# Cold-Head Vibrations of a Coaxial Pulse Tube Refrigerator

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## ABSTRACT

We report on the measurements of mechanical vibrations of a two-stage pulse tube refrigerator. With the intention of building a compact cold head, we have developed a prototype of a two-staged GM-Type pulse tube refrigerator (PTR), which prominent feature is a totally coaxial cold finger. The refrigerator uses an active type of phase shifting, where one rotary valve unit controls the entire fluid dynamics in both stages. Novel lead-coated screens make up the inhomogeneous regenerator matrix of the low-temperature regenerator. Even without the use of rare-earth regenerator materials, the cryocooler reaches a no-load temperature well below 6 K. The PTR provides 5 W at 18 K at the second-stage cold head, while the first stage achieves 34 W at 80 K with an electrical input power to the compressor of 6 kW.

Vibration measurements were performed in each of the three Cartesian coordinates of the pulse tube using a Michelson-Interferometer. The frequency spectrums for the three directions are presented for two cooling temperatures: 270 K and 10 K. The vibration amplitude is smaller than 9 micrometers parallel to the cold finger axis; perpendicular to the cold finger axis, the vibration amplitude is smaller than 1.5 micrometers.

## EXPERIMENTAL SETUP

An ordinary bench without special damping devices is the base of the experimental setup. The core of the assembly is the two-stage PTR prototype [1, 2] that is connected to a Leybold RW6000® compressor unit that provides the necessary pressure difference for the refrigerator. The PRK prototype is not specially prepared for the vibration measurements or equipped with additional elements to lower vibrations—like the standard configuration of Wang and Gifford [3].

The PTR cold fingers are installed in a vacuum chamber, see Figure 1. A corrugated pipe makes the connection between the vacuum chamber and a turbo molecular pump that provides a constant pressure of $10^{-3}$ Pa. The molecular pump and the compressor unit are supported by an electrical supply that is operating at a frequency of 50 Hz; this apparatus is found to influence the experimental results. The vacuum chamber has three optical windows to allow the laser beam to be injected into the chamber along the three coordinate axes. In order to create the necessary reflex refraction, a small reflecting badge is attached opposite each window on the cold head of the second stage. The coldfinger includes the first and second stage in a fully coaxial design. The total length of the coldfin-

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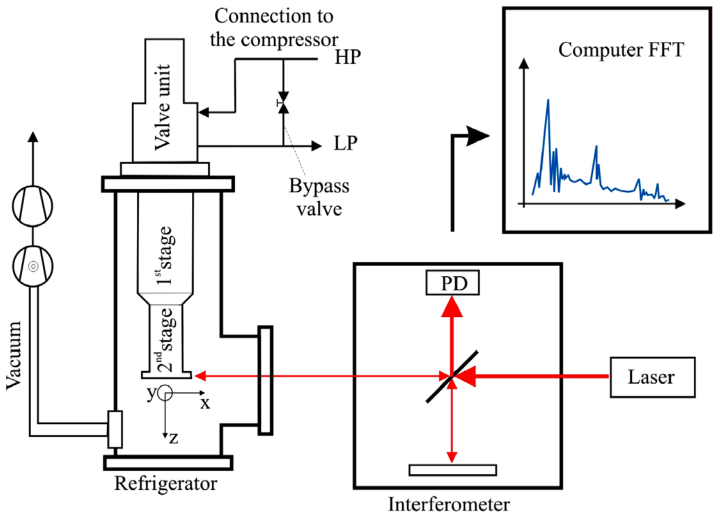


**Figure 1.** Schematic of the measurement setup, including the two stage cold head [1,2,4] and the commercially available Michelson like interferometer – vibrometer made by SIOS® [5].

ger is 500 mm, and both cold tips are made of pure copper. To prevent a falsification of the results by attenuation of the vibration level, thermal shielding materials around the second-stage cold head were omitted. The direct consequence is an increased temperature level because of a higher amount of transferred heat by radiation. Therefore, the achieved no-load temperature is about 10 K.

