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# TESTING A LOW-COST SENSOR SOLUTION FOR MACHINE CONDITION MONITORING

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***Abstract***— The MachMoS sensor node is a compact, wireless system for vibro-acoustic and temperature monitoring first presented in 2024. It is controlled by an ESP32-C3 and integrates a KX134 MEMS accelerometer, ICS-43434 microphone, and pt1000 resistive temperature detector. The sensor is enclosed in a low-cost enclosure which is made of a combination of machined aluminum components, a fused filament fabricated lid, and off-the-shelf hardware. This paper reports on qualification testing of the device conducted to date. Due to memory constraints, accelerometer and microphone data rates were reduced to 12.6kHz and 21.854kHz, respectively, down from 25.6kHz and 51.2kHz. Vibro-acoustic testing confirmed the MachMoS node reliably captures vibrations up to 6kHz and acoustic signals beyond 7kHz. Frequency content analysis showed consistent peak frequency discrepancies of 1.5% and 0.7%, likely due to clock inaccuracies. Nonetheless, anti-aliasing filters were effective. Ingress protection testing confirmed an IPX7 rating after enclosure refinements, reinforcing the applicability of fused filament fabrication in the low volume production of low-cost enclosures. Temperature testing demonstrated accuracy of ±0.25°C and operation down to -15°C. The MachMoS sensor node exhibits reliable sensing capabilities, with future work focused on code optimization, clock accuracy, and extended temperature range.

***Keywords-Machine Condition Monitoring; Open-Source; Open-Access; Machine Monitoring Platform; Hardware Design; Hardware Testing.***

## I. Introduction

Machine condition monitoring (MCM) has historically relied on temperature, vibration, and acoustic data to assess machinery health. Long before the advent of modern sensors, humans relied on their own senses for monitoring. However, industrial automation has reduced the physical presence of personnel in factories, shifting the responsibility of monitoring to smart sensors and remote diagnostic systems to prevent costly downtime and failures. With the increasing automation of not just machinery but also data interpretation through artificial intelligence (AI), MCM must also evolve. A critical challenge in AI-driven fault detection and prognosis is the limited availability of real-world training data. Industrial MCM data is typically proprietary, restricting researchers to synthetic or controlled laboratory datasets. Unfortunately, models trained on these datasets often exhibit poor generalization and high sensitivity to noise, rendering them ineffective in real-world industrial applications [1], [2].

To counteract data scarcity, research has increasingly focused on optimizing model accuracy with limited data. While valuable, this approach overlooks the vast industrial datasets that could significantly improve AI-driven MCM [3]. As big data and Industry 4.0 technologies advance, data collection, storage, and processing have become more accessible than ever. This work introduces a cost-efficient, open-access prognostics and health management (PHM) system for researchers and details the testing of an open-access smart sensor node for real-world data acquisition. The system comprises a platform for MCM, as well as a low-cost rugged and waterproof sensor solution that is manufacturable by most modern machine shops equipped with a mill, a lathe, and a fused filament fabrication (FFF) 3D printer. The work focuses on the validation of the microelectromechanical system (MEMS) accelerometer and microphone pair as well as the thermometer setup used through comparison against sensors used in the field, as done previously by Gopalakrishna et al. [4] and K. Guru Manikandan et al. [5]. Additionally, the work aims to evaluate the water-tightness of the enclosure, as little research has been conducted on the use of FFF for the manufacturing of watertight enclosures despite the manufacturing method having shown promise in submersion testing [6].

## II. OpenPHM and MachMoS Node Device

While many sensors exist for MCM, these are often prohibitively expensive for small industry stakeholders, and sold as part of closed Internet of Things (IoT) systems which do not allow for data to be exported nor uploaded to custom services. OpenPHM is a PHM platform developed by the Dumond Design Lab (DDL) for researchers and industry alike, which offers data upload through secure Hypertext Transfer Protocol (HTTP) requests [7]. Due to the ease of uploading to OpenPHM, some existing IoT systems in industry could be reconfigured to upload their data to the site directly. The end-goal is to create a community of researchers that will have access to vast quantities of data acquired in industry, which can be used to train MCM-specific AI models. In exchange for their data, industry partners will have access to cutting edge MCM AI models for monitoring the health state of their machines [8].

