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Requirements for Sensor Integrating Machine Elements

A Review of Wear and Vibration Characteristics of Gears

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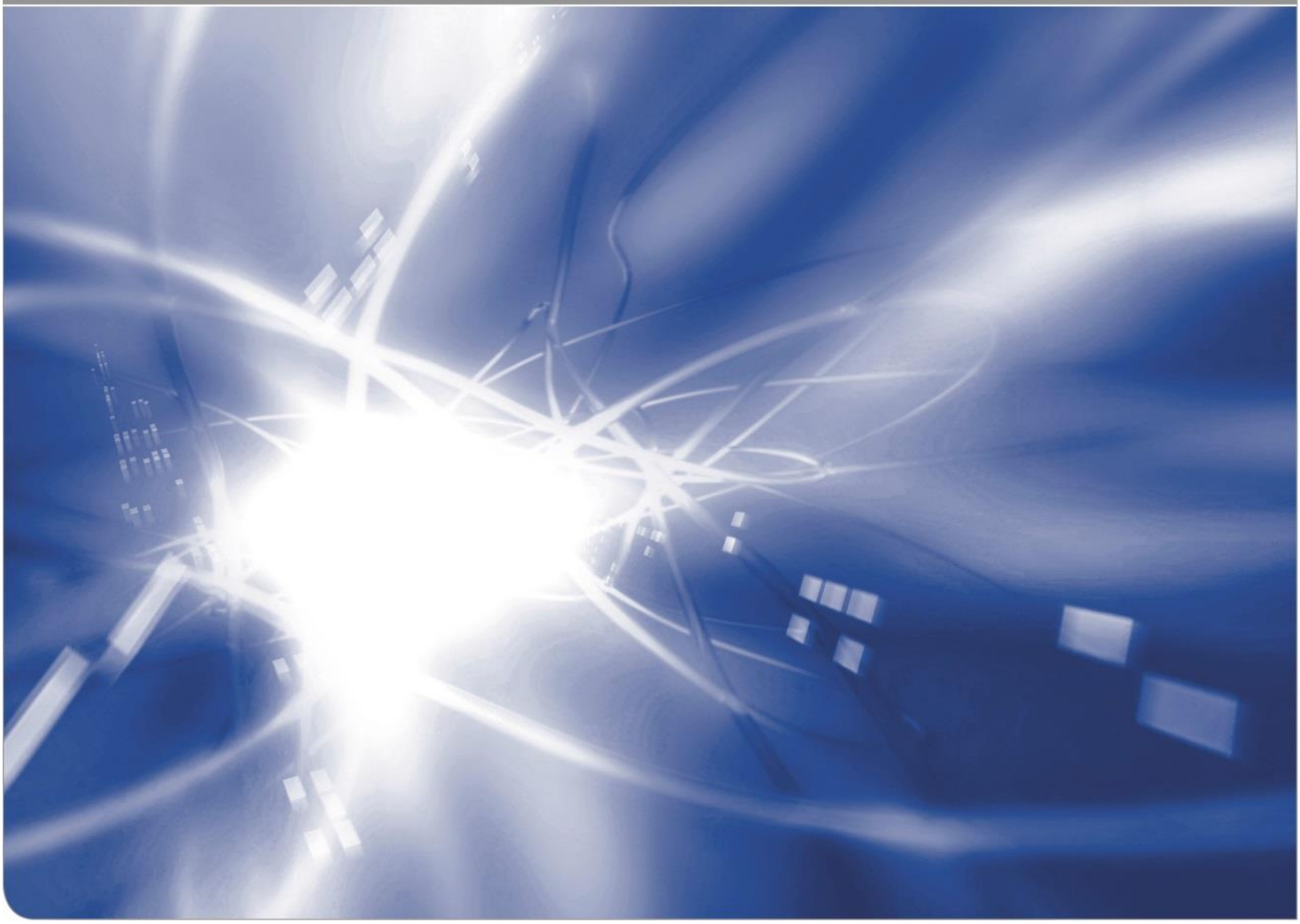

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Requirements for Sensor Integrating Machine Elements: A Review of Wear and Vibration Characteristics of Gears

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Abstract

For condition monitoring of machines sensor integrating standard machine elements provide advantage in acquiring high-quality, robust data from individual machine elements and reducing effort in signal processing. However, research covering small and inexpensive consumer-grade MEMS sensors with respect to integration and measurement requirements for wear detection is limited. In order to define such requirements, the state of the art of vibration-based condition monitoring of gears is reviewed and summarised. The focus is on the characteristics of progressive wear and how it might show in the vibration signal. The review finds that correlation between wear and vibration characteristics of gears exist, but the interpretation of the vibration signals is challenging and requires purpose-built signal processing methods. The review also concludes that integrated MEMS acceleration sensors are theoretically able to measure the vibration characteristics of gears to detect wear. Important characteristics are the gear mesh acceleration with its frequencies and harmonic multiples (GMF_i). Frequency range requirements for the sensors depend on the operating conditions of gears, the upper frequency limit needs to be greater or equal to 1.3 $GMF_{i,max}$. For the measuring range requirements, upper limits of 20 g RMS can be extracted within certain conditions. Data analysis requires a minimum frequency resolution which affects the size of memory needed for an integrated sensor system. However, there is a lack of research whether the sensitivity and internal noise behaviour of available MEMS sensors is good enough to measure relative changes in the vibration signals caused by wear.

