Development of a sensor- and cloud-based condition monitoring system for the detection of gear damage

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ABSTRACT | This paper presents the development of a sensor- and cloud-based condition monitoring system for the detection of gear damage in agricultural machines. Undetected gear damage can result in fatal damage causing huge costs due to downtime and upcoming repairing. Based on the study of synthetically damaged gears, the effect of tooth damage in gearboxes and therefore on the vibration signal is analysed. From these findings we develop a condition monitoring system for the usage in agricultural machines. For the measurement of the resulting vibration signal, caused by the gear, a piezoelectric vibration transducer is used. An application-specific sensor system is developed, which consists of analog filters, analog-to-digital converters, processing units and communication interfaces. The sensor system can analyse data in real-time and transfer it to a cloud computing system over an encrypted connection for more computation intensive calculations and data driven long-term analysis. The cloud computing system receives the transferred data, analyses it and stores significant information, like measurement metadata and analysis results, in a database. The stored data can be viewed by the owner of the agricultural machine and used for planning repairs or maintenance.

Introduction

During harvest time agricultural machines require a very high level of availability. Due to the harsh environmental conditions, the gearboxes of these machines are exposed to a numerous number of loads. In particular, dust and soil picked up by the agricultural machine can lead to various types of damage and in long term even to total failure of the moving and rotating machine parts. Despite regular maintenance of the machines, heavy-duty machine components such as gearboxes can fail due to this type of damage during harvesting. Figure 1 shows characteristic damage patterns of gearboxes which can result from bearing damage or tooth fractures. In such cases, the repair and downtime of the machine cause enormous costs. Early damage detection via a vibration signal analysis is a solution for this in order to be able to carry out repairs or maintenance in a targeted manner and to minimize machine failures and the associated costs. Current approaches to the condition monitoring of agricultural machines mainly describe the offline analysis of different methods. In the field of temperature monitoring, temperature fluctuations of machine components are investigated in order to detect various problems, such as inadequate lubrication [1].

Another area of analysis is the investigation of oil samples. Here, foreign particles per volume, the input of iron, metals or other impurities, the temperature or the consumption are analysed [2]. Other material or structural defects can be investigated using ultrasonic or X-ray analysis [3]. These are mostly carried out offline and are not very common due to high costs. Damage to bearings is determined by vibration analysis. In particular, damage to bearings can be determined by geometry-dependent damage frequencies [4]. At present, there is no specific vibration-based condition monitoring system available in the agricultural sector that analyses the condition of the existing components and a possible remaining useful lifetime to prevent unforeseen machine failure.

This paper presents the development of a sensor- and cloud-based condition monitoring system for the detection of gear damage in agricultural machines. For this purpose, piezoelectric vibration transducers are used to measure the vibration signal of the gearbox on the agricultural machine. The sensors are attached to the gearbox via a screw connection to ensure a good signal coupling for the mechanical vibrations [5]. The recorded signals will be processed in real time on the agricultural machine in order to detect serious damage to machine components, such as tooth fractures. An electronic sensor system is being developed for these investigations on the agricultural machine. In addition, long-term investigations of the components are to be developed in order to derive a possible remaining lifetime estimation from these findings. Since this calculation is considered over a long period of time and a higher computing effort is required for these investigations, the data is analysed by means of a cloud-based calculation server. For this purpose, data from defined vehicle scenarios (such as the residual unloading due to the high speed) is transferred via an established Internet connection from the electronic sensor system to a developed cloud server. After a successful data transmission this server handles the advanced signal processing and stores the results in a database. By accessing the database, repairs and maintenance can be planned better in future.
based on the condition of the machine components. The remainder of this paper is organized as follows. In Section 2 the condition monitoring system is described with a focus on the electronic sensor system, which consists of the signal analog-to-digital conversion, the local damage analysis and the communication interface for the data transfer to the cloud system. Section 2 also deals with the cloud computing system, which receives the incoming data and analyses it. Section 3 outlines measurements carried out with the sensor system integrated in the agricultural machine to collect field data. Furthermore, the experimental investigation for the detection of synthetic tooth fractures is described, which serves as a basis for the detection of real damage. Finally, a conclusion is drawn in Section 4.