The MachMoS Node is a low-cost open-access temperature and vibro-acoustic measurement device that is part of an IoT system designed by the Dumond Design Lab (DDL) at the University of Ottawa. The device is to be used in conjunction with OpenPHM and is pre-configured to send data to gateway devices that are designed by the DDL. The design of the node/gateway pair is part of an effort to provide industry with a simple, low-cost solution to their PHM needs. The node device was designed in 2024 based on requirements set by stakeholders and the DDL. The device design is open-access and its enclosure is designed to be manufacturable by most machine shops, thus featuring an aluminum 3-axis CNC milled base, manually turned aluminum centre stem and Fused-Filament Fabricated (FFF) Acrylonitrile Styrene Acrylate (ASA) cover (3D printed cover) [8]. However, the node is yet to be tested against its mechanical and electrical requirements. This paper reports on the tests conducted for durability and accuracy/precision. The design metrics tested and reported in the paper are as follows:

The MachMoS Sensor Node shall

- support the reliable capture and transfer of signals which oscillate at 6kHz
- support the capture and transfer of temperature data with ±1°C accuracy
- meet IP54 (IP67 preferred) ingress protection as laid out by IEC 60529
- be rugged enough to work at temperatures from -40°C to 130°C

## III. TESTING

### A. Accelerometer and Microphone Testing

The MachMoS node is equipped with a *Kionix* KX134-1211 tri-axis accelerometer, as well as a *Invensense* ICS-43434 microphone. To ensure the usefulness of the device, it is imperative that the frequency range, data rate, immunity to aliasing, and the measured amplitudes of the accelerometer/microphone pair be tested thoroughly.

To achieve this, the device was tested using a vibrator/exciter driven by a waveform generator. The accuracy of the device is compared to results acquired using an off-the-shelf accelerometer and microphone combination. As for the range of the devices (bandwidth) and response, these are evaluated by testing the system at various frequencies within the desired range and comparing the acquired data to that of an off-the-shelf analog accelerometer and microphone. Finally, the achievable data rate of the device is validated by setting the KX134-1211 to its maximum ODR (25.6kHz) and the microphone to double that ODR (51.2kHz) and ensuring that none of the data is lost or corrupted during data capture.

Since the exciter setup itself is not tested to a standardized specification, it is not possible to know what output is expected given particular input signal amplitudes and frequencies. Drawing a baseline helps in evaluating the node device through comparison of the baseline and node data. However, baseline measurements on equipment with an unknown response has its issues. Measurements cannot be taken individually as the exciter's response is different depending on the center of gravity of the device under test (DUT) as well as the load on the exciter. Due to this, both benchmark and node accelerometers must run simultaneously to ensure they are measuring the same vibrations.

#### 1) Experimental Setup

In this test, a *Brüel & Kjaer* vibration exciter type 4809, which can oscillate at frequencies ranging from 10Hz to 20kHz, is used as a vibration source. To drive the exciter, a *Bogen* Classic C60 Mixer Amplifier is used to amplify signals from a *Keysight* 33500B Waveform Generator. To monitor the signal going to the vibration exciter, a *GW Instek* GDS-1152A oscilloscope is used. As a benchmark accelerometer, the IMI 623C01 accelerometer from *PCB Piezoelectronics* is used to create a baseline measurement. The IMI 623C01 has a rated linear bandwidth of 0.8Hz to 15kHz, a resolution of 100µg, and at most 7µg/√Hz of spectral noise, making it an accurate and reliable sensor for benchmarking the KX134 (tested at 6kHz, it has a resolution of at most 240µg and is much noisier, with 300µg/√Hz of spectral noise at its lowest data rate). As the benchmark is a single-axis accelerometer, it is necessary to orient it along one of the axes of the KX134. The vibration exciter is therefore equipped with a custom mount made of steel, which can hold the benchmark accelerometer in three different orientations, all oriented to the KX134. As the vibration exciter can only move along one axis, the MachMoS node is oriented at a compound angle of 45° around the horizontal axis (pitch) and 45° around its vertical axis (yaw). The setup is shown in Fig. 1, where the benchmark can be seen in phantom lines in its three possible configurations, aligned with the KX134.

A benchmark microphone (not shown in Fig. 1), the *PCB Piezoelectronics* 130F20, is also used in the setup. The microphone is mounted to a tripod to ensure it is reasonably isolated from the vibrations generated by the test setup. The 130F20 is rated for capturing signals between 10Hz and 20kHz.