1 Introduction

Gearboxes are essential components of many machines, which is why gearbox damage is of great relevance to their reliability. Failures of wind power plants, for example, are often caused by damages in the multi-stage gearboxes [1]. Also, gearbox damage is one of the most common causes of failure in helicopters [2]. Therefore, condition monitoring of gearboxes during operation is state of the art for many machines. Techniques in usage include structure-borne sound and vibration data analyses of the gearbox housing [2–4], particle measurement in the oil circuit [5], opto- or encoder-based vibration measurements [6, 7] or radial distance measurements of specific parts of shafts or gears [8]. The vibration data analysis is the most common [9] and highly suitable for in-situ measurements [10, 11]. For this reason, the focus of review is on this method.

A disadvantage of gearbox housing vibration analysis is the long transmission path between the source of wear and the sensor. This causes losses in the quality of the measuring signal, as the uncertainty is increased due to disturbances and noise such as the influences of adjacent machine elements, making the interpretation of the measured data more difficult. In order to overcome this shortcoming, acceleration sensors can be mounted directly on the gear. It is shown that in-situ vibration measurement provides higher quality data, e.g. concerning signal to noise ratio [12–14].

In addition, gears as machine elements with integrated sensor technology represent an important step towards digitalization in mechanical engineering. To embrace this technology safely and without considerable effort, extensive, reliable and high-quality data on the operating status of machines must be measured. This is possible by machine elements with integrated sensor technology [15, 16].

However, the integration of sensors in-situ is a challenging task, since the environment inside a machine is harsh and measurands, like vibrations, can have high amplitudes and frequencies. Sensors also need to be small, as the space for installation is often limited. Consumer-grade MEMS sensors are predestined for a compact integration on rotating machine elements, since they are available in very small sizes and do not require external measurement amplification. However, it is unclear if and how MEMS accelerometers can be used to detect and, if so, predict the state of wear of the gears in-situ. To answer the question, a detailed literature review is conducted with focus on two questions:

- How does wear of gears effect its vibrations?
- What are the requirements for in-situ MEMS sensors to measure vibrations influenced by wear?

2 Method of Investigation

A literature review consisting of three parts is conducted in order to answer the previous questions. To identify the correlation between wear and vibrations, first the types and characteristics of wear occurring on gears are reviewed (chapter 2.1). Second, the state of the art of vibration-based condition monitoring of gears is investigated to extract which characteristics of the vibration signals are relevant and need to be measured (chapter 2.2). In conclusion of the two first parts, a correlation between wear and vibration can be confirmed, if it exists (chapter 3.1). In the third part, research projects using in-situ acceleration measurements of gears or rotating machine elements are reviewed to identify measured characteristics (chapter 2.3). Requirements for the in-situ sensors are derived of the second and third part (chapter 3.2). The review process can be seen in the following Figure 1.

The review was conducted by the use of common research databases Researchgate, ScienceDirect (Elsevier), KITopen as well as the search engine Google Scholar. Also, standards were taken into account using the database perinorm.

