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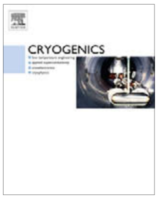

Vibration spectrum of a pulse-tube cryostat from 1 Hz to 20 kHz

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ABSTRACT

The vibrations of the cold finger of a low-vibration helium pulse-tube cryostat are measured from 1 Hz to 20 kHz using an optical interferometer specially designed to measure small amplitude vibrations at high frequencies in the presence of large vibrations at lower frequencies. While the vibrational amplitude is dominated by the contribution at the fundamental compressor frequency of 1.4 Hz, the pulse tube contributes mechanical noise at frequencies up to 15 kHz, where the spectral density is measured to be 4×10^{-12} m/Hz$^{1/2}$. Root-mean-squared vibration amplitudes of 5.2 μm and 3 μm are measured along perpendicular axes in the horizontal plane, and 1.0 μm in the vertical direction. The effect of a suspended sample holder for the purpose of attenuating high-frequency vibrations is evaluated. Finally, the cryostat is shown to be considerably noisier than typical laboratory floors.

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1. Introduction

Closed-cycle cryostats enable experimental studies at low temperatures with the great convenience of eliminating liquid cryogen handling and consumption. The most commonly employed technologies for closed-cycle cryostats below 4 K are the Gifford–McMahon refrigerator and the pulse tube. Pulse tubes are notable for the fact that the cold head itself contains no moving parts. A matter of universal concern, however, is the vibration associated with the closed-cycle system. Non-interferometric optical sensors and piezoelectric accelerometers have been used to measure the vibration of the cold fingers in closed-cycle cryostats in a frequency range from near DC to 800 Hz [1–3] and to 7 kHz [5]. A typical value for the peak to peak vibration amplitude at the cold stage of a pulse tube cryocooler along one coordinate axis is 14 μm, with the bulk of the motion taking place at a frequency in the vicinity of 1 Hz [1]. In addition to measurement, various methods have been used to control the vibrations [6,7,3,5,8]. In most cases, the emphasis has been on reducing the vibrations at low frequencies, where indeed most of the vibration occurs.

There are a number of experiments that could benefit from the use of closed-cycle cryocoolers in which the vibrations are of interest in a higher frequency range. Such experiments include research into controlling the mechanical degrees of freedom of micromechanical and nanomechanical systems, with resonance frequencies that can span the kHz–GHz range. A natural question that arises is whether the pulse tube contributes significantly to the vibration level at frequencies higher than those studied in earlier work. This requires a sensor with a large bandwidth and large dynamic range. In this paper, we start by describing an optical interferometer that was specifically developed for measuring vibrations in a closed-cycle cryostat, providing the sensitivity to see small fluctuations in displacement at high frequencies, even in the presence of rather large low-frequency vibrations. We then show the results of measurements of the displacement spectral density at the cold finger of a typical commercial 4 K pulse-tube cryostat along three cartesian axes out to 20 kHz, and find that vibration associated with the pulse tube is significant out to 15 kHz. We furthermore show the result of a simple attempt to attenuate the vibrations with a mechanical low-pass filter. Finally, we put these quantitative results in perspective by comparing them to vibration measurements made with an accelerometer on typical laboratory floors.

2. Cryostat description and optical vibration measurement

The cryostat studied here [9] employs a two-stage pulse tube to cool a sample to a temperature of below 4 K in vacuum, with a cooling power of 0.5 W. It was procured with a "low-vibration" option, incorporating a copper braid to decouple the cold head from the mounting plate to which the sample is attached. In addition, the rotary valve is separated from the cold head by a distance of approximately 1 m. The cryostat is mounted on a granite table with a mass of approximately 360 kg in an underground laboratory. The vacuum chamber is equipped with five optical windows. Three mirrors, oriented with mutually orthogonal normal directions, are attached to the sample mount, such that light sent through the optical windows can be retroreflected.

