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Design of sensor integrating gears: methodical development, integration and verification of an in-Situ MEMS sensor system

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Abstract

State of the art vibration-based condition monitoring at gearbox housings faces uncertainties in the interpretation of measurement data due to signal transformations and noise. The state of research shows that direct measurements at the source of vibrations with integrated sensors provide higher quality data. Capacitive MEMS sensors seem predestined for integration, but there is limited research covering compactly integrated MEMS sensor systems for condition monitoring by vibration measurement. In this contribution an integrated MEMS sensor system is designed methodically based on VDI 2206. A sensor system is selected based on requirements extracted of previous contributions and verified on a rotational shaker test rig. Afterwards it is integrated on a gear wheel in a gear test bench. Several verification measurements using different principles and locations are performed to verify the measurands. Results show that the gear mesh vibrations including the sidebands can be measured with the integrated sensors which provide superior signal-noise-ratios compared to other locations. This proofs that the sensor integrating gear system is principally able to perform high quality condition monitoring.

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Keywords: Sensor Integrating Machine Elements, Sensor Integration; In-Situ Measurement; MEMS; Verification; Vibrations; Gear; Condition-Monitoring

1. Introduction

Gears are key elements of many machines and hence damages in gearboxes often cause complete breakdowns that are very costly. Due to this vibration-based condition monitoring of gears is established in the state of the art [1], especially on high load systems like wind turbines [2] or helicopter transmissions [3]. However, most of the condition monitoring systems do not measure directly at the source of vibration, the tooth contact, but on the housing or other easily accessible parts [1]. This leads to uncertainties in the interpretation of the measurement data or even a loss of information since the signal transforms in long transmission paths and noise interferes [4, 5].

Integrated measurements that are closer to the gear provide robust and higher quality data, but previous work has been limited in that matter [4]. Some research projects support that integrated measurements provide better SNRs, e.g. by detecting tooth breakage in helicopter gears [6] or by vibration monitoring on planetary gears [7, 8]. Heider [9] mounted piezo sensors directly on the gear, achieving very good vibration measurements. An overview of existing integrated vibration measurements on gears can be found in [10]. However, there is a lack of compactly integrated sensors for gears including a data acquisition system being able to measure the vibrations on the gear for the use of condition monitoring and wear prediction.

The design of such a sensor integrating gear is challenging due to the location of the sensor, space restrictions and environment conditions, for example [4, 11]. Furthermore, the data transfer from the rotating part and the energy supply must be considered. Consumer-grade capacitive MEMS sensors seem predestined for this task because of their small size, availability, robustness and low energy consumption [12].

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This contribution addresses these problems by designing and verifying a sensor integrating gear. This is prototypically implemented by a MEMS sensor system mounted on a gear.

Nomenclature

DAQ	Data Acquisition System
FFT	Fast Fourier Transformation
GMF	Gear Mesh Frequency
MEMS	Micro Electro Mechanical Systems
SNR	Signal to Noise Ratio
SPI	Serial Peripheral Interface – Bus System
TSA	Time Synchronous Averaging

2. Method

2.1. Methodical approach

The objective of this contribution is to design and verify an integrating sensor system for a gear consisting of capacitive MEMS acceleration sensors.

The methodical approach is based on the V-Model, see Figure 1, according to VDI 2206 [13]. **First**, the requirements on the sensor system including design space are defined. **Second**, the system is designed by defining functions, separating the systems into modules and assigning solutions to the modules. **Third**, the solutions of the modules are designed domain-specifically. **Fourth**, the solutions are combined into the system including verification tests on two integration levels: the "sensor system" and the "sensor integrating gear".

