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Advanced Analysis of MEMS Accelerometers for Monitoring Reciprocating Refrigerant Compressors

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ABSTRACT

Monitoring machine vibrations of rotating equipment such as pumps, fans or turbines has been established as a main part of condition monitoring in recent years. With this type of vibration monitoring, it is possible to detect mechanical failures like bearing problems, motor unbalance, as well as shaft or angular misalignment. In addition to selecting appropriate measurement points and necessary accelerometers, specific knowledge and experience are required to analyze machine vibrations correctly. For refrigerant compressors, several manufactures offer monitoring solutions for ‘easy to measure’ standard parameters such as temperature, pressure or electrical signals. Those signals are collected electronically and processed into a representative output signal in order to set machine failures. Additional sensor signals from refrigerant plant monitoring are also available for correlation. However, the predictive power of all these measured parameters in relation to specific components, in particular the compressor, is limited. Extending available information by vibration signals of the compressor can significantly increase the informative value. So far, however, this has only been commercially attractive in special cases due to comparatively high costs for sensors and measurement technology. This paper discusses an alternative approach by applying low-cost MEMS accelerometers. A well-chosen set of sensors have been evaluated experimentally with respect to worked-out requirements. Experimental results are analyzed within the time and frequency domain and compared to industrial accelerometers. Additionally, initial measurements on the compressor shell and an expansion valve were carried out for prove of concept. It can be shown that MEMS accelerometers can be used to monitor basic mechanical vibrations such as the compressor or evaporator fan speed and furthermore flow-induced noise generated by refrigerant flowing through an expansion valve.
1. INTRODUCTION

Today, refrigerant compressors are widely used for refrigeration and air conditioning systems. Beside the condenser and evaporator, the compressor itself plays an important role. Because of that, it is meaningful to monitor all its operating and thermodynamic parameters. Up to now, this is common standard in the sense of observing the operating pressures and temperatures on the high- and low-pressure side and by monitoring the electrical values of the compressor. As possible fault conditions, a distinction must be made between compressor failures caused by the system or with reference to the environment, and failures caused by the compressor itself, whereby both can be in correlation with each other. Furthermore, these faults can occur transiently, periodically or as a single event and be classified accordingly. In example, refrigerant overcharge, undercharge and leakage belong to system faults, whereas lack of lubrication and electrical faults of the electric motor are classified as component faults. In this context, liquid refrigerant entering the working chamber can be considered as a transient compressor fault. This event is also known as liquid slugging, which can cause short term damage of the compressor. Laughman and Armstrong (2006) were able to detect this fault condition by observing a change in power consumption and phase currents. They also investigated a pressure change on the high-pressure side during liquid slugging events as well. Furthermore, Laughman and Armstrong (2006) reported a significantly increase of the cylinder pressure in case of liquid refrigerant entering the cylinder. Although the condition of the refrigeration circuit can already be determined well by monitoring operating pressures and temperatures, these measured variables are usually subject to a certain thermal inertia with respect to thermal diffusion through sensor mounting. In addition, in most cases invasive measuring methods are involved, which make a subsequent installation considerably more expensive and prone for leakage. The question therefore arises to what extent the operating values mentioned can be supplemented by measuring vibrations in order to detect plant and compressor faults with sufficient certainty. Acoustic and vibration analysis of refrigerant systems and compressors have already been applied in context of NVH measurements. For example, Soedel (2007) has investigated the causes and effects of valve and compressor shell vibrations. Vendrami and Pellegrini (2016) cites vibration optimizations of the compressor suspension dampers to minimize noise in a low-frequency range between 0–400 Hz. Investigating compressor vibrations can also lead to identify resonance frequencies of the accumulator or the internal compressor muffler. As a result, their excitation by the compressor vibrations and thus the occurrence of audible noise can be minimized by means of structural adjustments (Wang & Xie, 2021). Besides monitoring vibrations at the compressor in order to optimize its structural components, it is also possible to measure vibrations at any given point of the refrigerant loop. For example, the condenser or evaporator fan speed can be monitored by use of vibrations and faults such as imbalance or breakdown can be examined. Flow-induced noise near the expansion valve due to variations in vapor quality manifests itself by pipe vibrations as well and can thus be detected and monitored as stated by Zhang and Elbel (2021). In order to derive individual compressor faults, limited information is available regarding vibrations and their correlation with existing process parameters. So far, vibration studies have tended to focus on component optimization and the associated noise reduction. To which extent compressor and system faults can be detected in terms of vibrations and determined independently of the compressor type, remains to be examined. Closely related to this question is the correct choice of suitable acceleration sensors, especially if the system price of a subsequent vibration monitoring system and thus the price of the sensors should be as low as possible. In context of this publication, an evaluation of adequate, market-available MEMS accelerometers will be presented and first possible use cases will be discussed.