Both benchmark devices are connected to a Sensor Signal Conditioner (*PCB Piezoelectronics* Model 482C), which is wired to a computer via a Universal Serial Bus (USB).

The test consists of starting the exciter at a set frequency and amplitude, which is verified on the oscilloscope for accuracy. A Python script is then used to simultaneously start capturing data with the benchmark and MachMoS node. The capture lasts one second, and the data is saved to the computer. The data is then displayed for analysis.

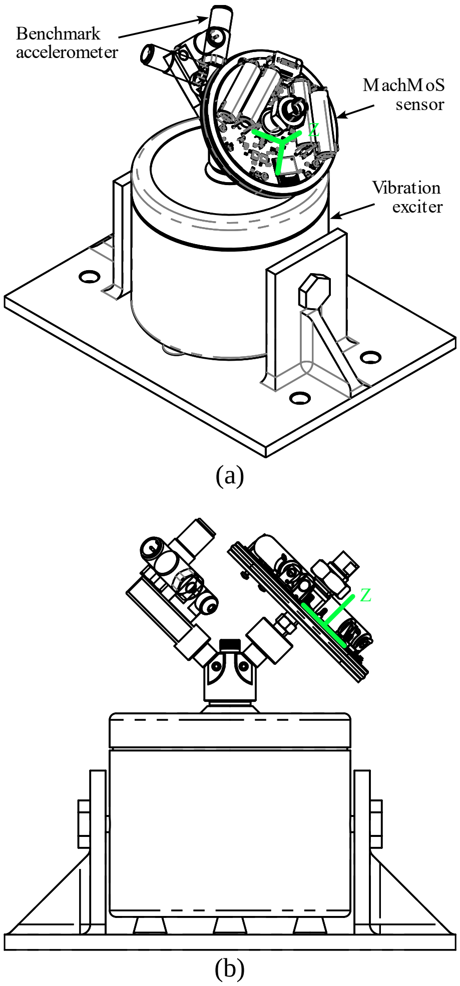



Figure 1. Vibration test setup (KX134-1211 coordinate system shown in green)

2) *Results*

a) *Data Rate*

While testing the achievable data rate of the MachMoS device, it was determined that the on-board flash memory is not fast enough to support the accelerometer and microphone capturing data simultaneously. A second of data (the expected capture length) at the maximum capture rate is 301.2 kilobytes (kB). Given the ESP32-C3's random access memory (RAM) being limited to 400kB, only 98.8kB of free memory is left, which is insufficient to store the program that is used to operate the sensor (not to mention memory fragmentation at runtime). Due to this, it is necessary to move data from the ESP32-C3's RAM to the on-board flash memory (4 Megabytes, MB) as fast as possible to make room for more data uptake from the RAM. However, transferring data from the RAM to the flash requires the single core operating on the ESP32-C3 to intermittently cease capturing accelerometer data, making the transfer complex. Efficient use of interrupts might allow the transfer, but this has not yet been implemented. As the device does not have enough free RAM to store a full second of data at the maximum data rate, the accelerometer's rate was reduced to 12.6kHz and the microphone to 21.854kHz. This leads to a total of 141.162kB for one second of data, pending code optimization which will reduce RAM usage and potentially allow the use of the flash memory.

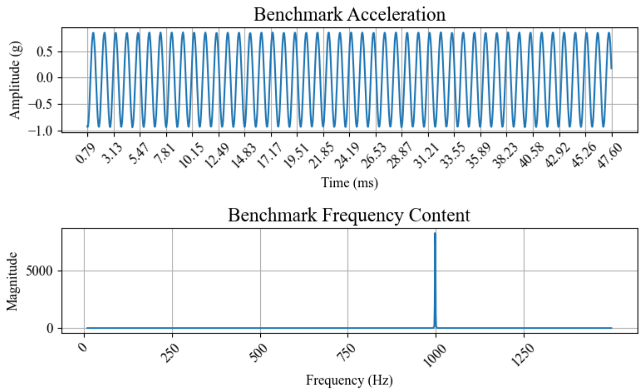
b) *Vibro-Acoustic Measurements*

Given the modified capture rate on the accelerometer, the maximum Nyquist frequency for the setup was determined to be 6.4kHz, such that testing was limited to that frequency. Tests were conducted for 20Hz, 50Hz, 100Hz, 500Hz, 1kHz, 2kHz, 3kHz and 6kHz to cover most of the range. Since the plots of the results are large, it is impossible to show them all. However, an example of the accelerometer and microphone data, as well as their frequency content for the 1kHz capture are shown in Fig. 2.

