vessel. If enough attention is paid to the cleaning of mechanical parts (motors, screws and nuts), the performance of the whole positioner is roughly the same at room and cryogenic temperatures.

The self-braking of the screws makes it possible to use the system in a pulse mode. As we needed in fact an angular position system, we chose to vary the angles of the cradle and boat by small discrete values. Typically, each motor and screw rotate by one tenth of a turn with a

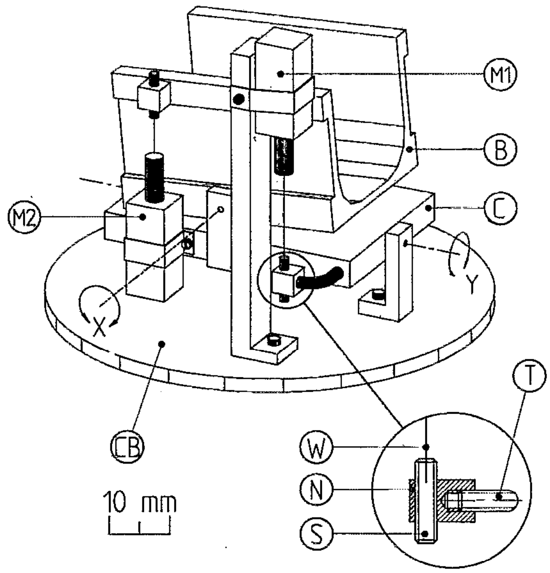

FIG. 1. Schematic view of the experimental setup: $M1$ fixed motor, $M2$ mobile motor, B boat containing the crystal, C cradle supporting the articulated boat, and the mobile motor W tungsten wire, S brass screw $1.5\times 30/100$ mm, N stainless-steel nut, T nut axis (brass screw $1.5\times 30/100$), CB bottom of the experimental pressurized cell.

square pulse of 1 V amplitude and 0.5 ms duration. This gives an angular displacement of 1.25×10^{-3} rad for the cradle and 0.6×10^{-3} rad for the boat but for precise final positioning, the motor can be operated with shorter pulses in order to obtain the required precision ($0.01°=1.7\times 10^{-4}$ rad). Since the boat could be observed from the outside through two sets of windows, an accurate measurement of rotation angles could be obtained from the angle of reflection of two laser beams.

At liquid-helium temperature, the resistance of the motors is 7 Ω. The energy for a pulse 1 V amplitude and 0.5 ms duration is 7×10^{-5} J. This corresponds, for a repetition rate of 0.3 Hz, to a heating power of 20 μW. With a circulation rate of 700 μmol/s of ^{3}He-^{4}He in the dilution refrigerator, the boat could be rotated at 30 mK. Alternatively, if the dissipation required is lower, one can reduce the repetition rate and obtain the same angular variation in a longer time. The torque available on the axes of rotation of our system is 12 mN m/A and thus 1.7 mN m of torque for the rotation of cradle and boat in the conditions of our experiment, corresponding to a non-negligible mechanical energy. But, if the allowed dissipation is higher, the system can easily supply a greater mechanical energy.

With minor changes, such a system can be used for rotations with different amplitude or speed, as well as for precision translations.

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[1] A. A. Moulthrop and M. S. Muha, Rev. Sci. Instrum. **59**, 649 (1988).
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