Figure 1 displays the setup used for vibration measurement of the second-stage cold tip of the coaxial PTR. The reflected laser beam is part of a Michelson-like interferometer called SP-S 120 that is commercially available from SIOS Messtechnik GmbH [5]. The built-in Laser works at a wavelength of 632.8 nm and provides a resolution of 0.3 nm. The measurable frequencies range from 0 to 500 kHz, and the amplitudes have to be less than or equal to 20 mm. More details can be found in [5]. The data of the interferometer are processed via computer and evaluation software developed by SIOS®. This software allows recording of the vibration spectrum via FFT and the maximum deviation for each frequency.

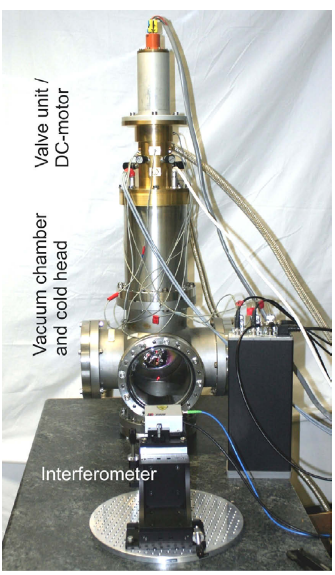


**Figure 2.** Picture of the two stage PTR within the vacuum chamber. There is a compact configuration of the valve unit and the coldfinger (there is no split configuration). The whole assembly is mounted on an undamped laboratory bench. The picture shows the interferometer measuring the vibrations in the x-direction. A second, decoupled, laboratory bench was used to measure vibrations in the y-direction. The second bench was placed to the left side of the PTR (y-direction) and is not shown in this picture.

The measurements were made at nearly ambient temperature level ($T_2$=270 K) and at the no-load temperature of the refrigerator ($T_2$=10 K). At a temperature of 270 K, the full pressure difference that is provided by the compressor unit causes high temperatures at the pulse tubes warm ends. A bypass valve between the high and low-pressure connecting lines controls the pressure difference at both pulse tubes; this permits a controlled cooldown procedure, thus ensuring the integrity of the PRK components. The referred-to bypass valve guarantees control of the cooldown procedure and sets the Äp to values lower than 0.77 MPa. The maximum pressure difference after cooldown (closed bypass valve) is $Äp_{cold}$=0.77 MPa, corresponding to the output of the Leybold RW6000® compressor unit with a filling pressure of $p_{fill}$=1.60 MPa. The vibration spectrum is measured in all three coordinate directions, with the point of origin situated in the centre of the second-stage cold tip. The z-direction is orientated parallel to the pulse-tube axis, while the x and y-directions span the plane perpendicular to the z-axis; the x-axis is situated in the same direction as the corrugated pipes are connected to the compressor unit.

## EXPERIMENTAL RESULTS

The measurements shown in Figure 3 display the vibration spectrum in the x-direction for two different temperatures: 270 K and 10 K. The amplitude levels at all frequencies up to approximately 50 Hz are a little bit higher at 270 K. Furthermore, the ground level at frequencies below 10 Hz is two orders of magnitude higher at 270 K than at 10 K. Higher stiffness at low temperatures is a reason for the lower amplitude level at 10 K and for the significantly lower vibrations ground level at low frequencies. The lower pressure difference at 270 K is also a reason for the only slightly increased vibration level over the whole frequency spectrum. Noticeable peaks in the amplitude are at the fundamental operating frequency of 2.74 Hz and at the harmonics. The higher harmonics are caused by the pressure fluctuation, which is not an ideal sine form. Additionally, peaks were found to occur at 7.7 Hz and at 50 Hz. The 50 Hz peak is caused by the commercial power frequency which supplies the compressor unit and is transmitted via mechanical vibration through tubes and the corrugated pipes to the PTR. The 7.7 Hz peak is not clearly assigned to a source, but is probably caused by the vacuum chamber, maybe in interaction with the molecular pump as discussed later. The maximum amplitude of the vibration of the second-stage cold head in the x-direction is less than 0.8 μm.