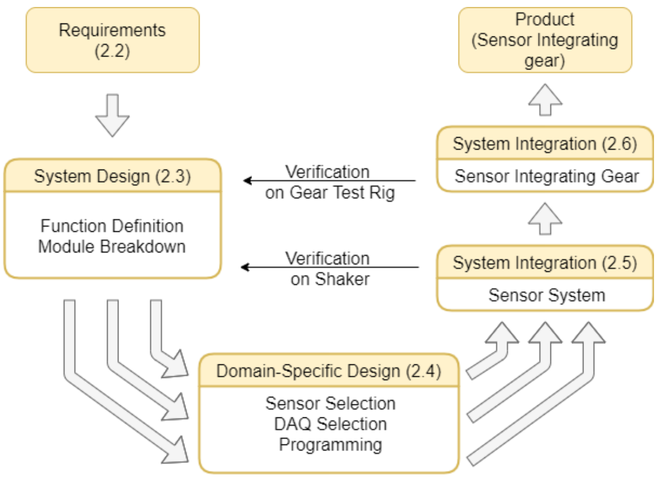

Figure 1: Methodical Approach for Design based on VDI 2206 [13]

2.2. Requirements

A literature review is conducted to extract the requirements on the sensor system in terms of sampling frequency, measurement and frequency range, frequency resolution. The results are presented in Chapter 3.1

2.3. System Design

The system "sensor integrating gear" needs to measure vibrations directly on the gear. Therefore, the system consists of two modules: sensor and data acquisition system (DAQ). Those two combined are called the "sensor system". Mounted on a gear as an autonomous unit with energy supply the term "sensor integrating gear" is used (Figure 2). For redundancy, two acceleration sensors directly mountable on the gear were included in the sensor system. Furthermore, a DAQ connected to the sensor via wires and an energy supply to rotate on the gear shaft was selected. The DAQ needs to read the sensor and store the data. An editable program to run on the DAQ to modify sampling rate and data processing was also required.

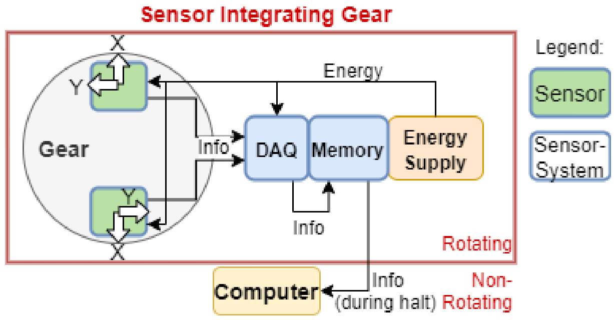

Figure 2: System Design: Sensor Integrating Gear

2.4. Domain-specific Design: Module Solutions

The selection of the sensor influences the DAQ by means of the connecting interface. Therefore, the sensor is selected first. Capacitive MEMS acceleration sensors can be differentiated by the type of signal provided: "integrated" providing standardized analog signals, or "intelligent" providing digitized signals via communication bus [14, 15]. "Intelligent" (digital) sensors were preferred because of lower integration efforts. Several sensors were researched and summarized in a table to compare and choose one according to the requirements. With the selected sensor (introduced in chapter 3.2) a DAQ was selected that provides an interface to communicate with the sensor and sufficient memory to store the data.

The DAQ needs to sample the measurement data from the sensor with a defined and editable rate that meets the requirements introduced in chapter 3.1 and store it in a computer readable format. To ensure a constant sampling rate a timer interrupt function needs to be implemented. A minimum amount of samples must be buffered for each sensor (chapter 3.1) in internal memory and afterwards logged to the SD-Card during non-measurement periods. For these tasks, development boards featuring a microcontroller and an SD-card socket were searched. Microcontroller programming for adjusting sample rate and data storage format were conducted with languages C/C++. Furthermore, the sensor system needs an energy supply enabling the integration on the rotating gear, which is also considered in the search.