Condition monitoring system

The condition monitoring system can be divided into two subcomponents. The first component is the sensor system integrated in the agricultural machine. This is used for data acquisition of the vibration signal, the rotational speed and the inflow and outflow pressures of the gearbox oil engine as well as for local evaluation and data transfer to the cloud computing system. The second component is the cloud computing system, which is responsible for receiving and storing the data in a database as well as for the visualization via a web frontend. In this section both system components are introduced.

Sensor system

The sensor system is integrated on the agricultural machine. A total of four sensor values are read via this system. These are the vibration signal, the rotational speed of the gearbox, the inflow and the outflow pressures of the oil engine. The oil engine serves as the drive of the gearbox in the agricultural machine. The block diagram of the sensor system is shown in Figure 2.

Cloud computing system

The second key component of the condition monitoring system is the cloud computing system. This receives the data, stores it in a database, analyses and finally visualises it via a web frontend. The block diagram of the cloud computing system is shown in Figure 3. The cloud computing system consists of several components. The core components for the communication to the sensor system are the MQTT server (also called broker) and the MQTT clients, which can both send and receive data. The broker takes over the exchange of the data between the clients. The dispatcher receives and manages the data. The data is first decrypted. Afterwards, the metadata is stored in a MySQL database and the sensor data is transferred to a data server via the SSH file transfer protocol (SFTP). The dispatcher then initiates an analysis request to the analysis client via the MQTT connection. The analysis client performs various calculations with MATLAB, which are then stored in the database and on the data server.

Experimental study

In this section a field study is described in which the developed sensor system was integrated in a loader wagon for grass cuttings for one harvest season to collect field data. Furthermore, a laboratory investigation is described in which synthetic gear damage in a gearbox and the behaviour in the vibration signal is outlined.

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In-vehicle data acquisition

The vehicle type is a loader wagon, which is used during harvesting to collect grass cuttings from the field and later unload them at a collection point. The sensor system is mounted under the vehicle
as shown in Figure 4. The image on the left side shows the mounted sensor system highlighted in a red box. The entire electronics is built into a splash-proof housing in order to be adapted to possible harsh environmental conditions during harvesting. The image on the right side shows the various components of the sensor system.

Of particular interest for the vibration signal are the rotational speed and the pressure difference at the oil engine, which is equivalent to the converted torque in the gearbox. During operation of the vehicle, a distinction can be made between the three phases loading, unloading and residual unloading. The pressure differences and rotational speeds occurring in these phases are shown in Figure 5. The three phases are separated by trickled lines. During the loading phase an increasing pressure difference and an approximately constant rotational speed can be observed. The drops in pressure difference and rotational speed can be explained by the fact that during this phase the gearbox is only temporarily active to move the chain transport floor and thus distribute the load more evenly over the loading area. During the unloading phase the pressure difference and thus the torque drops. The rotation speed is low and increases only negligibly. Finally, in the residual unloading phase, the rotational speed is increased in order to transport the remaining load from the vehicle. In this phase the pressure difference increases.

Detection of gear damage

In order to detect serious damage to machine components, such as gear damage, a detailed investigation on this damage type is needed. For this purpose, a gearbox with a synthetic tooth fracture is studied in a laboratory set up. Figure 6 shows the schematic design of the two-stage gearbox under investigation and the position of the synthetically introduced damage. Figure 7 shows the implementation of the real tooth damage on gear G2 highlighted. For the investigations, the gearbox was driven in a test setup with an input shaft speed of \( n_{in} \approx 104 \text{ min}^{-1} \). A piezoelectric vibration transducer is attached to the gear housing (material: grey cast iron) via a screw connection. The vibration signal of the piezoelectric transducer is sampled at a sampling rate of \( f_s = 51.2 \text{ kHz} \) and a resolution of 24 bit.

