

PAPER • OPEN ACCESS

Measurements of pressure oscillations and mechanical vibrations

To cite this article: S Putselyk 2019 *IOP Conf. Ser.: Mater. Sci. Eng.* **502** 012167

View the [article online](#) for updates and enhancements.

Measurements of pressure oscillations and mechanical vibrations

S Putselyk

FERCHAU Engineering GmbH, Butzweilerhof-allee 4, 50829 Köln, Germany

E-Mail: sergiy.putselyk@gmail.com

ABSTRACT: Proper measurement technique in particular during trouble-shooting is important for helium cryogenic facilities. Vibration analysis of rotating components as well as pressure monitoring of helium flow can reveal malfunctioning equipment or could give information on the position and sources of the pressure oscillations, e.g. thermo-acoustics or density-wave oscillations. In the present paper, the measurement equipment for monitoring of vibrations as well as pressure oscillations is presented.

1. Introduction

Long-term operation between failures as well as reducing the maintenance periods are important parameters for the modern cryogenic facilities. It is important to correctly detect the malfunctioning equipment, so proper measurement technique in particular during troubleshooting is important for cryostats, cryogenic facilities, or refrigerators. Vibration analysis of the rotating components like turbines or screw compressors as well as pressure monitoring of helium flow can reveal the malfunctioning equipment or could give information on the position and sources of the pressure oscillations, e.g. thermo- acoustic, density-wave, or oscillations caused by rotating equipment.

In the open literature sources, publications on measurement equipment for the helium refrigerators as well as on software or algorithms, which facilitate an interpretation of the measured data, are very limited [1, 8]. This paper presents measurement equipment for the vibration analysis as well as the pressure oscillations.

In the first part, a short review of the vibration measurements applied during standard operation or maintenance periods in cryogenics or low temperature physics is given. The second part describes the pressure measurement equipment and its application areas. Possible sources of pressure oscillations are also discussed there. Next section is devoted to a data analysis.

2. Vibration measurements

2.1. Short overview of application areas

Complexity of the vibration measurements depends strongly on a frequency range and a sensitivity level. Main applications areas could be summarized as follows:

- Cryostats for the ultra-low temperature physics. Dilution units with nuclear demagnetization stage (one or two) require careful damping of vibrations caused by a building or rotating equipment, e.g. pumps. Typically, air bags for damping off mechanical vibrations are installed, and the whole



cryostat could be lifted up by several millimetres. Typical vibration frequency of the buildings is up to 0.1 Hz (mainly in micro- and milli-Hertz range), so inexpensive accelerometers, mounted on the cryostat vacuum vessel, could be applied.

- For some special experiments in the low temperature physics, e.g. on Josephson effect in superfluid He3 or He4, the cell vibrations inside of the cryostat must be precisely measured. This is related to the fact that cell vibrations could cause the pressure variations inside the cell with the superfluid He3 or He4, which in turn destroy the flow of the superfluid component inside small channels. For such experiments, a very elaborative measurement technique is typically developed. Due to a low frequency range and required high sensitivity, superconducting magnetometers based on SQUID techniques are applied, i.e. a superconducting pick-up coil is placed around vibrating elements and the signal is amplified by the SQUID device.
- Mobile and relative inexpensive devices, devoted to a simple monitoring of the vibration spectra of rotating equipment. Such measurement equipment could be very inexpensive, and sensors could be screwed inside the devices under tests, or fixed with small magnets [1, 8]. Such devices are very helpful in monitoring of a long-term variation of the vibration spectra and for a detection of deviations from normal operational parameters of the devices under test, e.g. pumps or screw compressors. It is worth to note that without a detailed knowledge of the pump or the screw compressor design, the exact localization of the malfunctioning part, e.g. bearing, rotor, etc., is very difficult. Though for a routine and continuous monitoring, it is sufficient to permanently install several sensors at the most critical locations.
- Monitoring of the rotational equipment operating at high frequencies, e.g. cold compressors, circulators, or turbines. In this case, sensors must be rigidly fixed on the components and measure three coordinates. Though frequency range is “high”, i.e. up to 15 kHz, it is still sufficiently low that it is possible to find suitable sensors on the market.

So, for the measurement of vibrating equipment with the rotational frequencies up to 15 kHz, it is possible to take a simple accelerometer based vibration measurement device with a sampling frequency of 500 kHz or more.