For data postprocessing and analyzation on a computer, common methods like TSA, FFT and SNR are used. TSA removes noise by removing non-synchronous parts of the signal. For TSA a pseudo tach signal was constructed from the periodic characteristics of the vibration data following Bechhoefer [16]. To evaluate the capabilities of vibration signals as condition indicator the signal quality is investigated. It is quantified by the signal to noise ratio. The desired signal is considered as the gear mesh acceleration and its sidebands which are affected by wear.

2.5. System Integration and Verification: Sensor System

Integration: In a first step the sensor system, consisting of the two modules sensors and DAQ (chapter 2.3) was built up. Sensor interfacing was configured code-wise by implementing libraries from the manufacturer and adjusting output range and offset calculation. Before the second step of integration into the gear it was aimed to verify if the system complies with the requirements in an environment close to reality.

Verification: Rotating spur wheels create vibrations characterised by specific frequencies and amplitudes. Wear can cause changes in these characteristics [10]. Thus, the sensor's capability of sensing amplitude changes that are important for condition monitoring and wear detection was tested with different frequencies and amplitudes. The sensor system (introduced in chapter 3.1) was mounted to a shaker test rig (Figure 3) with the aim to compare its accuracy to well established piezo accelerometers. The mounting positions were similar to the real gear mounting.

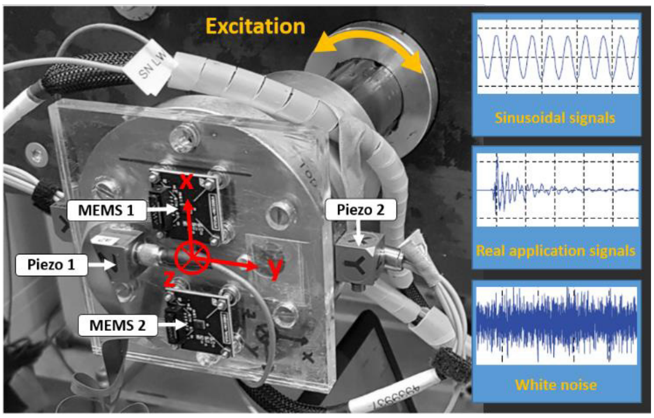

Figure 3: Sensor System Verification on a Shaker Test Rig

The excitation procedure matched a realistic gear engagement. Due to frequency limitations of the shaker, multiples of the GMF could not be investigated. For the evaluation of sensor accuracy, excitation complexity was steadily increased. Vibrations were applied individually first and further collectively by adding sinusoidal excitements. Finally, recorded time signals of previous gear vibration investigations on an angle grinder and white noise were applied on the shaker (Figure 3). Furthermore, the consistency was assessed via parallel testing and comparison of two MEMS sensors and two piezo sensors (results in chapter 3.2).

The shaker was excited torsional to reproduce torsional gear vibrations, tangential to the y-axis of the sensors. Different radii between the sensors and the axis of rotation were used to check for linearity of amplitude responses.

2.6. System Integration and Verification: Sensor Integrating Gear

Integration: The sensors were mounted on the gear with axes oriented tangential and radial to gear rotation (Figure 2). The gear mesh vibrations can be measured with the axis tangential to gear rotation. The radial axis is not usable since the centrifugal force causes a radial acceleration that exceeds the measurement range of the sensor at the operation speed. However, the radial acceleration signal can be reconstructed from tangential acceleration measurements by subtracting the two signals of the tangential accelerometers [4].

For **verification** of the sensor integrating gear, a redundant configuration of sensors was installed. A rotary laser vibrometer recorded the torsional vibrations of the gear wheel parallel to the sensors mounted on the gear wheel. This measurement technique serves as a reference for evaluating the signal quality of the integrated MEMS sensors.

In addition, two accelerometers were mounted on the bearing block. These sensors should enable a comparison with state-of-the-art condition monitoring analysis, which use gear box vibrations. Two different types of accelerometers were used. One piezo sensor, which meets the requirements of laboratory measurement technology, and the capacitive MEMS sensor (introduced in chapter 3.2). The sensor setup is depicted in Figure 4.