Figure 8 shows the block diagram of the digital signal processing used. The recorded vibration signal is first filtered via a digital Butterworth band pass filter of the 50th order. For the detection of a tooth fracture, the cut-off frequency of the digital high pass filter \( f_{HP1} = 50 \text{ Hz} \) and that of the digital low pass filter \( f_{LP2} = 200 \text{ Hz} \) is used. The frequency range was determined empirically. Following the band pass, the signal envelope is calculated [6]. For this calculation, the spline interpolation of the maximum values of the filtered signal is calculated. After each local maximum, a window of \( k = 10 \) values is skipped and then the next local maximum is searched in a window of \( k \) values. A resampling filter is applied to the signal envelope, which consists of a low pass filter with a cutoff frequency \( f_{LP2} = 20 \text{ Hz} \) and down sampling by a factor of 500. This is advantageous because the calculation of the following Fast Fourier Transform (FFT) does not require further calculation of already filtered out high-frequency signal components and a shorter calculation time is required, which is beneficial for a future realtime implementation on the sensor system. Furthermore, there is a gain in dynamics because the quantization noise is distributed over the entire sampled signal bandwidth and is therefore lower in the useful signal bandwidth after the filters have been applied. In order to investigate the characteristic course of the vibration signal caused by the tooth damage in more detail, several successive time windows of the signal peak values caused by the tooth damage are examined. The signal is adjusted by correcting the time offset, which was calculated on the basis of a cross-correlation [7].

Figure 9 shows, on the one hand, the time windows aligned by correcting the time offset in grey and, on the other hand, the signal mean value of the superimposed time windows in red. The illustration shows the characteristic signal curve in the case of a tooth fracture. The signal amplitude increases significantly during tooth engagement with a damaged tooth and shows a recurring course. The characteristic course only occurs once per revolution of the gear.
Therefore, the condition can be derived for an examination of tooth damage that a complete revolution of a gear must be considered. Figure 10 shows the frequency spectrum of the envelope curve for a measurement series without tooth fracture and one with tooth fracture. A fundamental frequency occurs at $f_{\text{fund}} = 0.497 \, \text{Hz}$, as well as harmonic oscillations at $f_{\text{fund}} \cdot n$ for integer multiples $n$ in the measurement series with tooth fracture. The amplitudes of these frequency bands differ strongly from those of the intact gearbox. These frequency bands, which are clearly different from the spectrum of the reference gearbox, correspond to damage frequencies which can be determined on the geometry of the gearbox. For the investigated tooth damage at the gear $G_3$, the tooth engagement frequency $f_{G_3}$ results according to the following equation:

$$f_{G_3} = \frac{n_{\text{in}}}{60} \cdot i_1^{-1} = \frac{n_{\text{in}}}{60} \cdot \frac{z_2}{z_1} \approx 0.49 \, \text{Hz}$$

For the investigation, the gearbox was driven at an input shaft speed of $n_{\text{in}} \approx 104 \, \text{min}^{-1}$. The gear ratio $i_1^{-1}$ results from the tooth meshing with the number of $z_2$ of $G_2$ and $z_1$ of $G_1$. The determined fundamental frequency corresponds approximately to the theoretical frequency for the tooth mesh of the tooth damage at $G_3$: $f_{\text{fund}} \approx f_{G_3}$. The significantly increased signal power is therefore caused by the tooth fracture. An implementation of this signal processing on the sensor electronics will detect tooth fractures during the use of the agricultural machine in the future.

### Conclusion

This paper presents a developed condition monitoring system for monitoring gear damage. A distinction was made between the sensor system for data acquisition and local evaluation and the cloud computing system. Furthermore, the implementation of the sensor system in the vehicle was examined and field data, which have a significant impact on the occurring gearbox vibrations, were presented. In parallel, laboratory investigations on synthetic tooth damage were considered and a signal processing system for the detection of this damage was set up. In future investigations, a representative load spectrum will be derived from the field data obtained and, based on this, more realistic investigations of gear damage at variable speeds will be carried out. For this purpose, the detection algorithm will be further developed to provide reliable results in the vehicle in the future. Furthermore, realistic long-term measurements are to be carried out with the load spectrum in order to investigate wear phenomena.

### REFERENCES


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