2. SENSOR EVALUATION

2.1 Selection of appropriate MEMS accelerometers

Compared to analog piezoelectric accelerometers, which are generally used in industry for vibration analysis (e.g. BK4520 from Brüel & Kjær), MEMS accelerometers offer advantages in terms of price and integrated functionalities (Pietro & Rotondo, 2018), since most of the time, they are digital accelerometers. Generally, the right choice of accelerometer depends on the phenomena to be detected. These phenomena or fault events can be periodic or aperiodic. Periodic events and the associated signals can thus be described within frequency domain, aperiodic ones by transients in time domain. According to Shannon, the maximum frequency of a captured periodic event can only be half of the sampling frequency. So it must be within the usable bandwidth of the sensor in order to be adequately represented later within a Fourier frequency transformation. Therefore, the necessary sensor bandwidth and sampling frequency are determined by the phenomena to be identified. Acceleration signals can be categorized into three sections in terms of frequency: a low frequency range of less than one kilohertz, a medium-frequency range of one to five kilohertz and a high-frequency range of greater than five kilohertz (Pietro & Rotondo, 2018). Typically, the compressor and
fan speed fall into the low-frequency range, whereas pressure pulsations and flow-induced noise caused by refrigerant
flow are located in the high frequency range (Zhang & Elbel, 2021) and expressed periodically depending on the
flow conditions. Beside frequency ranges, the expected vibration amplitude in m/s² is also important to consider. If
the excitation amplitude exceeds the sensor’s maximum measurement range, the sensor signal is cut off. Today’s
digital MEMS accelerometers can address frequency ranges up to five kilohertz (Pietro & Rotondo, 2018) with a
measurement range of ±16 g and a resolution of up to 12-bit. In comparison, analog piezoelectric accelerometers offer
a higher bandwidth alongside an extended amplitude range and accuracy, but this correlates with a significantly more
expensive price. In addition to the sampling frequency and amplitude range, the number of axes has to be considered
in relation to the measurement position. As a rule of thumb, three-axis accelerometers should be used, since the
direction of excitation is initially unknown. An overview of all sensor specifications elaborated in the context of this
publication are given in Table 1 for a narrower selection of MEMS accelerometers. As a reference sensor, the three-
axis accelerometer BK4520 from Brüel & Kjær was chosen. Criteria for selecting MEMS accelerometers were a wide
bandwidth, a useful temperature range and a low price.

Table 1: Overview of the most important specifications for accelerometers.