Optical interferometry is a convenient technique for measuring vibrations without making mechanical contact. The interferometer

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used in this work is shown in Fig. 1. It is a heterodyne Michelson interferometer, specifically designed to resolve small displacements at high frequencies superposed on large-amplitude vibrations at low frequencies. A full description appears elsewhere [10], but the operation of the interferometer can be summarized as follows. Light from a stabilized helium–neon laser is split into two beams of orthogonal polarizations by means of a polarizing beamsplitter (PBS), each of which is sent through an acousto-optic modulator (AOM) driven by an oscillator such that the nominal frequency difference between the two beams emerging from the AOMs is 1.5 MHz. One of the oscillators is a synthesizer running at 38.5 MHz, and the other one is a voltage-controlled crystal oscillator (VCXO) tunable by 15 kHz about a nominal frequency of 40 MHz. The light from the two beams is recombined and coupled into a polarization-maintaining single-mode optical fiber, by means of which it is brought to the granite table supporting the cryostat. After emerging from the fiber, it is collimated and split back into its two component beams, of orthogonal polarization and differing in frequency by 1.5 MHz. The frequency of one of these beams is fixed, and drives the "reference" arm of a Michelson interferometer. The reference mirror is firmly attached to the granite table. The frequency of the other beam is tunable by means of the VCXO, is retroreflected from one of the mirrors on the sample mount in the cryostat, and drives the "measurement" arm of the Michelson interferometer. The beams are recombined by means of polarizing optics and fall on a photodetector, providing a signal with a nominal frequency of 1.5 MHz.

The interferometer is used in two distinct modes, corresponding to the detection of vibrational motion at frequencies below 3 kHz and frequencies above 256 Hz. In both cases, the signal is demodulated at 1.5 MHz with a digital lock-in amplifier, which outputs the phase difference between the demodulated signal and the reference oscillator. Feedback to the VCXO is used to force the signal to track the reference by driving the phase difference to zero. Physically, this corresponds to applying a frequency shift to the AOM to cancel the Doppler shift imposed by the instantaneous mirror velocity. For frequencies within the servo loop bandwidth (typically DC – 3 kHz), the VCXO control voltage thus provides a direct indication of the mirror velocity. For frequencies outside the servo bandwidth, the feedback can be ignored, and the phase error can be taken as a direct indication of the mirror displacement. By concatenating spectra taken within the servo bandwidth and outside,

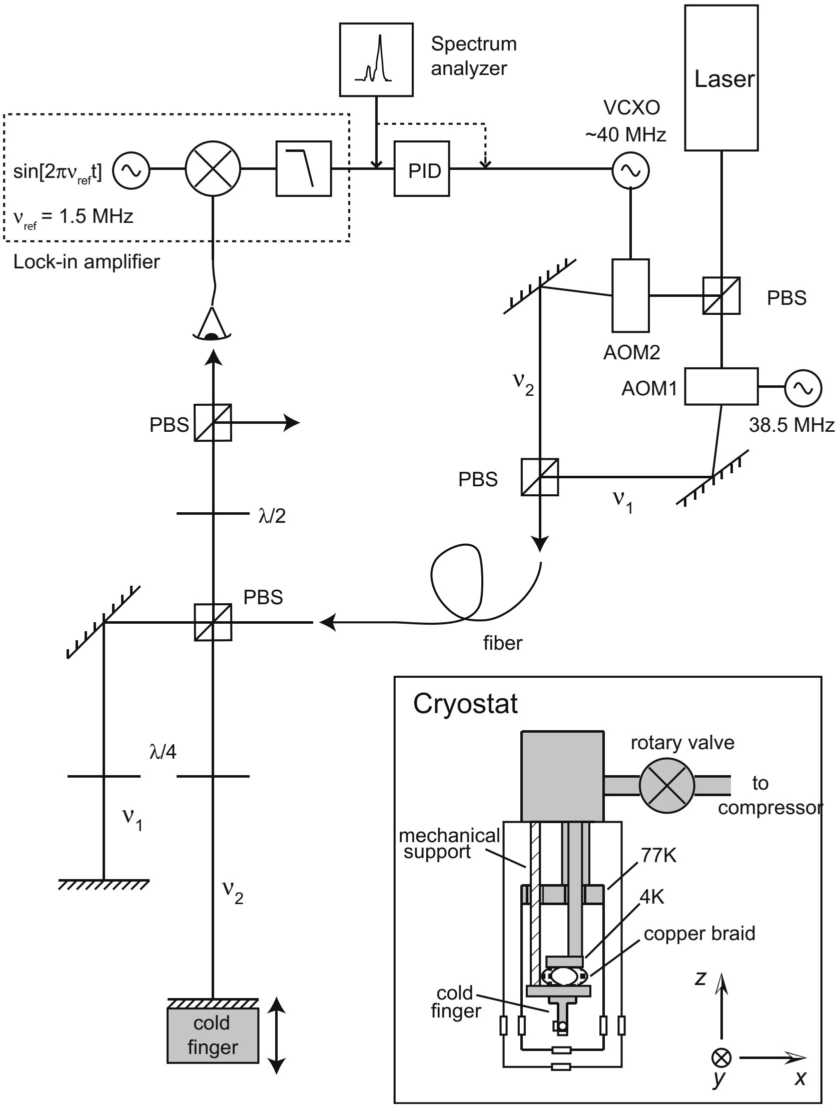

Fig. 1. Layout of interferometer and cryostat. Quarter-wave plates, denoted by $\lambda/4$, are used in each arm of the interferometer to flip the polarizations of the returning beams. A half-wave plate, $\lambda/2$, rotates the polarizations of the beams leaving the interferometer by 45°, and a polarizing beamsplitter, PBS, is used to obtain interference. The feedback loop is closed by a proportional-integral-derivative (PID) controller.

