1. Introduction
Predictive maintenance is of high importance in particular for mining industry. The main goal is to maximize the availability of a machine by minimizing the downtime [1]. In mining companies, the maintenance cost itself can be 30-60% of total operation costs [2].

The operating condition of a mobile machinery, such as a wheel loader, can vary instantly, as it is heavily influenced by how the vehicle is operated and by the environment around it [3]. As an example system for mobile work machines, wheel loaders are vehicles that are mainly used in construction and mining industries for handling and transporting various materials. According to results in [2], maintenance of wheel loaders plays a major role in total maintenance of mining machines. Therefore, prediction of a wheel loader’s condition is crucial to reduce downtime and costs, and increase availability and production in mining industry.

The results in Figure 1, from [4], suggest that among various parts of a wheel loader, drivetrain-related failures occur most often. Drivetrains of heavy-duty vehicles are complex mechanical and dynamical systems [5-7] and can require advanced analyzing and monitoring tools [8, 9]. Due to the critical role of drivetrain in availability of a wheel loader, in particular in mining industry, vibration-
based condition monitoring can be applied on drivetrain components such as cardan joint shaft between drive and driven sides of the vehicle.

![Repair Frequency vs Type of Failure](Figure 1)

Figure 1. Repair frequency and percentage of total repairs versus type of failure, from [4].

The cardan joint shaft is amongst the most commonly used universal joints for torque transfer when the input drive and output driven shafts are not aligned, [10] such as the situation in wheel loaders, where front and rear sides of the vehicle may not be on the same axis of rotation. Cardan shafts, as one of the vehicle drivetrain components, can be heavily torque-loaded [11], and therefore, may experience misalignment between input and output sides, unbalances, and looseness or operating clearance of internal components such as rolling bearings [12].

The predictive or proactive maintenance strategies use primarily non-destructive Condition Monitoring (CM) testing tools to assess machinery drivetrain health status and performance [13]. The condition monitoring is mainly performed by external sensors, which are attached to the machine. These sensors can measure physical parameters related to the machine condition such as temperature, vibrations, and torque. By analysing sensor data, it is possible to enhance maintenance strategy and take required further repair actions. It is widely accepted that the vibration analysis is capable of finding machine element fault(s) and their location(s) in a reliable way compared to other monitoring methods [14]. The mechanical damage is usually referred to changes in geometric properties of the machine. These sudden changes may generate additional dynamic forces acting in the system, which can be diagnosed based on the system responses [9].

Although many studies have been conducted and published on the usage of vibration analysis for drivetrain components such as cardan shaft [12, 15], the lack of knowledge about the performance of available vibration analysis tools in real-world conditions motivates further experimental studies and investments in research works for CM in mobile applications. Mobile machinery are operated under harsh and non-stationary conditions. Therefore, in order to gain required diagnostic information, additional data on the operating status of the machine are required in a vibration-based CM tools.

The current study aims to show and investigate application of the metadata from the machine CAN bus in vibration-based cardan shaft condition monitoring. The remaining of the manuscript is organised as follows: in the next section a theoretical background of cardan shaft damage diagnosis is given. Then, the proposed fault diagnosis methodology together with the description of case considered studies are explained. Subsequently, vibration-based damage diagnosis of cardan shafts with the help of CAN bus data are studied experimentally using test rig and field data. Finally, some concluding remarks are highlighted.

2. Cardan shaft damage mechanism

The analysis of dynamic behavior of a joint for damage detection purposes requires appropriate understanding of its kinematics. The kinematics allow to analyze the characteristics of design and geometry parameters and also study their individual effects on the general motion and vibration of the
joint. Cardan shafts or Hooke’s joint [16] are considered as classic joints which are common in mobile machines. In the current study, two common types of faults are investigated in some detail.

According to [14], when a torque transmission shaft has three or more bearing supports, for example when front and rear axles of a wheel loader are coupled together, there is a potential for misalignment, which can be parallel misalignment, meaning that one of the two shafts is displaced laterally, but still parallel to the other, or angular misalignment, where the axis of one is at an angle to that of the other. The angular misalignment of cardan shafts can introduce bending deflections to both input and output shafts while rotating with respect to the shafts. The excited bending modes of shafts show themselves then as harmonics of the shaft’s rotational speed in the frequency spectrum. This is considered as the basis for cardan shaft angular misalignment detection using vibration signals. Figure 2 shows a typical cardan shaft with an angular misalignment.

Figure 2. Simplified illustration of an angular misalignment at cardan shaft.