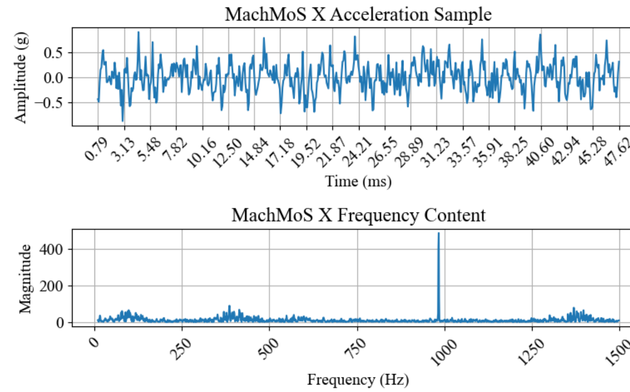
As can be seen in the figure, the accelerometer benchmark signal is very clean compared to the KX134 accelerometer. Despite this noise, however, the frequency content of the signals are conclusive on the vibrations being primarily at or around 1kHz. In this example, the peak for the benchmark is at 998Hz, whereas those of the MachMoS node is found at 983Hz (specifically, 983.70 ± 0.02 Hz, a 1.5% error) for all three axes (after using quadratic interpolation to find the true peak between frequency bins). This discrepancy should be investigated further but could be caused by inaccuracy in the KX134 internal clock, or the ESP32-C3 clock, though it is important to note that the 1.5% error is consistent within ±0.1% across all tests conducted. It should also be noted that a test conducted at 6.3kHz was too attenuated to draw conclusions. The peaks for the microphone tests were at 998Hz and 991Hz for the benchmark and MachMoS node, respectively (0.7% error, also consistent within ±0.1 throughout the tests). As the MachMoS microphone uses the Inter-Integrated Sound (I2S) protocol, for which the clock signal is generated by the ESP32-C3, the discrepancy in frequency can only be attributed to the accuracy of the clock signal generated by the ESP32 in this case.

As for the amplitude of the raw signal, as measured by the device, the benchmark measured an amplitude of approximately 1.8g peak to peak. While it is not possible to know what a benchmark placed along the Y and Z axes would measure exactly, vector math can be used to estimate that the exciter was generating accelerations of approximately 3.6g along the vertical, such that the Z-axis of the KX134 would have measured an acceleration of 2.5g. The Y axis is oriented at the same angle as the X axis relative to the vertical, and such, should read the same values as the X axis.

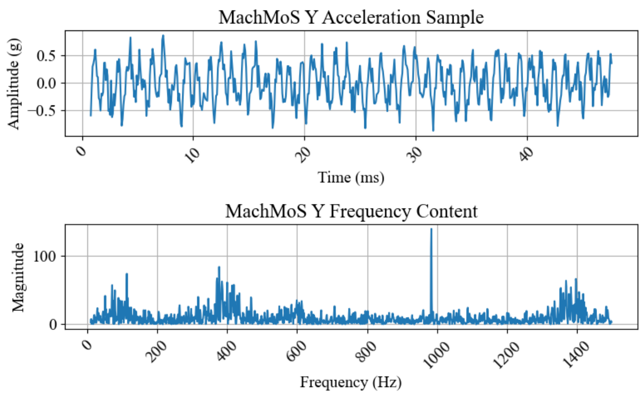
In the test, the MachMoS node measures peak to peak values for the X, Y and Z axes of 2.0g, 2.1g, and 2.6g peak to peak, respectively. If slices of 128 samples (10 cycles) are isolated, the average peak to peak amplitudes are 1.8g, 1.4g, 1.6g, and 2.1g for the benchmark, and X, Y, Z axes, respectively, a discrepancy of 0.2g, 0.3g and 0.1g on the full second of data, attributable to measurement noise and signal drift in the capture. It should be noted that the noise floor on the captures show noise at frequencies of approximately 100Hz, 400Hz, and 1.4kHz. While the enclosure's resonant modes might be suspected of causing this, the noise magnitude is similar in all captures, regardless of whether the exciter is set to a frequency below or above the suspected resonant modes, meaning that the most likely explanation is that the noise is introduced by the KX134 during capture. The microphone data does not feature this noise.