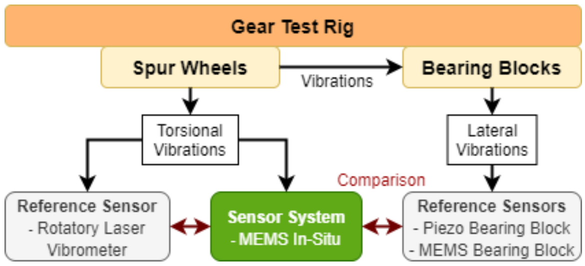

Figure 4: Sensor Integrating Gear: Verification on Gear Test Rig

The **piezo sensor** (PCB-3506A2) mounted on the **bearing block** has a dynamic range of ± 500 g peak acceleration, a sensitivity of 10 mV/g, a resonance frequency of > 25 kHz, and is linear in response up to 5 kHz. The data obtained was used to ensure the recording of all relevant vibration events that occur with continuous wear.

The **MEMS** sensor system on the **bearing block** is similar to the sensor system on the spur gear. Vibrations were measured in vertical orientation to the bearing block and in horizontal, orthogonal to the axis of rotation. The mounting was done with adhesive wax.

The redundant detection of the oscillation of the rotational acceleration is carried out by means of a Polytec OFV-4000 **laser rotary vibrometer**. In contrast to the inertial accelerometers, the angular velocity is measured optically and the rotational acceleration is determined. The speed is recorded with a sensitivity of 100 °/s/V, then high pass filtered with 1 Hz and low pass filtered with 5100 Hz. TSA was applied to all signals by using a pseudo tach signal constructed a harmonic of the gear mesh.

3. Results

The results consist of the final design of the two integration steps *sensor system* (consisting of MEMS sensor and microcontroller) and *sensor integrating gear*. Furthermore, the results of the two levels of verification tests (the shaker test rig and the gear test rig) are shown. In conclusion, findings of the verification for the sensor integrating gear are described.

3.1. Requirements

The sensor needs to measure the GMF and its multiples up to 5th order. These parameters are influenced by the operating conditions of the gearbox like shaft rotational speed and number of teeth of the gear. [10]

As an operation point for the gear stage in this contribution a rotational speed of 800 rpm was used. Gears with 70 and 90 teeth were chosen. With the formulas from [10] the maximum vibration frequency to measure is the 5th multiple of the GMF: 4.95 kHz. This results in a minimum sampling frequency of 9.9 kHz. For a measurement range upper limits of 23 g can be extracted [10].

For frequency spectrum data analysis a minimum resolution needs to be specified which allows the smallest distance between sidebands in the spectrum to be resolved. The smallest distance in this case is the shaft speed of 800 rpm (13.3 Hz). Hence the number of minimum datapoints to store in one continuous record in the microcontroller's memory calculates to 745 for one sensor using formulas from [10].

3.2. Sensor Subsystem

Design: The chosen sensor was the *IIS3DWB* from *STmicroelectronics*. It is a digital triaxial MEMS acceleration sensor with a bandwidth of 6 kHz and range of ± 16 g. The range does not meet the requirements. However, it is the only one available providing such a high bandwidth. The measurand outputs are integer values with a size of 2 Bytes. The sensor's resonance frequency of 6.9 kHz is above the area of interest.

We used a development board, *Adafruit Feather M0 Adalogger*, that carries a *Cortex M0* microcontroller and connects to the two sensors via SPI communication. It has a socket for a microSD card and a battery management system. It has 32 kB of internal memory which is sufficient to store two times 745 datapoints (chapter 3.1) from the sensors, which is 2.98 kB. We use a 500 mAh Lithium-Ion Polymer battery as energy supply.