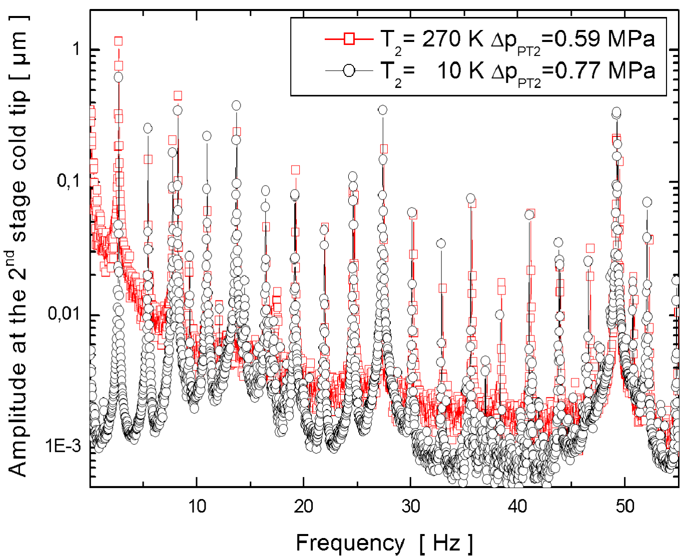


**Figure 3.** Frequency spectra of the measured vibrations in x-direction at 270 K and 10 K. The variation in the pressure difference is caused by a not fully closed bypass valve at 270 K to do not spoil the PTR. The maximum amplitude at 10 K is 0.8 μm in x-direction.

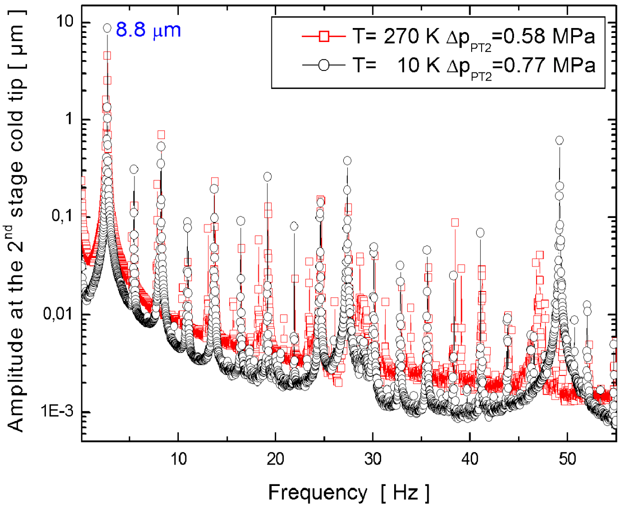


**Figure 4.** Frequency spectra of the vibrations in z-direction at 270 K and 10 K. The variation in pressure difference is caused by a not fully closed bypass valve at 270 K to do not spoil the PTR. The maximum amplitude of vibration is show at the corresponding frequency. The main gas flow is parallel to the z-direction and causes the highest amplitude value 8.8 µm.

The vibration amplitude in the z-direction at a temperature of $T_2$= 270 K is a little bit less than the vibration level at 10 K, see Figure 4. It is important to note that the higher peak at the operating frequency of 2.74 Hz, which has a maximum value of 8.8 ìm, is caused by the pressure oscillation in coaxial direction within the cold finger. Higher stiffness of all components and assemblies is the reason for the lower vibration level at lower temperatures.