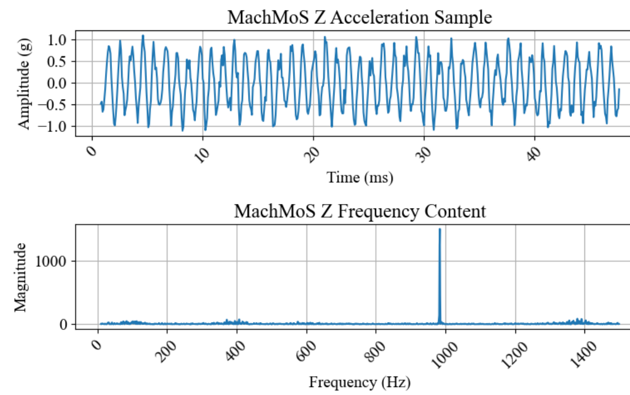

(a) Benchmark Accelerometer (along X, normalized)



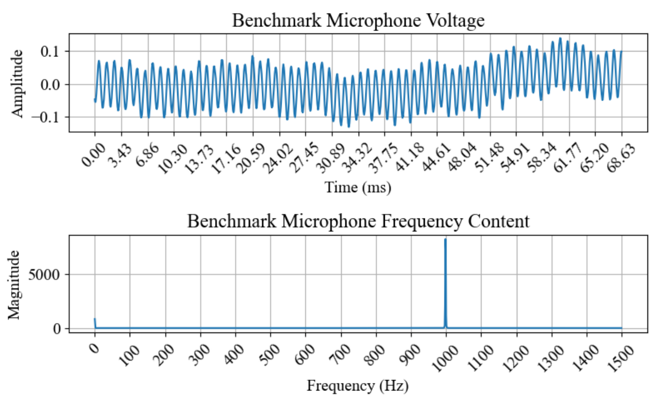

(b) MachMoS Accelerometer X Axis (normalized)



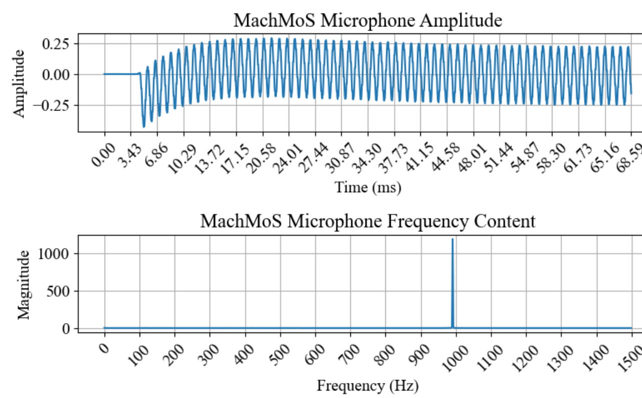

(c) MachMoS Accelerometer Y Axis (normalized)




(d) MachMoS Accelerometer Z Axis (normalized)




(e) Benchmark Microphone




(f) MachMoS Microphone

Figure 2. Accelerometer and Microphone Results. All data is shown normalized and trimmed

*c) Anti-Aliasing Testing*

An important consideration when selecting the KX134-1211 and ICS-43434 was to make sure these sensors were equipped with an anti-aliasing low pass filter, as aliased signals can lead to erroneous machine diagnostics and are very difficult to filter once a signal is captured. On the accelerometer, the filter cut-off can be set to either half of the output data rate (ODR) or a ninth of the rate. All tests were conducted with a filter cut-off of ODR/9 (1.42kHz). A low pass filter with a cut-off at 41.7% of the sampling frequency is also built into the microphone. To test for aliasing in the accelerometer data, the exciter was set 600Hz higher than the Nyquist frequency of the accelerometer (6.4kHz), to 7kHz. As the signal frequency is higher than the Nyquist frequency, the peak in magnitude in the frequency content is expected to fold back into the frequency content representation of the signal, leading to an expected peak at 5.8kHz. The resulting frequency plot shows a peak at 6989Hz in the benchmark, and peaks for all three axes at 5898Hz in the accelerometer data, showing aliasing, though these peaks are lower than the noise floor for the capture and the measured signal is significantly weaker than that of the benchmark. The discrepancy from the expected peak (5811Hz) is 1.5%, as observed in the previous captures. The microphone (Nyquist frequency of 10.9kHz, filter cut-off of 9.1kHz) was tested at 12.6kHz for aliasing and shows no aliasing.