It is worth to note that in many cases, if abnormal vibrations of the rotating components are measured, which typically indicates on malfunctioning parts inside, this equipment must be sent to the manufacturing firm for repair or maintenance activities. It should be particularly noted that only few cryogenic groups, e.g. JLab [2], have sufficient experience in the maintenance and repair of the large screw compressors, e.g. assembling/disassembling, vibration measurements, adjusting of rotor clearance, etc. So, if any deviation from the normal operation is noticed, the maintenance or repair actions are typically done by specialized companies, which also have versatile vibration measurement equipment and are able to find more details on the malfunctioning item from measurements at their factories or workshops.

It is also possible to apply norms, e.g. ISO 20816, ISO 10816-3, ISO 7919, VDI 3836, VDI 3839 for setting threshold values on the mechanical equipment, e.g. screw compressors, pumps, electrical motors. It should be particularly stressed that these norms give guidance values, and exact ones must be agreed between customers and manufacturers.

2.2. Measurement set-up

For the case of vibration measurements with a good signal-to-noise ratio (S/N), e.g. factor 2 or more, it is sufficient to choose typical measurement devices found on the market. In this case the classical measurement set-up includes:

- Sensor: it is chosen for required measurement range and could be of three types depending on the parameter to be measured, i.e. acceleration, velocity or displacement. In the most practical cases, velocity sensor is sufficient.
- Signal amplification and conditioning: Typically, inexpensive electronics based on MOSFET technology is sufficient.
- Signal filtering and integration: In order not to spoil the signal-to-noise ratio, the frequency range

must be limited (in ideal case, only frequency range to be measured has to be selected by filters). This is achieved by applying filters, e.g. low-pass or band-pass ones. In many cases, band-stop filters are also applied in order to suppress undesired influences from other sources of vibrations. For the further improvement of S/N ratio, an integrating filter could be applied.

- Data storage and analysis.

The analogue-digital conversion could be performed either after signal amplification and filtering or only after signal amplification from the sensor chip (sensor chip typically includes sensor and first amplification stage). The second method typically gives better S/N ratio and provides more flexibility on a signal processing. Further details on the classical vibration measurement could be found in the specialized literature [5-6].

In case if S/N ratio is 1 or below, a customized measuring system must be applied. The best experience could be summarized as follows:

- Chip (sensor with signal amplifier): the most sensitive chip should be chosen. Typically, capacitive quartz piezoelectric sensors give the best signal response.
- Lock-in amplifier: in order to improve the signal, a very narrow pass-band filter must be applied. This could be realized by Lock-in amplifier, e.g. Stanford SR810/830/850/860. The Lock-in also amplifies the signal to high voltage for Analogue-Digital-Converter.

Figure 1 shows the measurement set-up used for a detection of the mechanical movement of metal components (or metallized membrane) for the temperature range of 10 mK and below. Main challenge is a reduction of the cryogenic heat load, which should be below 1 μ W for operation with the dilution unit or 1 nW for the nuclear demagnetisation stage.

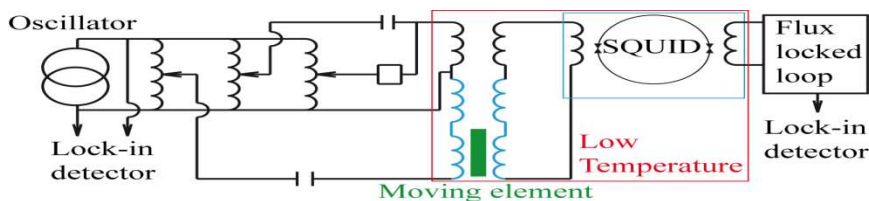


Figure 1: Measurement set-up for vibration measurement at cold state for the temperature range of 1 μ K – 10 mK

In many cases, it is also necessary to calibrate the measuring set-up by introducing vibrations on the device under test (DUT). The best suitable vibrating sensor for temperature below 1 K is based on piezo-elements. Its resonance frequencies are either known or could be measured, and frequency variations are also possible in a relative wide range.

It is also possible to perform the vibration measurements at cryogenics temperatures on small objects, e.g. experimental cells. The best practice is to apply bare-chip capacitive measuring sensors and piezo-elements for the calibration. Extra efforts should be taken for calibration of single components and the whole measurement set-up at cryogenic temperatures.