Verification: In the following section, the results of the sensor testing on the shaker are presented. Exemplary measurement results at four different frequencies are shown in Figure 5 and Table 1. The MEMS sensor system is compared to the piezo accelerometer, which are both mounted on the same acrylic glass board for reasons of comparison. Differences are mainly caused by noise, less by signal peak values. No distortion in frequency domain is seen in the responses of the MEMS accelerometer as well as the piezo. It stands out that the response of the high-end piezo accelerometers is narrower banded (Figure 5). However, the MEMS sensors show better SNRs. Tests with white noise over a frequency band of 1 to 1000 Hz showed that there is no inaccuracy area in terms of frequency or amplitude distortion. Furthermore, there is no significant difference in phase and sensitivity. The MEMS accelerometer was capable of measuring small amplitude changes and showed linear response with an accuracy of ± 3% in this case.

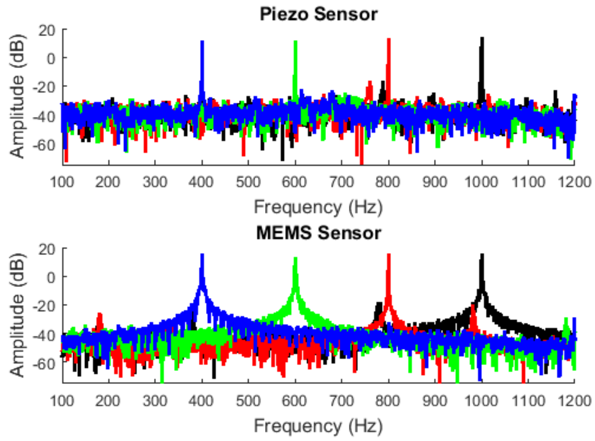

Figure 5: Results of Sensor System Verification on Shaker

Table 1: Signal to noise ratios of tested sensor types (MEMS and Piezo)

	1000 Hz	800 Hz	600 Hz	400 Hz
SNR (MEMS)	23.27 dB	28.32 dB	24.14 dB	33.37 dB
SNR (Piezo)	20.3 dB	18.73 dB	18 dB	16.8 dB

3.3. Sensor Integrating Gear

Design: Two of the MEMS acceleration sensors, named MEMS1 and MEMS2, were mounted on the front face of one of the spur gears with sensing axes in opposite polarity using double-sided adhesive tape (Figure 6).

For tangential acceleration measurements of the pinion, both sensors were oriented with sensitive axes ("Y") perpendicular to the axis of rotation (Figure 6). Position accuracy was ensured using an alignment gauge, fabricated by means of laser cutting and placed relative to the shaft of rotation.

As stated before, the MEMS sensors are connected to a microcontroller by wires. The microcontroller and battery are mounted in a specifically designed housing which is mounted on the drive shaft (Figure 6). The housing is 3D-printed and the unbalance is reduced by design to reduce vibrations.

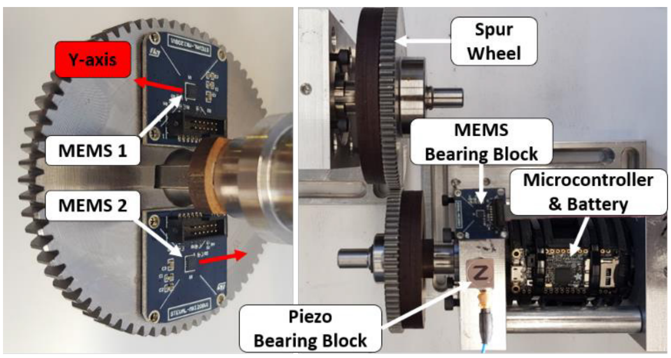

Figure 6: Design of the Sensor Integrating Gear

The measurement strategy intends for 5 minutes of measuring and 55 minutes of sleep mode per hour which preserves energy. The changes in the gear vibration signal due to wear are slow enough in our test scenario that measurements every hour are sufficient to track the changes. With this strategy the battery lasts > 1000 hours of operation until recharging is necessary.