<table>
<thead>
<tr>
<th></th>
<th>BK4520</th>
<th>IIS2DH</th>
<th>IIS3DWB</th>
<th>KX1341211</th>
<th>ICM42688P</th>
<th>ADXL1002</th>
</tr>
</thead>
<tbody>
<tr>
<td>amount of axis</td>
<td>3</td>
<td>3</td>
<td>3</td>
<td>3</td>
<td>3</td>
<td>1</td>
</tr>
<tr>
<td>measurement range in g</td>
<td>±500</td>
<td>±16</td>
<td>±16</td>
<td>±64</td>
<td>±16</td>
<td>±50</td>
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<tr>
<td>resolution in bit</td>
<td>24</td>
<td>8-12</td>
<td>16</td>
<td>8-16</td>
<td>16-18</td>
<td>12</td>
</tr>
<tr>
<td>maximum bandwidth in Hz (1)</td>
<td>x, y, z: 7000</td>
<td>x, y, z:</td>
<td>2688</td>
<td>x, y, z: 6300</td>
<td>x: 8200</td>
<td>x, y, z: 11000</td>
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<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>y: 8500</td>
<td></td>
<td>8400</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>z: 5600</td>
<td></td>
<td>y, z: -</td>
</tr>
<tr>
<td>sample rate in Hz (1)</td>
<td>48000</td>
<td>5376</td>
<td>26667</td>
<td>25600</td>
<td>32000</td>
<td>96000</td>
</tr>
<tr>
<td>temperature range in °C</td>
<td>-51 ... +121</td>
<td>-40 ... +85</td>
<td>-40 ... +105</td>
<td>-40 ... +105</td>
<td>-40 ... +85</td>
<td>-40 ... +125</td>
</tr>
<tr>
<td>type / interface</td>
<td>analog / BNC</td>
<td>digital / SPI</td>
<td>digital / SPI</td>
<td>digital / SPI</td>
<td>digital / SPI</td>
<td>analog</td>
</tr>
<tr>
<td>interrupt based operation</td>
<td>No</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
<td>No</td>
</tr>
<tr>
<td>price in $ (3)</td>
<td>1500</td>
<td>2.84</td>
<td>14.22</td>
<td>10.62</td>
<td>5.64</td>
<td>43.54</td>
</tr>
</tbody>
</table>

1 depending on the analog to digital converter which is used
2 bandwidth for analog piezoelectric accelerometers are mostly rated for an amplitude deviation of ±10 %,
MEMS sensors until a cut off frequency at 3 dB attenuation
3 current prices from mouser.com

To use MEMS accelerometers, a microcontroller, which represents the counterpart to an industrial data acquisition
system, is needed. This results in requirements regarding processor speed and memory size. Moreover, a suitable
digital communication interface between the microcontroller and the sensor element has to be chosen. To ensure
equidistant samples, a sufficiently high data rate (e.g. via SPI@ 8 MHz) and an ”interrupt-based” readout of the
measured values from the registers of the sensor element are required. Additional sensor functions such as automatic
filtering or threshold detection at sensor level can help to transfer functionalities and thus computation time from the
microcontroller to the sensor itself (Pietro & Rotondo, 2018). Sensor resolution and sampling frequency determines
the maximum possible time window in which transient or periodic events can be captured and subsequently analyzed
(Pietro & Rotondo, 2018).
2.2 Experimental setup

The selected MEMS accelerometers were tested by use of a shaker test rig. Therefore, the reference and MEMS accelerometer are attached on the top base plate. The signal generator is used to set the motion behavior of the one-dimensional excitation shaker system. Sinusoidal, harmonic oscillations with constant frequency and amplitude over the complete sensor’s bandwidth were applied, similar to Pietro and Rotondo (2018). In this case, the reference sensor is directly connected to a data acquisition system from HEAD acoustics, whereas the MEMS sensor is linked to an ESP32 microcontroller (see Figure 1). Frequencies and amplitude levels of the shaker can be defined by the signal generator as well as the shaker amplifier. When measuring the excitation, it is essential to synchronize the data acquisition and microcontroller system in order to ensure identical observation time windows for comparison. Thus, the microcontroller determines the start and end of the procedure and provides a trigger signal. Furthermore, the measurement duration is limited by the memory size of the microcontroller. The sample data, collected by the MEMS sensor, are first stored internally on the microcontroller and in case no more can be recorded, they are transferred to a computer for further processing. The observation period thus varies from about 1...80 seconds depending on the sampling rate and resolution of the sensor. In general, it was limited to a maximum of five seconds, since only stationary excitations with minor periods were considered. The shaker excitation frequencies were set to discrete ones within the useful bandwidth of MEMS accelerometers (Pietro & Rotondo, 2018). Investigated frequency start at low values, around the rotational frequencies of refrigerant compressors between 60...120 Hz and elevate up to several kilohertz. Amplitude and gain of the signal generator or shaker amplifier were left constant to keep the excitation conditions per frequency and MEMS sensor approximately the same. Since the transfer function of the shaker is frequency-dependent, it cannot generally be assumed that the acceleration amplitude remains constant per frequency. As a consequence, the time signals of both sensors were recorded for each excitation frequency and compared later on. This procedure is illustrated in Figure 1.