we obtain a measurement of the vibration spectrum from DC to 20 kHz.

3. Cryostat vibrations

Vibration spectra measured along two axes are shown in Fig. 2a. The upper trace corresponds to the horizontal direction parallel to the high-pressure helium line to the cold head, while the lower trace corresponds to the vertical direction (directions $\hat{x}$ and $\hat{z}$, respectively, in Fig. 1). The spectrum for the third axis lies between those shown, but is left out for clarity. The largest peaks are at the fundamental frequency of the pulse tube, 1.4 Hz, but peaks at discrete multiples of the fundamental are clear out to about 28 Hz. Corresponding root mean square (rms) displacements as a function of measurement bandwidth are shown in Fig. 2b. Here it is clear that the motion is dominated by the component at the fundamental frequency, while the contribution to the total rms amplitude of frequency components above 10 Hz is not discernible. The rms motion is seen to be 5.2 μm, 3 μm, and 1 μm along the $\hat{x}$, $\hat{y}$, and $\hat{z}$ axes, respectively, so it is clear that the bulk of the motion is in the horizontal plane. For experiments involving the position of a laser beam sent via free-space optics into the cryostat, the large-amplitude motion at the fundamental frequency is likely to be the motion of greatest concern.

In some cases, however, this low-frequency motion may turn out to be relatively unimportant. If light is supplied to the sample via an optical fiber, for example, the low-frequency motion would appear as common-mode motion to the light and the sample. The question then arises whether higher frequency mechanical modes of an experimental apparatus might be excited. A useful point of departure is to ask how much of the vibration shown in Fig. 2a is actually due to the pulse tube, and how much is present even if the pulse tube is off. The answer is shown in Fig. 3, which shows the displacement spectral density measured with the pulse tube on and the pulse tube off. For this figure we have added the displacement densities along the three cartesian axes in quadrature. The data were taken in rapid succession so that the sample head did not warm up significantly when the pulse tube was turned off. It is clear that the contribution of the pulse tube to the mechanical noise persists up to 15 kHz, where the spectral density is measured to be 4×10^{-12} m/Hz$^{1/2}$.

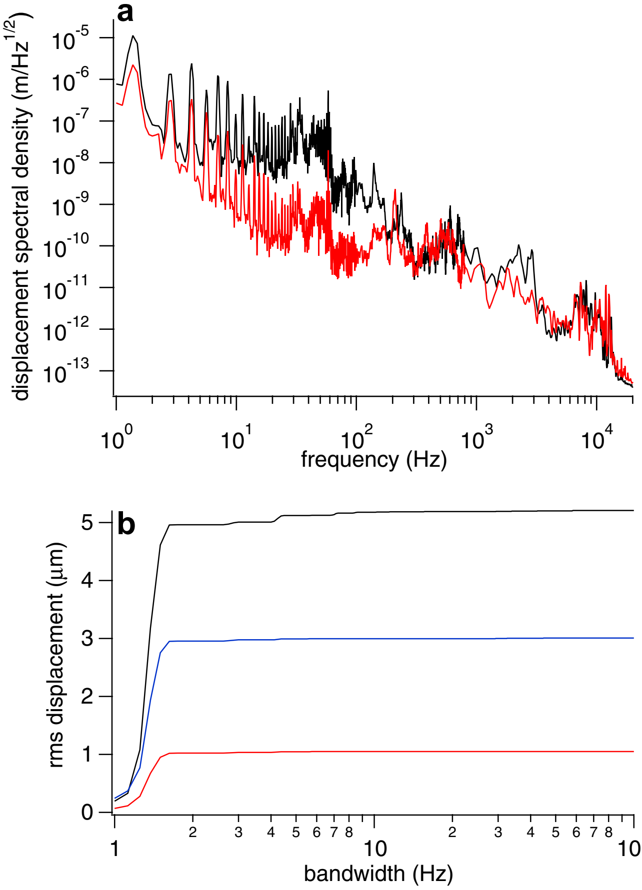

Fig. 2. (a) Measured displacement spectral densities along $\hat{x}$-axis (upper trace) and $\hat{z}$-axis (lower trace). (b) Root-mean-square displacement along $\hat{x}$-(upper trace), $\hat{y}$-(middle trace), and $\hat{z}$-(lower trace) axes. The motion in the horizontal plane is dominant over motion in the vertical direction.