3. Pressure measurements

3.1. Possible sources of pressure oscillations at low temperatures

Before one starts discussing of pressure measurement equipment, it is worth to discuss the possible sources of pressure oscillations inside the cryogenic system.

3.1.1. Thermo-acoustic oscillations. These oscillations occur in the capillaries placed between warm and cold sources. Due to a heat transfer between helium and the capillary wall, a temperature gradient along the capillary occurs, which leads to a periodic cooling (gas volume reduction) and or warming (gas volume expansion) of helium. Typical frequency range is 1-50 Hz. It is possible to indentify and influence these oscillations by placing a variable flow impedance and a small volume at the warm end of the capillary. It is worth to specially mention that if dynamic pressure measurements have to be carried out on the cold system, the connecting capillary should be quite large in the cross-sectional area in order to have low damping and less probability of the thermo-acoustic oscillations [3, 4, 7].

3.1.2. Density-wave oscillations. These oscillations occur in the supercritical helium, if operation points are located at different sides of the transposed critical line. Due to different thermal expansions coefficients, periodic expansions/shrinkage of helium volume occurs. It is possible to identify and influence these oscillations, if one changes the pressure level or mass flows in order to stay at one side of the transposed critical line. Typical frequency range is up to 10 Hz.

3.1.3. Standing waves. These waves are detected in transfer lines, where multiple reflections on walls occur. In many cases, it is quite difficult to identify them by changing of the mass flow, pressure or temperature, because sound speed is relative constant, and signal width is wide due to multiple reflections on different imperfections inside the transfer line, e.g. tee-pieces, welds, small bends. Typical frequency range is up to 10 Hz, but strongly depends on the size of transfer line.

3.1.4. Heat transfer in single or two phase helium. These oscillations occur in the cryogenic systems with heat transfer, if a restriction for the mass flow is present. In this case heating load leads to periodical increase and decrease of the temperature and pressure, this in turn leads to a variable mass flow over the restricting element, e.g. orifice. It is possible to identify and influence these oscillations by a variation of the mass flow or a heating power. Expected frequency range is up to 10 Hz but typically in mHz range.

3.1.4. Rotating equipment and cold check valves. Pressure measurements of the rotating circulators, compressors or turbines is a very challenging task at low and room temperatures, due to slow response time of pressure transmitters and damping in the connecting lines/capillary between sensor and rotating equipment. Other sources are rotating stall (surge), choke or shock waves, which are typically present at rotating equipment working in the near of Mach number 1 or below, but according to the authors' knowledge, no measurements of shock waves were performed for turbines or compressors at the cold state. It is worth also to mention that for the protection of rotating equipment against external pressure variations, the cold check-valves are usually installed. These devices could have periodic opening/closings of the free cross-sectional area, which leads to the pressure and mass flow variations. It is possible to identify and influence these oscillations by a variation of the mass flow. Expected frequency range is up to 10 Hz but typically in mHz range.

Pressure measurement in warm lines is relatively simpler in comparison to cold lines due an avoidance of connecting capillaries impedances and possible disturbance due to thermo-acoustic oscillations.

It is also important to choose the sensor with a maximal sensitivity for a given pressure range. In the cryogenic systems, the operation pressure can vary from few mbar till 20 bars, e.g. during cooling-down or warming-up, so finding sensitive sensors with a sufficiently high pressure overload is always a challenge. In some cases, it is possible to install two parallel pressure transducers with separating valves for specific pressure ranges, e.g. 4-20 bars and 0-100 mbar.

3.2. Measurement set-up

3.2.1. Room temperature set-up and warm piping system. The standard pressure measurement system applied for industrial automation systems uses simple and robust sensors, e.g. based on Siemens Sitrans, ABB, or Rosemount transducers, and has low data acquisition rate, typically 1-2 Hz. Such system could efficiently measure pressure oscillations in mHz range in the warm piping system. For the higher frequencies, it is possible to apply measurement sensors and standard set-ups specially developed for dynamic pressure measurements, e.g. 113B-Serie for room temperature and 102A10 for cryogenic ones from PCB Piezotronics. For the customized and inexpensive solutions, which could be applied for short-time measurement periods, it is possible to use "bare" pressure sensor chips with first stage amplifiers, e.g. Siemens (or Infineon) KPY-series.