2.3 Measurement results

A comparison of an example measurement in Figure 2 shows that the MEMS signal oscillates around a constant DC component of about 10 m/s². The acceleration signal of the piezoelectric sensor does not have this offset. In general, MEMS accelerometers can measure acceleration due to gravity and thus so-called DC components, whereas piezoelectric sensors cannot. At time domain, both signals can be compared with regard to their amplitudes $a$, the RMS value of the amplitude, the signal to noise ratio, the period $T$ and thus the signal frequency $f$. 

Figure 1: Shaker test setup and example FFT plot of a reference and MEMS signal
An automated identification of these parameters is complicated. Therefore, an alternative approach of analyzing time series has to be considered. As mentioned by several vibration guidelines, the Fast Fourier Transformation (FFT) is suitable for analyzing acceleration signals. In addition, Figure 2 illustrates two plots of a resulting FFT transformation being applied on both time series. The sampled acceleration signal is examined with respect to the frequencies that mainly occur in the signal. In our case of discrete, harmonic sinusoidal shaker excitations, we expect a "frequency versus amplitude" plot, which ideally represents the measured acceleration amplitude $a$ at the shaker excitation frequency $f$. It should be noted that the accuracy and validity of the Fast Fourier Transformation is subject to some fundamental effects, which must be taken into account. Those includes aliasing, filtering, the FFT length and the window type as mentioned by Pietro and Rotondo (2018). Those parameters are only explained in rudimentary form as follows.

**Figure 2:** Time and frequency domain representation of a reference and MEMS sensor signal

In general, the signal chain for processing acceleration signals consists of several stages as shown in Figure 3. Those stages are valid for evaluating time signals on a computer as well as on microcontroller. The sampling rate $f_s$ and thus the bandwidth $BW$ are determined by the sensor. In combination with a digital low-pass filter at sensor level, the time signal is protected against aliasing. Thus, the acceleration signal contains all captured vibrations within the sensor bandwidth $BW$.

**Figure 3:** Signal chain for acceleration signals as stated by Pietro and Rotondo (2018)
DC components such as gravity are still present in the signal of MEMS sensors at this point of the signal chain. In theory, these signal parts can also be observed in the frequency spectrum after an FFT analysis at f = 0, but it can be removed using a high-pass filter (see Figure 3). The axis orientation of the sensor element in combination with the effective direction of the acceleration caused by gravity and thus the resulting DC components per axis can be utilized to determine the position of the sensor element. This information is quite useful depending on the application. After applying a high-pass filter, it is possible to analyze the signal in time or frequency domain. For the evaluation at frequency domain, the signal is divided into overlapping blocks of equal block size \( N \) and the amplitude curve per block is weighted using a window function (Pietro & Rotondo, 2018). By default, a “Hanning” window is chosen. Now, the FFT calculation is performed for each windowed time segment. As a last step, all FFT results are overlapped to finally obtain the FFT plot for the analysis of the signal frequencies and amplitudes. This process is also known as the Short Time Fourier Transformation (STFT). For small observation windows and stationary signals, a single FFT for the complete windowed time series is sufficient. The sampling frequency of the sensor and the FFT length determines the resulting frequency resolution. The frequency resolution represents the frequency line intervals along the x-axis in the FFT plot and determines the extent to which superimposed, periodic signals of approximately the same frequency in time domain can still be distinguished from each other in frequency domain after applying the Fast Fourier Transformation. In our case, the FFT length for each measurement was set to \( N_{\text{FFT}} = 32768 \). Since the frequency resolution also depends on the sensor’s sampling frequency, it is recommended to reduce \( f_s \) for small excitation frequency ranges. Therefore, \( N_{\text{FFT}} \) can be less than using a higher sampling frequency \( f_s \). As a result, the frequency resolution remains the same. On the other hand, a high sampling rate means that enough data must be recorded to be able to guarantee a sufficient frequency resolution later. The internal sampling frequency for MEMS sensors can be adjusted by configuring the sensor’s register and for analog sensors by the A/D converter setup. In the vast majority of cases, saving much longer time periods inside the microcontroller results in a much higher price for the system.