In order to compare the measured values at the no-load temperature of $T_2$=10 K in the x- and z-directions, Figure 5 shows both frequency spectra side by side. The peak at the operating frequency of 2.74 Hz is one order of magnitude less in the x-direction than in the z-direction. This is caused by the pressure swing of the working-gas. The length in the z-direction of the pressurized cold head parts is about 8 times greater than in the x- and y- directions. This induces an correspondingly greater

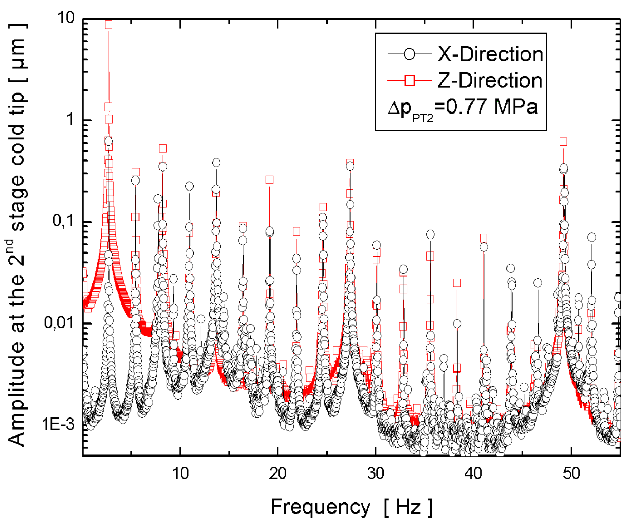


**Figure 5.** Comparison of the vibration spectra at 10 K at a pressure difference of 0.77 MPa. The diagram shows a vibration spectrum in the x-direction perpendicular to the coldfinger axis and a vibration spectrum parallel to the coldfinger axis (z-direction).

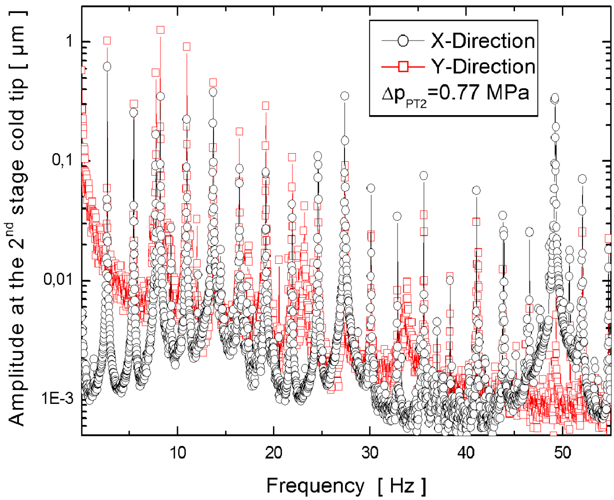


**Figure 6.** Comparison of vibration spectra at 10 K and at a pressure difference of 0.77 MPa. The graphic shows two spectra perpendicular to the inner gas flow direction. The x-Direction is in the plane of the corrugated pipes which connect the molecular pump with the PTR and possibly transmit vibrations from the pump. The measurement of y-direction was made at the base of a separated bench.

mechanical movement of the cold head. Another comparison was made between the x- and y-directions at low temperatures, which is shown in Figure 6. We anticipated an identical spectrum but found a lot of discrepancies that are generated by the experimental setup. In contrast to the other measurements, the setup for the y-direction had to be changed because of insufficient space for the interferometer; as a consequence, a second bench was used to support the interferometer. This arrangement decoupled the 50 Hz vibration caused by the vacuum pump. Additionally, we observed a higher amplitude level in the low frequency range; this is obviously caused by bench resonances. However, the vibration amplitude perpendicular to the coldfinger axis is well below 1 μm. This feature is essentially caused by the coaxial design, compare [7].

To understand the origin of the 7.7 Hz peak shown in Figure 7, the PTR and the vacuum chamber were run in different modes. At first the vibration level of the PTR was measured under normal