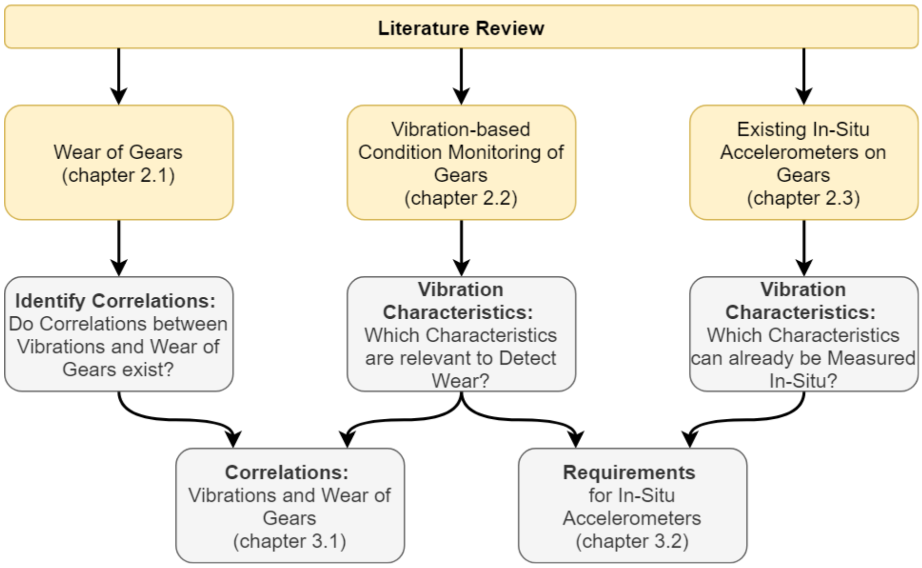

Figure 1: Procedure for determining the requirements for sensors

2.1 Wear on Gears – Indentifying Correlations

One relevant source for identifying wear of gears is the standard DIN 3979 [17]. It points out wear is a type of tooth face damage besides corrosion, erosion, pitting or deformation and generally refers to the abrasion of material when two bodies slide against each other. Tooth face damage and tooth breakage are two main gear damage mechanism [17, 18].

For evaluating wear of gears by vibration analysis types of wear and their characteristics that influence the vibration signal must be analysed. An overview of these types can be found in the following Table 1.

Table 1: Types of wear according to DIN 3979 [17]

Type of wear	Description	Characteristics
Normal wear	Shearing or plastic deformation of roughness peaks - levelling of surfaces.	• Smooth, shiny surface. • No influence on the function or service life.
Abrasive wear	Lapping material removal by solid impurities in the lubricant.	• Uniformly matt surface of the tooth flanks. • Structures of the production eliminated • The tooth shape can be changed and the tooth clearance (meshing behavior) increased.
Interference wear	Geometric deficiencies of the gearing or undercutting of the center distance as well as general errors in the bearing cause meshing problems, which lead to high pressures at the tooth head and root.	• Scraping marks in tooth height direction at tooth tip and root • Rounding of the top edge and hollowing of the tooth root • Amplification of the operating noise
Scratching	Contamination or roughness peaks of the counter flanks lead to depressions on the tooth flanks	• Isolated irregular line-type indentations in sliding direction
Scoring	Locally high loads on the tooth flanks lead to groove-like depressions in the flanks due to roughness peaks of the counter flank or contamination. This in turn causes scoring on the mating flank. Possible pre-stage to scuffing.	• Line-type indentations in the sliding direction over the complete contact path of the counter flank • Smooth groove bottom • Heavy material removal
Scuffing (a.e.: scoring)	Interruption of the lubricating film as a result of high sliding speeds or high flank pressure with low sliding speeds leads to local welds which are directly torn open again.	• Striped roughening in tooth height direction of different depth and width • Increased material removal at tooth root or head • Overheating of the material of the teeth

To examine the correlation between wear and vibrations it is also reviewed if these types of wear occur individually or combined because that most likely influences the vibration signals. Therefore, sources that conduct experimental studies on gears focusing on wear are considered. The results of the identification between wear and vibration are stated in chapter 3.1.

2.2 Vibration-based Condition Monitoring for Wear Detection on Gears

In condition monitoring and wear measurements in gearboxes it is established to analyse the vibrations of gear boxes in time and frequency domain for detecting faults or to evaluate the state of wear. Requirements for in-situ measurement were extracted from these sources. The research databases revealed many contributions about this topic. However, most sources relate on housing mounted sensors for the interpretation. Nevertheless, these sources were able to provide valuable information about the characteristics of the vibration signal that needs to be measured. The focus of this review was on wear detection by vibration measurement. The sources that were considered to be relevant for this review are introduced in the following Table 2. The results of this review are presented in chapter 3.

Table 2: Correlation between wear and vibration in literature

Authors	**Title**	**Field of Investigation**
Randall et al. [4]	Vibration-based Condition Monitoring: Industrial, Automotive and Aerospace	Application of vibration analysis for condition monitoring of machines. Presents state-of-the-art research results, covering vibration signals from rotating and reciprocating machines.
Samuel et al. [2]	A Review of Vibration-based Techniques for Helicopter Transmission	Reviews the state of the art in vibration-based helicopter transmission diagnostics and emerging trends that improve future transmission diagnostics.
Zhang et al. [19]	Gear Wear Process Monitoring Using a Sideband Estimator Based on Modulation Signal Bispectrum	Development of a gear wear condition monitoring approach based on vibration signal analysis using a sideband estimator.
Hu et al. [20]	Development of a Gear Vibration Indicator and its Application in Gear Wear Monitoring	Development of a vibration indicator to evaluate the effects of wear on gear performance based on a gear state vector. Verification by experimental studies.
Amarnath et al. [21]	Detection and Diagnosis of Surface Wear Failure in a Spur Geared System using EEMD based vibration signal analysis	Presents the results of experimental investigations carried out to assess wear in spur gears of a back-to-back gear box under accelerated test conditions considering specific lubricant film thickness and its effects on the fault growth on gear teeth surface.
Palihawadana [22]	Gear Condition Monitoring Technics	Considers methods of gear faults and wear and their influence on vibration signals using various analysis methods
Guo et al. [23]	Psychoacoustic Analysis of Gear Noise with Gear Faults	Different types of gear faults (e.g. wear and misalignment) are analysed using psychoacoustic metrics on a synthesized noise signal of an example gearbox.