![Figure 4: Amplitude (top) and frequency (bottom) deviation of different MEMS sensors compared to a reference sensor over discrete excitation frequencies, excitation direction: z-axis](image)

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A straight comparison of both FFT results with different sampling rates per MEMS and reference sensor is not trivial and leads to possible misinterpretations depending on $f_n$. Since both sensors are synchronized, they capture the same time window. However, $N_{\text{FFT}}$ is determined in advance. Thus, the FFT would be applied on time segments with different lengths. As a result, the frequency resolutions differs. In order to ensure a comparability of both FFT plots similar to Pietro and Rotondo (2018), it may be necessary to subsequently adapt the high sampling rate of the reference sensor to that of the MEMS sensor by means of a sampling rate conversion. As a consequence, the frequency resolution will be the same. Figure 2 illustrates such plot after performing the signal processing described above. At this point, it is possible to compare the amplitudes $a_1$ and $a_2$ as well as the frequency accuracy, since the excitation frequency $f$ of the shaker is known. If a ratio of both amplitudes is formed, a relative deviation of the amplitudes for a discrete range, while the IIS3DWB can be used for higher bandwidths with short observation periods.

In other words, not only the acceleration amplitude can be reconstructed incorrectly after applying a FFT, but also the corresponding frequency. Therefore, both deviations have to be taken into account. Figure 4 can thus be divided into three ranges: first, a low frequency range below 10 Hz with increased amplitude and frequency deviation (a), second, a linear range - depending on the sensor up to its cut-off frequency - (b), and finally one with an increasing low-pass characteristic (c). In most cases, however, the linear range of the frequency response is of greater interest, i.e. the range in which the captured amplitude corresponds to the real one. The frequency deviation is also negligible for this range. For each sensor, the linear range goes up to different cut-off frequencies, since internal sensor structures or filter settings differ. Because each sensor’s bandwidth is known, the 3 dB point, specified in the data sheet, can be verified within the amplitude deviation course. It turns out that in most cases the measured 3 dB point was found at lower frequencies than specified. According to the data sheet for sensor IIS2DH, its 3 dB point is published at 2688 Hz, but it was found to be at around two kilohertz (cf. Figure 4, mark d) in our measurements. The difference is even more obvious for the sensor ICM42688P from TDK. Referring to Table 1, its 3 dB point should be 8400 Hz for each axis. Nonetheless, it was situated around two kilohertz. In contrast to that, the cutoff frequency for the sensor KX1341211 is indicated as 5600 Hz for the excited axis in the data sheet. Experimentally, this point was determined around 4500 Hz. Thus, the difference to the measured 3 dB point is significantly smaller than with the sensor mentioned before. Where these discrepancies come from can only be assumed. However, it may be partly due to the way the sensor is fixed to the shaker or the design of the circuit board. The amplitude and frequency deviations for the low frequency range (a) could be narrowed down to an inappropriate selected excitation amplitude and measurement range for the MEMS sensor. In combination with a high pass filter, wrong amplitudes and frequencies were reconstructed. As a result, the deviations vary significantly. The only sensor that can sufficiently map high bandwidths up to 10 kHz is the ADXL1002. Unfortunately, this single-axis, analog MEMS sensor also requires an ADC and a stable supply voltage, on which the quality of the measurements strongly depends on. Also, the price of approx. 40 $ without ADC is much higher. A good alternative is the triaxial sensor IIS3DWB from ST, which is within the tolerance range of ±10 % up to five kilohertz for each axis.