3.1. Passive vibration attenuation

Various techniques have been employed to attempt to attenuate the vibrations in closed-cycle cryostats [2,4]. Copper and aluminum braids between the cold head and the sample aid in vibration suppression [3]. Mechanical isolation has been used to suppress vibrations at low frequencies by three orders of magnitude [7,3]. Some commercially available systems employ helium as a buffer gas to isolate the sample from mechanical disturbances imparted by the cryocooler. In a rather different approach, the mutual cancellation between two pulse tube units 180° out of phase with each other has been used [6] to reduce the amplitude of the low-frequency oscillation peak by 96%. Active feedback is a particularly elegant technique that has been used [5,8] to suppress low-frequency pulse tube vibrations.

If one is not concerned with the low-frequency vibrations comprising the bulk of the motion, because it merely acts in a common-mode fashion, one might still be interested in attenuating vibrations at higher frequencies. The simplest way to accomplish this is a mechanical resonant system; vibrations at frequencies substantially larger than the resonant frequency will be attenuated, at the expense of increased vibrational amplitude in the vicinity of the resonance. In the cryostat we have studied, the bulk of the vibrational motion is in the horizontal plane, suggesting a pendulum as mechanical resonator. In order to evaluate the usefulness of this approach, a sample stage consisting of a 0.280 kg brass plate was suspended from the cold finger by means of three copper braids. The braid thickness was chosen in order to provide weak mechanical coupling of the stage to the cold finger, while

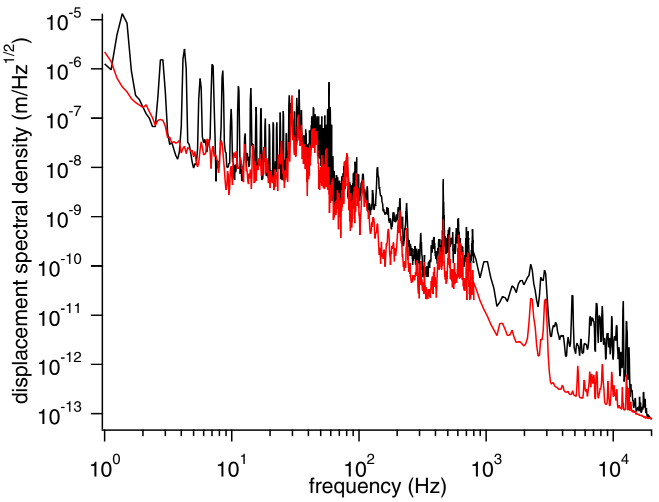

Fig. 3. Quadrature sum of measured displacement spectral densities along three cartesian axes, with pulse tube ON (solid upper curve) and OFF (dashed lower curve). Note that the influence of the pulse tube is clearly visible to about 15 kHz.

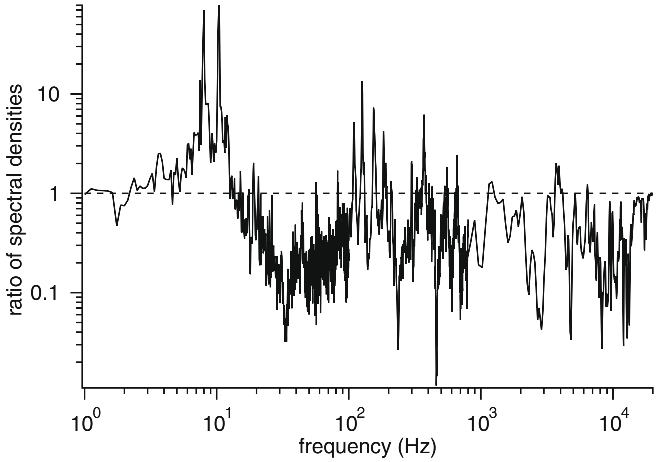

Fig. 4. Ratio of displacement spectral density with pendulum to that without pendulum; values below unity correspond to suppression of vibrational motion. The data used were for the quadrature sum of the measured motions in the horizontal plane.

maintaining good thermal coupling. Copper braids 0.3 mm thick, 2 mm wide and 23 mm long were used; the 23 mm length was the result of space limitations in the cryostat. The fundamental resonances of the suspension were observed to occur at 6.7 Hz, 8.1 Hz and 8.7 Hz. Thus, we would expect the suspension system to exacerbate the effect of vibrations from about 5 Hz to 10 Hz, and provide attenuation for frequencies substantially above 10 Hz.