Signal post processing: For a pseudo tach signal [13] the third harmonic of the gear mesh was used to determine a pulse signal. The following configuration of TSA showed best results: average of three rotations, Method: "FFT", resample factor of two.

Verification: In the following, the measurements of the designed sensor integrating gear are compared to the reference sensors described in Chapter 2.6.

MEMS Sensor Integrating Gear vs. MEMS Bearing Block

To gain insight of the MEMS vibration data, amplitude spectra were investigated. As expected, peak agglomerations are seen around the GMF and its harmonics (Figure 7). The sidebands and gear mesh vibrations appear much stronger in the spectrum of the integrated sensors. It is interesting to note that the highest peak of the spectrum of the sensor integrating gear is not at the GMF but up-shifted by exactly the gear rotation frequency (Figure 8).

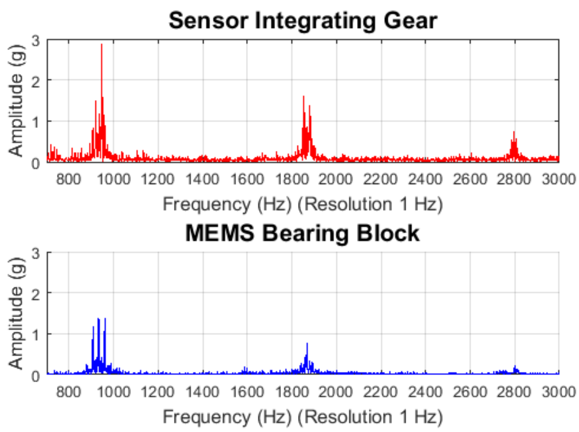

Figure 7: Sensor Integrating Gear compared to MEMS Bearing Block

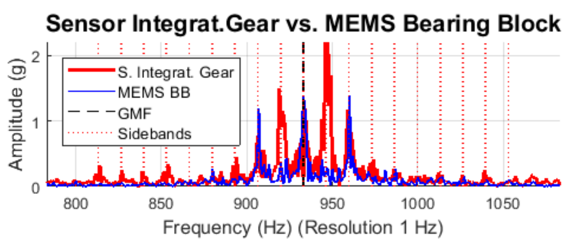

Figure 8: Spectrum Details (MEMS Sensor Integrating Gear Compared to MEMS Sensor on Bearing Block) showing GMF1 and Sidebands

Sensor Integrating Gear vs. Rotatory Laser Vibrometer

The Rotary Laser Vibrometer provides angular velocity, hence it is necessary to perform transformation to linear acceleration for comparison with the integrated acceleration sensors:

$$\omega_{rad} = \omega_{deg} * (\pi/180) \tag{1}$$

$$\dot{\omega}_{rad} = \frac{\omega_{rad}(t_{x+1}) - \omega_{rad}(t_x)}{T_a} \tag{2}$$

$$\alpha = \dot{\omega}_{rad} * r/g \tag{3}$$

where ω_{rad} is angular velocity (rad/s), a is linear acceleration, t_x is discrete time vector at the sample x, r is radius of MEMS sensor to the rotating shaft, T_a is sample time, and g is gravity.

Overall, both measurement techniques showed important vibration phenomena especially around the first GMF with high peaks (Figure 9). In the area of higher frequencies, the signal of the laser vibrometer was contained by lots of noise. TSA was applied to improve SNR. This enabled lower noise, but could not lead to a spectrum showing peak agglomerations, distinguishable from noise, around the second and third harmonic of the gear mesh for the rotatory vibrometer.