*3) Conclusion*

It is possible to conclude from the vibro-acoustic testing that the MachMoS node is capable of reliably capturing vibration signals up to 6kHz and acoustic signals up to (at least) 7kHz. While the signal to noise ratio is not as high as that of the benchmark, it should be noted that the frequency content of the signal shows a very well-defined peak at the frequencies of interest, showing that the device's data is suitable for condition monitoring. It may also be concluded that the device does not suffer from aliasing, an important characteristic for MCM sensors.

### B. Ingress Protection Testing

The MachMoS sensor node was designed to achieve an ingress protection (IP) rating of IP54 at a minimum, though an IP67 rating is preferred by industry. IP ratings rate the level of protection an enclosure offers a device as per requirements set by the IEC 60529 standard [9]. The first number in the designation refers to protection against ingress of solids (from least to most stringent: spheres, rods, and dust). The second number in IP ratings refer to the protection of a device against ingress of water. An X for any of these numbers refer to an untested parameter. The MachMoS device is not tested for solid ingress protection as part of this paper.

The test for the IPX7 level of protection consists of placing the DUT at a depth of 1m under water, for 30 minutes. The device is then opened and inspected for any water ingress. If water is present in the device, the quantity of water that ingresses the device must not be sufficient as to cause failure of the device. The standard additionally specifies that the test is to be performed with the device in the orientation in which the device is to be installed during normal operation [9].

The whole MachMoS device is tested as-is for ingress protection. However, the microphone hole at the bottom of the device is sealed. This is done as the hole is protected by an acoustic vent that is already rated against an IP standard. This acoustic vent is upgradable to IP67, such that it would meet IPX7. The IP rating of the MachMoS node would therefore be that of the least amount of protection between the enclosure with the sealed vent and that of the acoustic vent. The IP67 vent is not used by default in the device to keep the device cost as low as possible.

*1) Experimental Setup*

The electronics in the device are completely removed for the test and replaced by a sheet of absorbent towel, used to detect water ingress. The test is conducted as outlined in the IEC 60529 standard and considered failed if the towel or the inside of the enclosure is humid at the end of the test.

As the device does not have a specific orientation in which it is to be used, the test must be performed at various angles. In this case, the device is tested once upright and once upside-down. The device is made negatively buoyant and is oriented in the water using a weight with a 1/8 NPT tapped hole and union, attached to the bottom of the device in the first test, and to the top of the device in the second test.

Before the test, the hole in the bottom of the enclosure reserved for the microphone is blocked using vacuum sealant tape (also known as "tacky tape"), such as that which is used in composites manufacturing.

*2) Results*

Preliminary tests in a stainless-steel vat of approximately 0.2m deep did not lead to leakage of water inside the enclosure. This preliminary test allowed for the evaluation of the efficacy of the vacuum tape as well as the identification of voids in the 3D printed shell's outer surfaces.

The device was then moved to a 1.3m-deep concrete vat filled with salt water for further testing. An initial test was unsuccessful, as the enclosure could not close fully. The top of the device's enclosure was too tight against the bottom O-ring used in the device, which was attributed to shrinkage in the 3D printed lid. The diameter of the interfacing face was increased by 1% to account for shrinkage of the 3D printed cover following calibration tests. This allowed for the complete threading of the cover onto the device, sufficiently compressing the O-ring. The device was re-tested at the bottom of the vat in both upright and upside-down orientations. The test showed successful results, with no signs of ingress after thirty minutes, as prescribed by the standard.

*3) Conclusion*

It may be concluded that the MachMoS enclosure meets the requirements of IPX7, as prescribed in the IEC 60529 standard. While IP testing against ingress of solids was not conducted, a successful IPX7 test shows that the device offers some level of protection against solid ingress. The successful ingress testing of the device shows that an enclosure manufactured using FFF can be used in watertight applications.