To monitor refrigerant compressors, MEMS sensors must be able to address a wide range of signal frequencies. Therefore, a flat frequency response up to higher frequencies for each sensor axis is necessary to detect a variety of component faults. Our internal evaluation reveals the IIS2DH to be applicable for monitoring long periods within a small frequency range, while the IIS3DWB can be used for higher bandwidths with short observation periods.
3. USE CASE SCENARIOS

For an additional evaluation of the MEMS accelerometers beyond the tests on the shaker test rig, the sensors IIS2DH and IIS3DWB were further used to perform tests on a standard refrigeration circuit. For this purpose, two simple scenarios were defined and vibrations of the system were recorded with each MEMS sensor and one reference sensor. Both measurement positions are shown in Figure 5. The measurement axis for the sensors was always set to the axis that is perpendicular to the mounting surface. As a first scenario, the start-up and shutdown process of the test rig was chosen. This can be used to identify excited frequencies by the compressor speed as well as the rotational frequencies of the evaporator and condenser fan. In this case, the IIS2DH was mounted on compressor shell. The second test scenario describes transient flow-induced noise near the expansion valve after turning on the compressor. Transient flow conditions can be identified by the changing liquid-vapor-content inside the sight glass right before the expansion valve. For this scenario, measurements were taken directly on the expansion valve. Both sensors were fixed using hot glue at each measurement position.

![Figure 5: First measurement position (IIS2DH) on the compressor shell, second (IIS3DWB) directly on the expansion valve, compared to a reference sensor (Ref.)](image)

3.1 Test rig specifications

The utilized test rig consists of a compressor, which is integrated in a condensing unit (Type Tecumseh AET4423YHR), a hand valve as an expansion device and an evaporator with two fans. The rotational frequency of the compressor corresponds to the power supply frequency of approx. 50 Hz. The fan speed of the condenser is specified at 1300 rpm, which is equivalent to 21.6 Hz. With five rotor blades, the dominant, fifth harmonic of the condenser fan speed thus equals 108 Hz. In addition, there are also two fans in the refrigeration circuit used for the evaporator. They are similar in design and construction, which is why their dominant frequency remains the same. Moreover, it coincides with the frequency of the condenser. These mechanical frequencies of the test rig are located in the low-frequency range of less than 1 kHz and should therefore be detectable with both selected MEMS sensors. However, the test scenarios are transient events. The start-up and shutdown of the test rig takes place in a specific time window, as does the flow-induced noise near the expansion valve. As a result, these two scenarios were recorded separately from each other. In order to be able to capture the component’s vibrations, the maximum possible observation period of the digital MEMS system, which is determined by the memory size of the microcontroller (ESP32) and the sampling frequency of the sensor, was implemented in software. Thus, the time window for the IIS3DWB with 26.7 kHz sampling rate is a maximum of 22 s, and for the IIS2DH with 5.376 kHz sampling rate up to 90 s. Since the start-up and shutdown process for the first scenario is relatively easy to define, the measurement time for the IIS2DH can be significantly shorter and also limited to 22 s. The suction pressure of the test rig was about 1.2 bar in all operating states.
3.2 Compressor start-up process

Figure 6: Amplitude course over frequency and time after turning on the test rig, Dytran3023 reference sensor (left), IIS2DH MEMS sensor (right) on the compressor shell

The first scenario is used to test the IIS2DH, which is attached to the compressor shell. The test rig is turned on and off to determine the dominant frequencies at the intended measurement position. As a reference sensor, the Dytran 3023 was mounted right next to the MEMS sensor. For this purpose, the system was turned on after around five seconds and switched off again after another 10 s during the previously defined observation time window of 22 s. Analog to the measurements on the shaker test rig, a FFT plot can now be calculated.