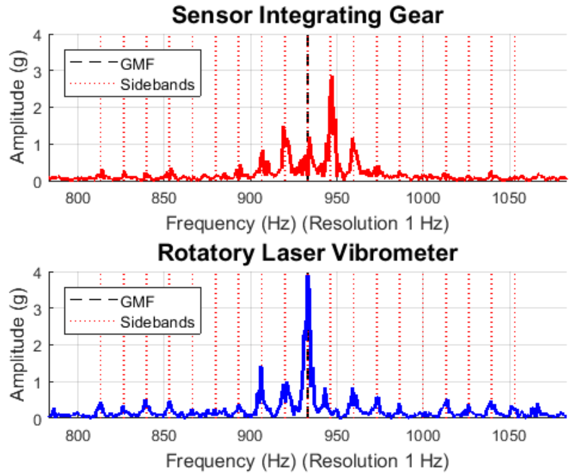

Figure 9: Verification of Sensor Integrating Gear with Rotary Laser Vibrometer

MEMS Bearing Block vs. Piezo Bearing Block

Both setups measurement results show frequencies from the lower end (shaft rotating frequency) up until the fourth harmonic of the GMF. In terms of signal quality, it is interesting to note, that the consumer-grade MEMS sensor system does not show an obvious inferior behaviour compared to the laboratory high-end piezo sensor setup.

4. Discussion

The results of this contribution show that it is possible to integrate a MEMS sensor system on a gear that is capable of measuring the relevant characteristics of the vibration necessary to conduct condition monitoring and wear prediction. The easy integration with sensors and microcontrollers that are commercially available at very low costs outlines the potential of such sensor systems. All of the significant peaks in the frequency spectrum can be explained by gear meshing physics, therefore errors are regarded as unlikely. Moreover, the frequencies of the peaks and the relation of the amplitudes are similar to the direct measurements with the rotary laser vibrometer, apart from a shift which is discussed later.

The verification results show a superior SNR of the integrated MEMS sensors compared to the reference sensors on the bearing block. This was expected because of the direct measurement at the source of the vibration. The sensors on the bearing block are prone to noise and other interferences which lowers the SNR and the quality of the measurement. This supports the results presented in the research projects referenced in the introduction [5–8]. Measurements are similar in a qualitative way, but differ quantitatively due to different operating conditions like rotational speed and load.

Beside the advantages, the integrated sensor system also showed shortcomings. First, the measurement range of the chosen MEMS sensor of 16 g was exceeded at a few times. This was expected because the requirement of 23 g was not met. It is expected that the vibrations will increase in amplitude if wear proceeds, which may cause more excitations of the measurement range. That most likely will lead to negative effects on the measurement results. For further studies it is attempted to use sensors with a higher range.

Second, the highest peak in the spectrum of the integrated measurements was not at the GMF as expected but up-shifted by exactly the gear rotation frequency (Figure 8, Figure 9). Hilbert [17] got similar results in his integrated measurements on a planetary gear with piezo sensors at the planet carrier. However, his explanations are not applicable in our scenario because they include oil sump and signal transmission specifics related to planetary gears. An effect of the gravity as reason is ruled out by Hilbert, since this would only be summed up in the amplitudes. Lewicki et al. [6] also received amplitude peaks shifted to higher frequencies and explained it with the rotating frame of reference of the gear-mounted sensor. This is a reasonable explanation, possible optimizations for analysis have to be investigated in future contributions.

Furthermore, the wear prediction ability needs to be validated. Therefore, studies are planned to operate the sensor integrating gears until wear occurs and measure the vibration interval-based. It is expected to see changes of the amplitudes in the frequency spectrum at the GMF and its sidebands and multiples [1, 10].

All in all, integrated MEMS sensor systems are an important step towards digitalization in mechanical engineering because they enable a reliable, high quality measurement without considerable efforts in measurement equipment and data processing or high uncertainty [4, 5, 11].

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References

[1] R. B. Randall, *Vibration-based Condition Monitoring: Industrial, Automotive and Aerospace*: John Wiley & Sons, 2011.

[2] P. Sopcik and D. O'Sullivan, "Anforderungskatalog für MEMS-Sensoren," *Elektronik*, vol. 69, no. 8, pp. 16–21, 2020.