2.3 Existing In-Situ Acceleration Measurements on Gears

In the third part of the review, research projects using in-situ acceleration measurements on gears or rotating machine elements were reviewed to find measured vibration characteristics. Relevant literature sources were arranged in a chart (chapter 3.2). In those sources the term in-situ measurement only specifies a location of the sensors inside the machine. However, that location is not always the relevant source of vibrations. The relevant source to detect gear faults, for example, is the gear itself, not the shaft. The literature differs in the use of the sensor principle. For better understanding the sources were arranged according to two fields: sensor (MEMS and Piezo) and location (Housing, Shaft, Planet carrier and Gear), as shown in Figure 4, chapter 3.2. Combining the second and the third part of the review, requirements for the in-situ sensors could be derived (chapter 3.2).

3 Review Results

In this chapter the results of the review based on the two questions asked in the introduction are presented.

3.1 Correlation between Wear and Vibration of Gears

The review shows that vibrations of gears change with geometric deviations of the working surface from the ideal involute tooth profile. These deviations are due to the types of wear presented before. An abrasion of material, like it is common for abrasive wear, increases clearances and changes the meshing behaviour. These geometric deviations and elastic deformations under load conditions are named transmission errors, the main source of gear system vibrations. From a sufficiently high sampled and Fourier transformed vibration signal, typical characteristics in a spectrum can be seen. Most important are the following ones. [2, 4]

- Shaft rotational vibrations
- Gear mesh vibrations
- Sidebands

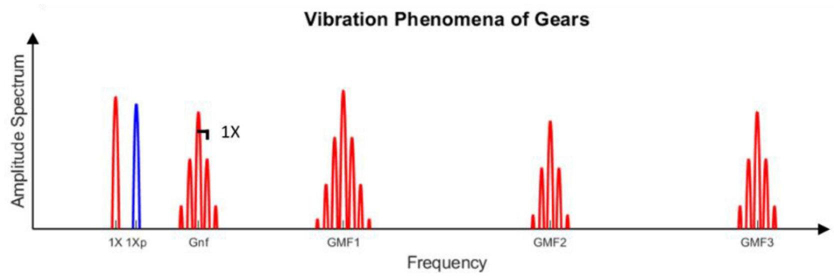

Figure 2: Qualitative frequency spectrum of acceleration on gears based on [4]

Vibrations with the **shaft rotation frequency** are visible in the acceleration signal due to the existence of unbalances in the rotating elements. In Figure 2, this is shown as "1X" (shaft of the larger gear wheel) for the first order and "1Xp" (shaft of the pinion - smaller gear wheel) at the fourth order. The transmission ratio equals the ratio of these frequencies. A high amplitude correlates to a high unbalance. [4]

The **gear mesh frequency**, in Figure 2 shown as "GMF", is the rate at which gear and pinion teeth periodically engage. This meshing frequency can be calculated by the product of shaft rotation frequency and the number of teeth of the respective gearwheel. Furthermore, harmonic multiples of the gear mesh vibrations and sidebands occur [4], which are designated "GMF2" and "GMF3" in Figure 2. **Sidebands,** a variance of the meshing frequency and shaft rotational frequency, occur due to complicated asymmetric modulation effects. These phenomena are distributed around the meshing frequency and its harmonics [19]. Moreover, the natural frequency of the gear stage is visible and shown as "Gnf" in Figure 2 [4].

Wear causes geometric changes of the teeth profiles and thus effects the transmission error, which influences the vibration signal. As wear proceeds the profiles deviate further from their initial states. However, the change of deviation is not linear neither deterministic, which makes it complex to determine the wear severity based on the vibration signal. [20]

Studies on wear severity analysis and its correlation to the vibration signal are rather sparse and conflicting in parts. On the one hand it is stated that the initial indication of wear will usually be an increase in the gear mesh acceleration and its harmonics whereas the typical, double scalloped wear pattern mainly increases the 2nd harmonic [4]. On the other hand research showed no increase in the 1st order gear mesh acceleration caused by wear, but in its 2nd and 3rd harmonics [22, 23]. Furthermore, there is no clear correlation with the progression of wear for shorter time periods, especially looking at the 2nd to 4th harmonics of the gear mesh frequency [24] (Figure 3). Only a long-term trend is noticeable.