### C. Temperature Measurements

The MachMoS sensor node is equipped with a pt1000 resistive temperature detector (RTD). This pt1000 functions by using a known transfer function of temperature to electrical resistance. The resistance of the pt1000 can be translated to a potential difference by an Analog to Digital Converter (ADC). The ADC used in the MachMoS device is the ADS1120 by Texas Instruments. This ADC is very well suited for this type of application as it is equipped with a configurable current source that can be used to excite the RTD with a known amount of current. Since the current is known, and the ADC reads the potential difference, Ohm's law can be used to calculate the resistance of the RTD at the moment of capture by simply taking the ratio of electrical potential to current, yielding the resistance of the RTD. The resistance can then be used in the Callendar-VanDussen equations to convert the resistance value to a temperature value.

To test a temperature device, it is possible to place the DUT in an environment of known temperature for long enough and to measure the temperature read by the device until it settles. The issue with this method is the need for an accurately regulated environment. A simpler method for testing adequately ingress-protected devices is to submerge the device in an ice bath, of which the temperature is known to be 0°C. The testing of the MachMoS node temperature sensor is different from that of the usual ice bath test as the device cannot be completely submerged in the ice water to allow for monitoring the device via a USB cable. This leaves the bottom of the enclosure partially exposed to ambient air, leading to some heating of the device which would affect readings. The test had to, therefore, be modified to measure the freezing of water around the MachMoS node, as explained in the experimental setup.

#### 1) *Experimental Setup and Assumptions*

In this testing setup, the MachMoS device is partially submerged in a bowl of ice water. This bowl is then placed in a freezer set to -16°C, with a USB cable leading to the device, to be used to monitor the device and capture temperature data. As the water in which the device is submerged transforms to ice, the temperature of the water is expected to plateau at 0°C for an extended period, and then to start falling again as the (now formed) ice is cooling. It was assumed that no supercooling occurs during the freezing process.

#### 2) *Results*

Results of the ice water test can be seen in Fig. 3. In the figure, a discernable plateau is present between -0.25°C and 0°C.

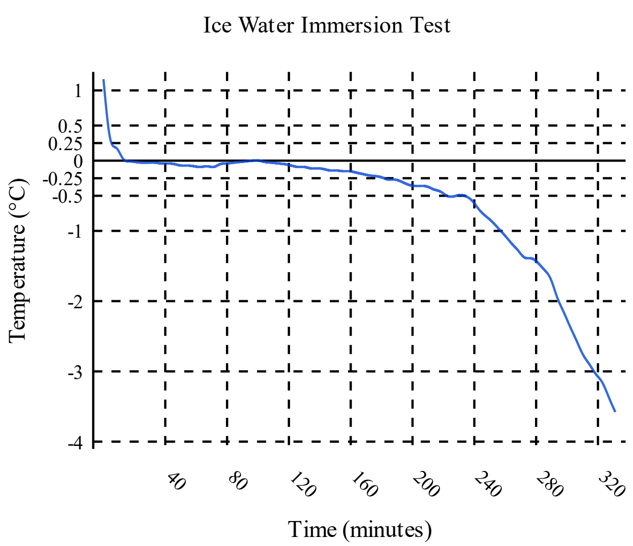



Figure 3. Ice Water Immersion Test

#### 3) *Conclusion*

From the results, it is possible to conclude that the MachMoS device is accurate to at least ±0.25°C. As a corollary to freezing the device, it may also be concluded that the device is capable of resisting temperatures below 0°C (down to -15°C) all-the-while capturing data. However, the original metric of -40°C must still be tested. Given the accuracy of the device, one must consider that the accuracy is unnecessarily high for the given application, in which the true temperature of the machine being monitored is not as important as the relative variation in temperature.

## IV. Conclusions and Future Work

It is possible to conclude from this work that the MachMoS device exhibits reliable vibro-acoustic and temperature sensing capabilities. Testing confirmed the device's ability to capture vibration signals up to 6 kHz and acoustic signals beyond 7 kHz, with minimal frequency discrepancies and no noise introduced by the enclosure's modal frequencies. The device's anti-aliasing filters were effective. The device also meets the IEC 60529 standard's requirements for the IPX7 rating after minor refinements. However, the IPX7 ingress test should be conducted on various 3D printed enclosures to ensure repeatability in the process. Finally, temperature testing showed an accuracy of ±0.25°C, with operational capability down to -15°C. While performance is robust, future work will focus on optimizing the device's code to allow for higher sampling frequencies, as well as improving clock accuracy, and testing the full operational temperature range. Future testing will further solidify the MachMoS node as a versatile solution for wireless machine condition monitoring, exploring the device's ability to support an external flux sensor, as well as evaluating the device's battery life and effective wireless range.

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