3.2.2. Room temperature set-up and cold piping system. In case of cold pipings, the connecting capillaries are long and have small cross-sectional areas (typically tubes 6*1 or 4*0.5 mm are installed), so the measured frequency of the cryogenic system is significantly influenced by the flow

dynamics in such capillaries. Moreover, thermo-acoustic oscillations could be also induced. In order to overcome this challenge, a relative wide tube, e.g. above 20 mm should be used (otherwise a cryogenic pressure transmitter, see next paragraph for more details, must be applied). Similar to dynamic measurements on warm piping, either customized “bare” chip sensors (e.g. KPY-series) or dynamic measurement set-ups could be applied.

3.2.3. Cryogenic pressure transmitters and cold piping system. At the present time, no cryogenic sensors and set-ups are available on the market for the cryogenic measurements at helium temperatures. For that reason, sensors should be tested and calibrated at helium temperatures before an installation inside the cryostats or cryogenic facilities. As an example of arbitrary chosen pressure transmitters, the KPY-series, could be considered. Specially for dynamic measurements, company PCB Piezotronics offers a cryogenic sensor, models 102A10 (maximal pressure is 6.8 bar, low frequency response 0.5 Hz, rise time <1 μ s, and operation range up to 250 kHz) working till LN2 temperatures. The minimal supply current is 2 mA, supply voltage – 24 V, so the total cryogenic heat load is around 50 mW. Other sensors, found on the market and designed for $T > 77$ K (but probably could be used down to 4K) can be summarized as follows: i) Kulite, CCQ-062, 093, CTL-190(M), 312(M), 375(M), ii) Omega, PX1005, iii) GP:50, 311-QX, 7710, 7720, 7730, iv) Omicron: CP6700.

4. Data analysis

Depending on goals of the pressure and vibration analysis, the processing of available data could be very different, e.g. from simple Fast Fourier Transformation (FFT) till waterfall (also called cascade, or dynamic Campbell) diagrams or in some cases till cross-correlations functions and probability analysis.

For routine measurements on screw compressors, pumps or electrical motors standard devices, e.g. *Machinery Health Analysers* from Emerson, are very helpful. Such device could also guide users to typical types of the machinery failures or measurements, e.g. bump tests, coast down, order tracking, synchronous analysis, orbit plot, cross-channel analysis of amplitude or phase, etc.

In case of signal-to-noise ratio below 1, ones needs to apply customized solutions for each case, e.g. using “analogue” methods, e.g. Lock-In technique, SQUIDS; or “software” ones, e.g. cross-/autocorrelation, coherence functions, etc.

5. Summary

In the present paper, a short overview on measurements of pressure oscillations and mechanical vibrations in the cryogenic systems is presented.

References

- [1] Pflueckhahn D., Anders, W., Hellwig, A., Knoblock, J., Rotterdam, S. 2014. Vibration Measurement and Analysis on a Helium Cycling Compressor, *International Workshop on Cryogenics Operation (poster session)*, Daresbury, UK
- [2] Knudsen, P. 2004, Availability, Maintenance and Reliability of JLab Cryogenic Plants, *International Workshop on Cryogenics Operation*, (session: Maintenance, Rapair and Reliability) Jefferson Laboratory, USA
- [3] Haug, F., and McInturff, A. 1990. Measurement of pressure transmission in long capillaries, *Advances in Cryogenic Engineering*, **35** p1583-1591
- [4] Casas J., et al. 2017. Design of 0-50 mbar pressure measurement channel compatible with the LHC tunnel radiation environment, *IOP Conf. Ser.: Materials Science and Engineering* **171** 012141
- [5] Smith, J. D., 1989, *Vibration Measurement and Analysis*, Butterworths & Co. (Publishers) Ltd, p162
- [6] Buzdugan, G. et al. 1986, *Vibration Measurements*, Springer Science + Business Media, p.347
- [7] Jeanmonod, N. et al. 2005. Qualification of sub-atmospheric pressure sensors for the cryomagnet bayonet heat exchangers of the Large Hadron Collider, *Advances in Cryogenic Engineering* **51** p1219-1226, see also LHC-Project-Report-980
- [8] Pirotte, O. 2016. Vibration monitoring of the rotating machinines of the CERN cryogenic systems, *International Workshop on Cryogenic Operation*, Fermi National Accelerator Laboratory, USA