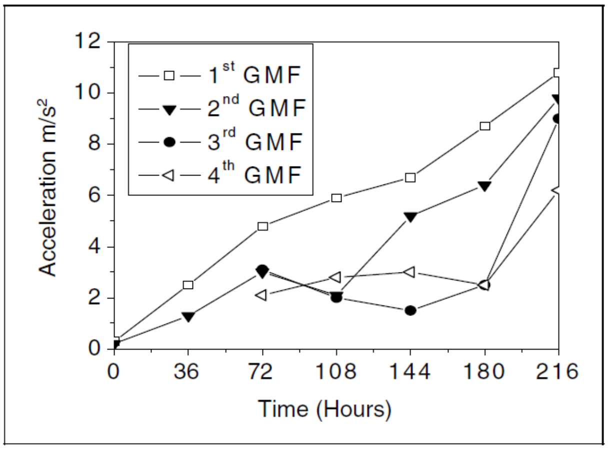

Figure 3: Gear mesh frequency and harmonics subject to runtime [24]

Furthermore, an indication of wear can be a change of sidebands that occur around the gear mesh frequency. Geometric tooth-to-tooth differences correlate with a change in the strength of sidebands. This change is due to the fact that the teeth wear out, which is why the clearance in tooth contact changes. That leads to an increase or decrease in the strength of the sidebands. In summary, this complex situation makes it preferable to take all significant meshing harmonics and their sidebands into consideration to get information about the state of wear. [4, 20, 24]

Some researchers developed special indicators for detecting gear wear mainly based on gear mesh vibrations and sidebands. Zhang et al. [19] developed a dimensionless indicator using the modulation signal bispectrum-based sideband estimator (MSB-SE) method. The results demonstrated that the proposed indicator can be used to accurately and reliably monitor gear tooth wear and evaluate the wear severity. Another indicator called the averaged logarithmic ratio (ALR) is introduced by Hu et al. [20]. An increase of the value compared to a fixed or a moving reference indicates that the gears deviate from its reference condition which most likely is caused by wear progression.

Usually the types of wear on gears do not occur individually, but in combination and can partly merge into each other [18, 20]. Therefore, it is not reasonable to commit to a single type of wear for the wear measurement. The wear types that offer the greatest potential for in-situ measurement of wear by vibrations of gear wheels are those in which material is removed and thus change the tooth form or meshing behaviour. This occurs with grinding wear, wear due to meshing failure, scoring and scuffing.

3.2 Requirements for In-Situ Acceleration Sensors

As introduced in chapter 2.3 the relevant existing in-situ acceleration measurements are clustered in categories of placement and sensor principle (Figure 4). Research covering the target area of MEMS sensors directly mounted on the gear is limited. The closest projects to this gap are the following: Piezo sensors mounted directly on the gear as in [25] and MEMS sensors mounted on the shaft of a gear as in [14]. They are reviewed in the following chapters 3.2.1 and 3.2.2. Afterwards, the requirements are derived in chapter 3.2.3

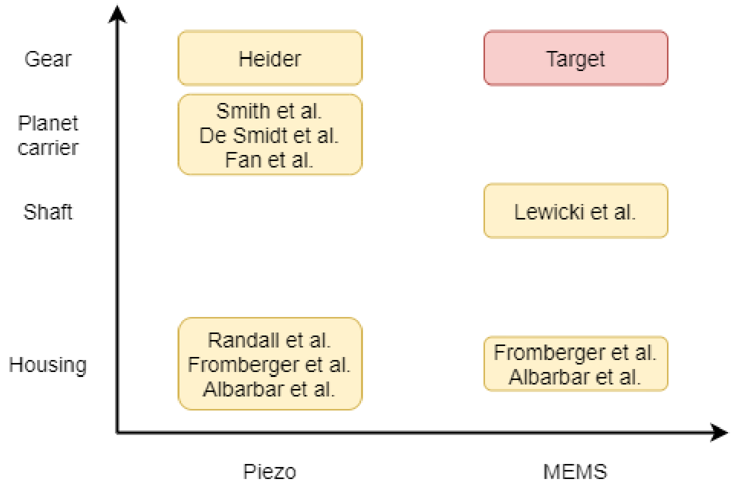

Figure 4: Classification of existing vibration measurements

Fromberger et al. [9] and Albarbar et al. [26] compare Piezo and MEMS accelerometers mounted on housings. The MEMS sensor and data-acquisition system Fromberger et al. used was able to measure some relevant characteristics but could not achieve the quality of the piezo sensor system. This is because the authors used a low budget Arduino Microcontroller. Furthermore, the MEMS sensor had a significantly lower bandwidth than the piezo sensor, MEMS sensors with higher bandwidths exist. Albarbar et al. used three MEMS sensors with different bandwidths, ranges and sensitivities for comparison on an industrial CNC-machine. The two sensors with higher bandwidths but lower sensitivity could detect most of the relevant vibration characteristics[1] contrary to the sensor with the low bandwidth but high sensitivity. In general the data collected showed lots of noise including extra un-interpretable peaks which the authors imputed to the nature of the MEMS accelerometers structure [26].