For superimposed frequencies in acceleration signals that are variable in time, an alternative visualization and analyzing method is recommended. In this case, the amplitude over frequency plot is extended by the dimension of time, which finally results in a three-dimensional plot as shown in Figure 6. In this case, the FFT is applied on different, overlapping time segments with block size $N$. Each block is windowed as well. After that, the resulting FFT’s are overlaid in order to get a time variable frequency representation. This method is also known as the Short-Time-Fourier-Transformation (STFT). An example computation of the STFT using matlab, which is used here, was implemented by Zhivomirov (2022) and is based on the theory described in Heinzel, Rüdiger, and Schilling (2002).

The compressor speed can be easily determined from this diagram. Although the compressor speed is not variable, a ramp course is still visible and caused by the inertia mass of the reciprocating piston. After reaching a steady-state condition, the compressor frequency can be identified as 50 Hz (black dashed line in Figure 6, mark a). In contrast to that, the course of the condenser fan speed can be read out from Figure 6 as a simple frequency line (mark b). Its course is constant over time due to the good rotor bearing. The fan rotation frequency can be estimated from Figure 6 around 110 Hz (mark b), which is approximately 108 Hz as expected from the data sheet. Moreover, the curve also shows a slight time offset between the compressor start-up and condenser fan start-up, which relates to the internal control of the condensing unit. In addition, the curve in Figure 6 shows a broadband frequency range with increased amplitudes after the system is turned on (see arrow e). Not only rotational frequencies are present in the spectrum of the compressor, but also a large number of other component’s vibrations. These include flow-induced noise, vibrations transmitted through the system piping, and excited resonant frequencies of the compressor shell (Soedel, 2007). All of these can be found overlaid in the frequency spectrum of the compressor. Compared to the right plot of Figure 6, the left one shows far more frequency components above 1 kHz. This can be attributed to the different sampling frequencies of each sensor. Since they are not the same, their sensor bandwidth does not match, too (mark c). For the reference sensor, the bandwidth goes up to 24 kHz. However, the MEMS sensor’s bandwidth only reaches 2688 Hz.

As a result, some parts of the spectrum cannot be addressed by the MEMS sensor. On the right side of Figure 6 (b), the gray area illustrates the invisible spectrum of the MEMS sensor.
3.3 Flow-induced noise near the expansion valve

As a second scenario for the refrigeration circuit benchmark, vibrations near the expansion valve were investigated. A sight glass upstream the expansion valve can serve as an indicator for transient liquid-vapor-flow through the expansion valve. After the system has been switched on, the sight glass fills up due to the refrigerant distribution. The two-phase flow through the expansion valve involves enhanced flow-induced noise. In our tests, this transient flow stabilization took place within the first 5-10 seconds after the system was switched on. From a vibration point of view, this behavior has been recorded with the IIS3DWB sensor on the expansion valve. The BK4520 sensor from Brüel & Kjær was taken as the reference sensor.

Figure 7 illustrates the result plots after applying a STFT on both time series. Again, rotational frequencies of the compressor and fans can be determined. Since the sampling frequency of this MEMS sensor is much higher than that of the IIS2DH used before, the bandwidth is significantly larger. Theoretically, according to Shannon, the bandwidth \( BW \) goes up to \( f_c / 2 \), in this case up to 13 kHz (mark c, right side of Figure 7).

The results thus reveal a fundamental problem of vibration analysis using MEMS sensors. Vibrations near the expansion valve, which show up in broadband, high-frequency components, seem to be detectable by using the IIS3DWB. However, since they are outside the linear frequency range of the sensor, but still within the bandwidth, the amplitude heights do not correspond to the actual ones (red circle annotation, Figure 7). This can clearly be observed by comparing both plots in Figure 7. The left one shows higher amplitudes above 6 kHz than the other one, as illustrated by arrow d. This makes it difficult to determine the event using a threshold in the time or frequency domain. Nevertheless, this phenomenon can be detected by amplitudes in the higher spectrum, which are still present - attenuated or not - for both sensors.