[3] P. D. Samuel and D. J. Pines, "A review of vibration-based techniques for helicopter transmission diagnostics," *Journal of Sound and Vibration*, vol. 282, 1-2, pp. 475–508, 2005, doi: 10.1016/j.jsv.2004.02.058.

[4] E. Kirchner, G. Martin, and S. Vogel, "Sensor Integrating Machine Elements: Key to In-Situ Measurements in Mechanical Engineering," in *23° Seminário Internacional de Alta Tecnologia: Desenvolvimento de Produtos Inteligentes: Desafios e novos requisitos*, 2018.

[5] G. Martin, S. Vogel, T. Schirra, G. Vorwerk-Handing, and E. Kirchner, "Methodical Evaluation of Sensor Positions for Condition Monitoring of Gears," in *NordDesign*, Linköping, Sweden, 2018.

[6] D. Lewicki, N. Lambert, and R. Wagoner, "Evaluation of MEMS-Based Wireless Accelerometer Sensors in Detecting Gear Tooth Faults in Helicopter Transmissions," NASA, Cleveland, USA, 2015. Accessed: Nov. 30 2020. [Online]. Available: https://ntrs.nasa.gov/archive/nasa/casi.ntrs.nasa.gov/20150010710.pdf

[7] Z. Fan and H. Li, "A hybrid approach for fault diagnosis of planetary bearings using an internal vibration sensor," *Measurement*, vol. 64, pp. 71–80, 2015, doi: 10.1016/j.measurement.2014.12.030.

[8] M. de Smidt and M. Ryan, "Internal Vibration Monitoring of a Planetary Gearbox," 2010. [Online]. Available: https://www.semanticscholar.org/paper/Internal-vibration-monitoring-of-a-planetary-Smidt-Ryan/4835f551011e17ea9bb4a2fb6e59ce6bb3d15515

[9] M. K. Heider, *Schwingungsverhalten von Zahnradgetrieben: Beurteilung und Optimierung des Schwingungsverhaltens von Stirnrad- und Planetengetrieben*. Zugl.: München, Techn. Univ., Diss., 2012, 1st ed. München: Verl. Dr. Hut, 2012.

[10] J. Peters, L. Ott, T. Gwosch, and S. Matthiesen, "Requirements for Sensor Integrating Machine Elements: A Review of Wear and Vibration Characteristics of Gears," Karlsruhe Institute of Technology, 2020.

[11] G. Vorwerk-Handing, T. Gwosch, S. Schork, E. Kirchner, and S. Matthiesen, "Classification and examples of next generation machine elements," *Forsch Ingenieurwes*, vol. 84, no. 1, pp. 21–32, 2020, doi: 10.1007/s10010-019-00382-1.

[12] M. Dörr, M. Ries, T. Gwosch, and S. Matthiesen, *Recognizing Product Application based on Integrated Consumer Grade Sensors: A Case Study with Handheld Power Tools*, 2019.

[13] *VDI 2206 - Entwicklungsmethodik für mechatronische Systeme*, 2206, VDI, 2004.

[14] H.-R. Tränkler and L. Reindl, Eds., *Sensortechnik*. Berlin, Heidelberg: Springer Berlin Heidelberg, 2014.

[15] B. Heimann, A. Albert, T. Ortmaier, and L. Rissing, *Mechatronik: Komponenten - Methoden - Beispiele,* 4th ed. München: Fachbuchverlag Leipzig im Carl Hanser Verlag, 2016.

[16] E. Bechhoefer and M. Kingsley, "A Review of Time Synchronous Average Algorithms," in *Proceedings of the Annual Conference of the Prognostics and Health Management Society*, San Diego, CA, 2009.

[17] M. Hilbert, *Investigation of the Gear Mesh vibrations of Planetary Gearboxes Considering phase modulation and Internal measurements,* 1st ed. Stolberg: Zillekens, Ralf, 2018.