In-situ vibration analysis on planetary gears is often researched. Smith et al. [13], De Smidt et al. [27] and Fan et al. [12] conducted hybrid vibration analysis by combining measurements of a piezo sensor on the housing as well as on the planetary carrier using slip rings. De Smidt et al. and Fan et al. concluded that the internal sensor on the planetary carrier was able to achieve better measurements

[1] Relevant vibration characteristics: fundamental running frequency, its multiples, the main line frequency and its multiple

than the sensor on the housing. Smith et al. got contradictory results, which could be caused by the use of the slip ring as the authors admitted. The contributions mention that better results could be obtained by using of wireless techniques.

3.2.1 Detection of Tooth Faults in Helicopter Gearboxes by Integrated MEMS Acceleration Sensors

Lewicki et al. [14] installed MEMS accelerometers on the rotating shaft of a helicopter gearbox with the aim of detecting tooth fracture. The gear mesh vibrations were measured and examined, which makes the results valuable for the purpose of this review. Using state-of-the-art error indicators [28] the MEMS sensors were able to successfully predict tooth breakage, but only with a short warning time. However, conventional reference sensors installed on the housing were not able to provide better predictions either. The investigations were limited to tooth fracture detection and suitability of the MEMS sensors in-situ. In this case, measurement was not taken directly at the location of the source of wear and vibration, the gears, but in a canister on the shaft. This resulted in a longer transmission path between the source of wear or damage, which influences the quality of the sensor data. gear wheels are not torsional rigidly connected to the shaft, which influences the signal transmission.

The sensor system integrated three analog accelerometers (Figure 5) with analog-to-digital converters, a microcontroller and memory chips. The accelerometers were aligned with the measuring axis both radially and tangentially to the shaft surface to measure radial imbalance and rotational acceleration. The sensors had a dynamic measuring range up to 250 g, a sensitivity of 4.4 mV/g, a resonance frequency of 22 kHz and a linear bandwidth up to 10 kHz. The signals of the accelerometers were filtered with an analog low pass filter with a cut-off frequency of 15 kHz. The sampling rate of the 16-bit analog-to-digital converters for the measurand was 43 kHz, thus complying with the sampling theorem [29]. With this sensor technology and data acquisition, the occurring gear mesh frequencies could be measured up to the seventh harmonic multiple. The measured accelerations are summarized in the following Table 3.

Table 3: In-situ vibration measurement results according to [14]

Operating condition	**Vibration/acceleration measurements**	
	Max. frequency	**Max. range**
525 Nm 6180 rpm	3^{rd} order: 5.9 kHz	Radial: 20 g RMS Tangential: 16 g RMS

The acceleration was measured for one second in 51 second intervals. This short continuous measurement time is probably due to limitations of the memory of the microcontroller board used. However, the measurement duration should be sufficient to map several complete rotations of the gear wheel. This was achieved in the presented setup with the speed of 6180 rpm (103 Hz). [14]

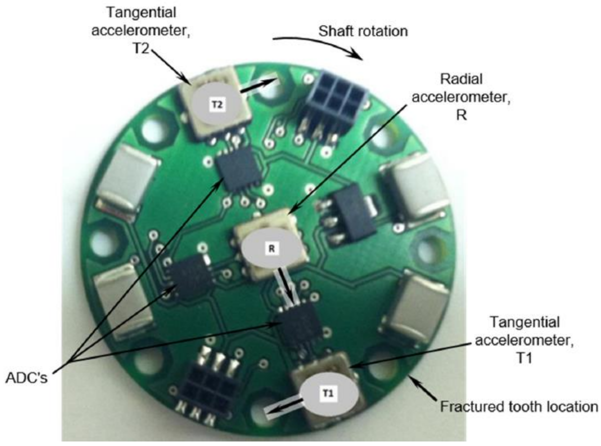

Figure 5: Accelerometer board mounted on shaft [14]

3.2.2 Vibration Characteristics of Gear Drives

With the aim of evaluating vibrations in gear drives, Heider [25] mounted piezo accelerometers directly on the gear using a disk. The signal transmission is analog using a rotary transformer and is processed and recorded by a spacious measuring amplifier. Due to that fact, this method is not suited for a compact integration. Nevertheless, the measurement values allow predictions on the amplitudes and frequencies of the gear mesh acceleration that might occur in applications.