Compared to the IIS3DWB, the ADXL1002 has a higher linear frequency range. The useful bandwidth for this sensor extends all the way up to 10 kHz. Since it is a single-axis accelerometer, the initial excitation direction must be known in order to detect the event correctly. Nevertheless, with this sensor, the acquisition of this test case is indeed possible without amplitude attenuation to be considered.
4. CONCLUSIONS

Malfunctions in compressors or refrigeration systems can lead to a change in operating parameters such as pressure, temperature and sometimes vibration. Most of the time, industrial accelerometers are used for the evaluation of vibrations in plants, which can be very expensive in terms of their price. As a result, a permanent monitoring, especially for small systems, does not appear to be cost-effective.

Within this work, MEMS accelerometers were investigated with regard to their suitability for monitoring reciprocating refrigerant compressors. The main criteria for selecting MEMS sensors can be summarized as:

- the number of measurement axes (3-axis),
- the linear frequency range of the sensor (up to five kHz),
- a low price (between 10 and 50 $),
- and the necessary communication interface (SPI).

In addition, an evaluation of preselected sensors was carried out by using a shaker test rig. Discrete excitation frequencies were set on a shaker. The recorded acceleration signals of each MEMS sensor were compared with those of an industrial sensor from Brüel & Kjær (BK4520) regarding their frequency and amplitude accuracy after applying a FFT. According to the results, the IIS2DH is suitable for three-axis measurements of low-frequency DC components up to less than two kilohertz, and the IIS3DWB sensor from ST is recommended for a high-frequency range up to five kilohertz. For measurements from 10 Hz to four kilohertz, the less expensive KX134-1211 sensor from Kionix can be used as an alternative, which has a larger amplitude range in g. In contrast, the single-axis MEMS sensors ADXL1002 and ADXL1003 from Analog Devices feature a bandwidth of up to 10 kHz. Those sensors are suitable for signals with high frequency components. However, this requires an external A/D converter with a sufficient resolution and sampling rate. Beyond the sensor evaluation, the signal chain consisting of an additional microcontroller was examined. Its marginal parameters are determined by the memory depth and processor speed of the microcontroller. This limits the maximum possible observation time when saving or processing acceleration data locally. In order to demonstrate possible application scenarios for monitoring refrigerant compressors with low-cost sensors, first measurements have been conducted on a standard refrigeration test rig. It can be shown that MEMS accelerometers can be used to monitor basic mechanical vibrations such as the compressor or evaporator fan speed and furthermore flow-induced noise generated by refrigerant flowing through an expansion valve.

NOMENCLATURE

Symbols:

- \( f, f_s \) frequency or sensor sampling frequency (Hz)
- \( a \) acceleration amplitude (m/s\(^2\))
- \( a_{1/2} \) amplitude of MEMS / reference sensor (m/s\(^2\))
- \( g \) gravity acceleration (9.81 \( \cdot \) 1 \( \cdot \) m/s\(^2\))
- \( T \) period (s)
- \( N \) block size (–)
- \( N_{FFT} \) FFT length (–)

Subscripts:

- NVH Noise Vibration Harshness
- BNC Bayonet Neill-Concelman connector
- MEMS micro-electro-mechanical systems
- A/D, ADC analog to digital converter
- SPI Serial Peripheral Interface (communication interface)
- RMS root-mean-square
- FFT Fast Fourier Transformation
- STFT Short-Time Fourier Transformation
- BW (sensor signal) bandwidth
REFERENCES

Heinzel, G., Rüdiger, A., & Schilling, R. (2002). Spectrum and spectral density estimation by the Discrete Fourier transform (DFT), including a comprehensive list of window functions and some new flat-top windows. Max-Planck-Institut für Gravitationsphysik, 12. (CrossRef)


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