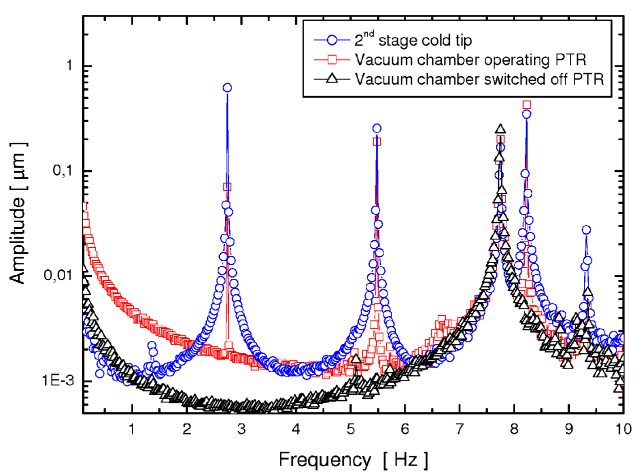


**Figure 7.** Comparison of different measurements in the x-direction is shown to clarify the origin of the 7.7 Hz peak. Circular points show the vibration spectrum measured at the 2nd stage cold tip. Foursquare points show the vibration spectrum at the vacuum chamber window while the PTR is operating and triangular points show the spectrum while switched off PTR.

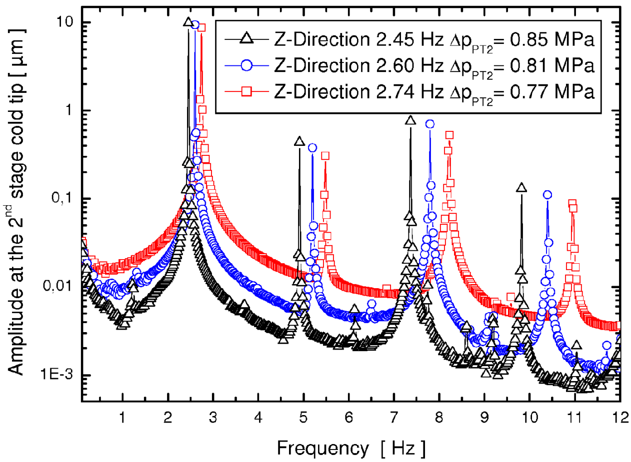


**Figure 8.** Comparison of the different operating frequencies. The higher harmonics are strongly coupled to the operating frequency. Different operating frequencies also cause different pressure differences and slightly different amplitudes.

conditions with the second-stage cold tip at 10 K. Next, the reflection badge was placed on the window of the vacuum chamber, and the PTR was kept running. Hence, the level of vibration interaction between the vacuum flange of the PTR and the vacuum chamber itself could be detected. The third part of the measurement re-included the vacuum chamber spectrum, but this time with the PTR switched off. There are obvious accelerations of the vacuum chamber at the operating frequency of the PTR and its harmonics. The bandwidth of the peaks of the vacuum chamber is smaller. Every time the peak at 7.7 Hz appears, one can conclude that it is caused by the complexity of the vacuum chamber, bench, and molecular pump, and is independent of the vibration spectrum of the PTR.

In summary, the adjustment of the peaks created by the different working frequencies in the z-direction at 10 K is shown in Figure 8. There is a proper adjustment of the peaks with the corresponding operating frequency and the harmonics of the PTR. With lower frequencies, higher pressure differences are enabled (provided by the compressor unit) and lead to respectively slightly increased amplitudes.

## CONCLUSION

The vibration measurements made on the newly developed two-stage PTR with a coaxial-design coldfinger demonstrate the advantages of the coaxial design. Without any special vibration cancellation methods the PTR achieves very low vibration amplitudes perpendicular to the coldfinger axis. From the Michelson-like vibration measurements a maximum amplitude of 0.8 ì m was deduced for the x-direction at an operating frequency of 2.74 Hz. The very low vibration amplitudes in the x- and y-directions are guaranteed by the coaxial design. The amplitude in the z-direction of 8.8 µm can be lowered by reducing the number of separated components of the coldfinger of the PTR and by using a split configuration separating the coldfinger from the driving unit (e.g. the first stage cold head is made of two copper flanges to allow experimental modifications of separated components during the prototype phase).

In the current configuration, without the usage of rare-earth material in the second stage regenerator, the coaxial two-stage PTR achieves a no-load temperature of 5.6 K and provides a cooling capacity of 1 W at 8 K.

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