The authors provide campbell diagrams that show the vibrations dimensionless by level. The reference values used are taken from the norm DIN EN ISO 1683 [30]. The values were transformed back to g-range for reasons of comparison. The measurement values are summarised in the following Table 4.

Table 4: In-situ vibration measurement results according to [25]

Operating condition	**Vibration/acceleration measurements**	
	Max. frequency	**Max. range**
1000 Nm 1000 rpm	3rd order: 2.1 kHz 5th order: 3.6 kHz	Tangential: 3.2 g (max. in spectrum)
1000 Nm 4500 rpm	3rd order: 9.6 kHz 5th order: 16.1 kHz	Tangential: 102 g (max. in spectrum)

Utakapan et al. [31] investigated the influence of microgeometric changes on the vibration characteristics of acceleration using an identical test setup. The authors show that even small geometric changes on the tooth flanks cause changes.

3.2.3 Derivation of Requirements

The requirements for in-situ sensor technology are derived from the previous chapters. It shows that requirements for the sensor technology depend strongly on the operation of the individual gear: especially on the shaft rotational speed, the load momentum and the number of teeth of the gears. The greatest measured values are used for limitation. In general, it can be said that the frequency bandwidth of the used sensor technology should be as high as possible, because it determines the maximum rotational speed of the gears at which the relevant gear mesh accelerations can be measured. The sampling rate f_s of the sensors must be at least twice the maximum frequency of the signal[2] $f_{signal,max}$ to comply with the sampling theorem [29].

$$f_s \geq 2\, f_{signal,max} \tag{1}$$

The frequency range ($f_{sensor,range}$, i.e. bandwidth) of the sensor must be greater or equal to the maximum frequency of interest of the signal ($f_{sensor,range} \geq f_{signal,max}$). In this case that is a multiple ($order_i$) of the gear mesh frequency (GMF). The GMF is the product of shaft rotational frequency f_{shaft} and number of teeth n_{teeth}.

$$GMF_i = f_{shaft}\, n_{teeth}\, order_i \tag{2}$$

The sources reviewed in this contribution investigated harmonic multiples up to 3rd or 5th order. Upper sidebands occur on frequencies higher than their carrier, the GMF. This makes it necessary to set the upper frequency of investigation greater than the frequency of GMF_{max} (approximately 30 %). The requirements for bandwidth and measuring range for measuring the shaft speed and gear mesh frequency are summarized in the following Table 5.

Table 5: Requirements for in-situ measuring system (common orders varying from 3rd to 5th)

Variable / characteristic	**Significance**	**Requirements for sensors**	
		Frequency range	**Measurement range**
Unbalance	Shaft rotational speed Unbalance vibration	$> f_{shaft}$	Up to 20 g RMS
Gear mesh frequency & Sidebands	Meshing behaviour – Progress of wear through material removal on tooth surfaces	$> 1.3\; GMF_{max}$	Up to 16 g RMS

With the relations from above, a requirement for the minimum sampling frequency is:

$$f_s \geq 2.6\; GMF_{max} \tag{3}$$

Also, the storage of the sampled data needs to be considered to select a suitable memory type. The number of datapoints N to be stored with respect to sampling frequency f_s, sampling period T is calculated by:

$$N = f_s\, T \tag{4}$$

The data acquisition system must be able to continuously record a minimum number of datapoints which results in demands for the memory size. The minimum amount of datapoints to capture in one record (i.e. minimum sampling period) can be derived from the frequency resolution Δf of the Fourier-Transformation. It needs to be low enough to resolve the lowest occurring frequency distance of the vibration phenomena of interest, which is the distances between sidebands usually appearing with the shaft frequency. The sampling frequency f_s is related to the gear mesh frequency *GMF* as formulated before (Equation 3). With this the number of datapoints N can be calculated which enables the selection of an appropriate memory. [32, 33]

$$N = \frac{f_s}{\Delta f} \tag{5}$$

[2] Requirement: the bandwidth of the signal is limited (band-pass filtered)

If several sensors are used in combination, it must be ensured that the measured values are taken at exactly the same time. This is achieved, for example, with special analog-digital converters. The sensitivity of the sensors should be as high as possible to measure relative differences of the amplitudes in the frequency spectrum, caused by wear progress. The investigation presented in chapter 3.2.1 achieved good results by using analog MEMS accelerometers with a sensitivity of 4.4 mV/g.

4 Discussion

In the following the results of the review are discussed based on the questions asked in the introduction.