Optical vibration measurements were carried out as before, with one exception. The suspension allowed rotation about the vertical axis that was not formerly present, and resulted in the reflected beam being sent back at a small angle that oscillated in time. We overcame this difficulty by defocusing the beam from the fiber so as to create a weakly divergent beam in the interferometer. In this way a good interference signal was obtained at all times. Fig. 4 shows the ratio of the magnitude of the displacement spectral density in the horizontal plane measured using the suspension to that measured without the suspension, obtained by summing in quadrature the densities along the $\hat{x}$ and $\hat{y}$ axes. As expected, vibrations are amplified at frequencies from about 3 Hz to 12 Hz. For the most part, they are suppressed for frequencies above 12 Hz, with some notable exceptions near 150 Hz and 400 Hz. We believe this to be a consequence of the fact that our suspension has a more complicated modal structure than a simple pendulum. The suspension did not significantly alter the time for the cryostat to cool down to base temperature in the absence of a heat load, nor the base temperature reached by the sample stage.

4. Further comparisons

While the measurements shown in Fig. 2 provide a rather complete description of the vibrations present in the cryostat, showing displacement spectral densities in units of m/Hz$^{1/2}$, it is also useful to compare them to that of a typical laboratory floor. To this end, a commercial accelerometer was used to measure the velocity spectral density in a bandwidth of 400 Hz on the floor of two laboratories at the National Institute of Standards and Technology. Neither laboratory was equipped with any special vibration-attenuating apparatus. One laboratory, however, was in a basement, and had a substantially lower level of vibration than that of the other laboratory, which was located on a second floor. Fig. 5a shows the velocity spectral densities of the cold finger in the cryostat, as shown in Fig. 2a but expressed in terms of velocity rather than displacement, compared to that measured on the floor of the two laboratories. The cryostat is seen to be noisier than the floors over the entire frequency range. Fig. 5b shows the rms velocity as a function of measurement bandwidth obtained by appropriate integration of the curves of Fig. 5a. The cryostat (located in a basement) provides a far noisier environment than either laboratory floor.

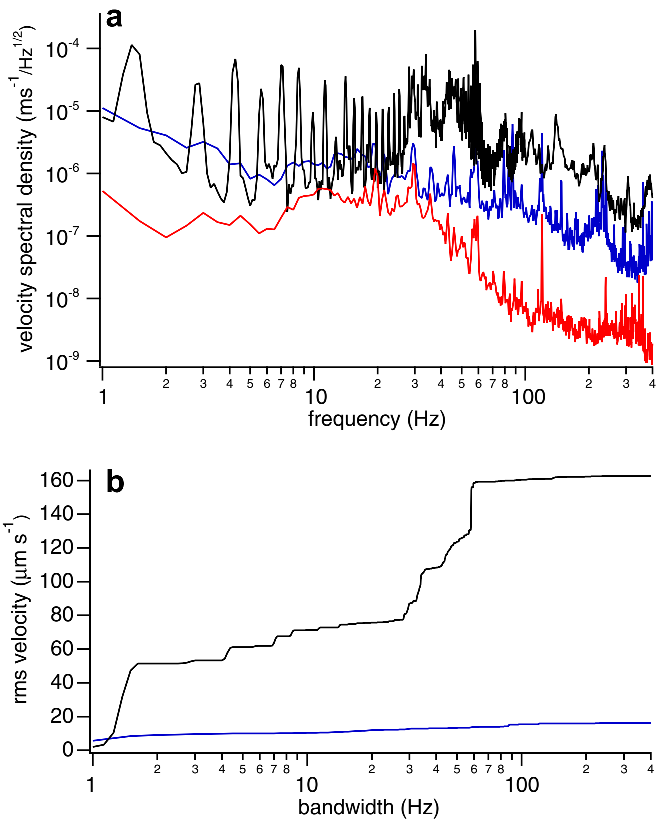

Fig. 5. (a) Quadrature sum of measured velocity spectral densities along three cartesian axes of cryostat cold finger (black/solid line), compared to that of a second-story laboratory floor (blue/dotted line) and a basement laboratory floor (red/dashed line). (b) Corresponding rms velocities as a function of bandwidth. Data for basement laboratory floor not shown. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

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