4.1 Correlation between Wear and Vibration

The review showed that correlations between the progress of wear and vibrations of gears exist. Starting from an initial state without wear, it is thus possible to measure a change in the tooth engagement accelerations and particularly in the sidebands as wear progresses.

However, the interpretation of the vibration signals is challenging and requires purpose-built signal processing methods. Some researches contradict each other e.g. in the progression of the amplitudes of gear mesh acceleration as stated in chapter 3.2. This may be due to the fact that the different types of wear on the gear wheel presented before overlap in practice and cause different and sometimes even opposite changes in the acceleration amplitudes.

Indicators for detecting wear exist. Most of them rely on a monotonic increase of the amplitudes at gear mesh frequencies and sidebands to indicate a progression of wear. However, this is only applicable for a relatively long period of runtime. For short-time observations, the gear mesh and sideband ratios could become smaller. Since most indicators summarise those ratios the results show random fluctuations making a prediction of wear impossible for shorter time periods.

Furthermore, such indicators rely on complicated methods that require considerably high implementation and computational efforts. Also, the methods contain sophisticated noise reduction to be applicable for housing mounted sensors. So providing better signal to noise ratios could improve the results even more. Also, vibration peaks from other machine parts overlap. An individual measurement directly on each gear by integrated sensors could yield results more distinctly without overlapping signals and better signal to noise ratios.

4.2 Requirements for In-Situ Vibration Measurements

The requirements that could be extracted out of the measurements conducted in the research projects, reviewed (chapter 3.2), only serve as limitation values. It is not appropriate to derive absolute values, because the requirements are dependent on the specific operation parameters of the machines. That also means that the bandwidth of the sensor limits the maximum shaft speed of the machine. If the machine goes faster, the relevant vibration characteristics for wear progress cannot be measured anymore. Fortunately, in this case analog MEMS sensors have no disadvantage compared to piezo accelerometers that are commonly used for vibration data analysis of gears because the bandwidths are within the same range (ADXL1005: 23 kHz [34], Brüel & Kjær 4518: 20 kHz [35]). Even some digital MEMS sensors provide bandwidths up to almost 7 kHz. Concerning the sensitivity the review revealed that MEMS sensors with a lower sensitivity could detect more vibration frequencies than the one with higher ones. This result is unexpected, it was assumed that a higher sensitivity provides a more exact measurement. The authors explained this behaviour with the occurrence of noise and extra un-interpretable peaks due to the nature of the MEMS accelerometers structure.

When comparing MEMS sensor technology to piezo it has to be mentioned that MEMS sensors can be integrated into machine elements with less effort. Most analog MEMS accelerometers do not need signal amplification. Therefore, they can be integrated into gears or other machine elements in a very compact way with a microcontroller serving as data acquisition system. It is possible to combine complete datalogging systems on small printed circuit boards and mount it on machine elements.

The review shows that MEMS acceleration sensors are suitable as in-situ sensors for measuring vibration with a sufficient quality. It was shown that tooth faults could be detected. Theoretically they are able to measure wear as well, as they are able to measure the relevant vibration characteristics like the gear mesh acceleration with several harmonic multiples, if the operating speed stays within boundaries as mentioned before. However, there is a lack of research if the sensitivity of available MEMS sensors is high enough to measure relative changes in the vibration signals caused by wear. Moreover, influences of continuous changes in tooth flanks due to wear on the vibration signal is not deterministic, which makes it challenging to determine the wear severity based on the vibration signal.

5 Summary

The integration of sensors close to the source of wear of gears - the tooth contact - allows carrying out high-quality measurements to analyse the wear condition. Short signal paths allow a good signal-to-noise ratio to be expected and reduce effort in signal post processing methods. Consumer-grade MEMS accelerometers are a good choice for compact integration because they are very small, readily available and do not require external signal amplification. In-situ vibration analysis of the acceleration of gears is already used in research projects, but not for the purpose of wear prediction.

Experimental studies can proof the concept of in-situ measurement with MEMS acceleration sensors. Therefore, a gear test rig with sensor integrated gears will be set up to experimentally evaluate the correlation of wear and vibrations. First, a suitable MEMS acceleration sensor has to be selected in regard of the specifications determined in this contribution. The sensor needs to be verified to proof that it is capable to measure the relevant accelerations with a sufficient quality. Also, a data acquisition device that can be integrated beside the sensor on the rotating shaft needs to be selected. It should be able to read the sensor and store or stream the data with a sufficient rate.

Concerning the mounting of the sensor(s) it needs to be evaluated how many sensors are necessary and which orientation performs best. Furthermore, investigation is required to verify the in-situ measurement of the MEMS sensors with a different measurement method to discover potential shortcomings and prevent a possible false rejection of the method.

6 Acknowledgements

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