The angular misalignment can be studied mathematically using the equation (1), which shows the relative instantaneous angular velocity of output to input [17] as

\[
\frac{\omega_2}{\omega_1} = \frac{\cos \alpha}{1 - \sin^2 \alpha \sin^2 \theta_i}
\]  

(1)

where \(\frac{\omega_2}{\omega_1}\), \(\alpha\), and \(\theta_i\) are output-to-input ratio of instantaneous angular velocity, the misalignment angle, and the instantaneous shaft rotating angle (depending on the vehicle steering condition), respectively. For small misalignment angles, say \(\alpha\) up to about 10°, \(\cos \alpha\) and \(\sin^2 \alpha\) can be considered as 1 and \(\alpha^2\), respectively. Considering

\[
\sin^2 \theta_i = \frac{1}{2} [1 - \cos(2\theta_i)]
\]  

(2)

the following approximation of the output-to-input ratio of instantaneous angular velocity can be calculated:

\[
\frac{\omega_2}{\omega_1} = 1 - \left(\frac{\alpha^2}{2}\right) \cos(2\theta_i)
\]  

(3)

Equation (3) shows that angular misalignment vibration may appear as second harmonic of shaft velocity in the spectrum. Moreover, according to Equation (3), the angular misalignment excites the system with second harmonic only when there is a steering angle between input and output.

Another common type of damages or faults that can appear in the cardan shafts is the axial rolling bearing looseness or bearing clearance of cardan shaft. In case of sudden change in speed or torque direction, the bearing clearance fault shows itself as impact-like excitations to structure as the rolling bearing itself oscillates and slides inside the cardan shaft. In practice, impulsive forces apply broadband excitations to the system over frequency range rather than producing a discrete frequency peak in the spectrum. However, if the direction of shaft velocity or torque remains unchanged, the rolling bearing inside the cardan shaft is expected to shift to a side and change the center of gravity.
from the center to aside, hence producing an unbalance dynamic force at each shaft revolution to the system. These periodic dynamic forces can then be picked by vibration sensors as increasing peaks at shaft rotational frequency harmonics.

Therefore, even though the vibration data can reveal the aforementioned fault types, without additional information about the operational conditions of the machine (e.g. steering and torque), it can be challenging to detect and diagnose misalignment or clearance of cardan shafts. Moreover, as vibration behaviour and trend of the machine also change with operational conditions such as speed and torque, vibration signals require to be analysed together with additional sensor data. The machine condition data, available on Controller Area Network (CAN) bus of wheel loaders, can significantly increase the reliability of vibration analysis for condition monitoring. The CAN bus protocols have been developed by Robert Bosch GmbH in 1986 at the Society of Automotive Engineers (SAE) congress in Detroit, Michigan [18]. In order to investigate and study the cardan shaft damage detection using vibration analysis with the help of additional metadata from the CAN bus, the current study focuses on basic time and frequency domain analyses applied on the cardan shaft signals.

3. Approach
In conventional vibration analysis approaches, vibration signals together with RPM data are processed and analysed to identify the damages without considering machine operating conditions [14]. However, using only vibration and velocity signals for detecting and localizing mechanical damages on mobile work machines may not reveal all required diagnosis information.

Under the light of previously discussed findings, in the current study, a damage detection procedure based on the combination of vibration, velocity, and machine condition signals is proposed and applied for cardan shafts in wheel loaders. Therefore, two typical damage types, namely, misalignment and bearing clearance, are considered and analysed by the proposed procedure. In what follows, detection of both damage types using vibration and metadata are discussed in some detail. The diagnosis of the misalignment fault is done based on the vibration analysis and expected behaviour of the system in the presence of the fault as described in the section 2. The so-called reference-based vibration analysis of the misalignment fault seeks to identify amplitude increase in the second order harmonic of the cardan shaft speed during a steering manoeuvre. Therefore, the synchronized steering data from CAN bus is used to select critical segments for further analysis.

The diagnosis of the bearing clearance fault is done by comparing statistical indicators, e.g. standard deviation, of the vibration signals for healthy and faulty states of the system at similar operational conditions when there is a change in torque/speed (e.g. non-linear acceleration manoeuvre). These operational conditions can be identified based on the conjunction of accelerator pedal, and vehicle speed all from CAN bus data. In addition, if the machine has a constant torque, the bearing clearance fault leads to an increase of the cardan shaft harmonics in the amplitude spectrum, as mentioned in section 2. In order to track speed fluctuations, order tracking-based amplitude spectrum is used to reveal diagnostic information in the frequency domain. Figure 3 shows the reference-based vibration analysis method for diagnosis of cardan shaft clearance fault. The CAN bus data is used for identifying the meaningful time periods in which the analysis has to be carried out and for selecting the appropriate vibration-based analysis routine.
4. Case studies
In order to investigate the proposed methodology in section 3 using damage types discussed in section 2, two various experimental setups are used.

Firstly, to investigate the vibration signature of both damage types, the bearing clearance and angular misalignment, are examined using a test rig. For this purpose, a complete drivetrain of a wheel loader type GHH SLP3H was mounted on a test rig to apply required input excitation, i.e. torque, to capture vibration signals from two case studies using two different defective cardan shafts. Figure 4 shows a picture together with a schematic illustration of the complete test rig and the wheel loader drivetrain. A number of additional vibration sensors were used to capture vibration signals from the test rig mounted drivetrain.

For real-world applications, the field measurements were carried out in a salt mine, operated by company K+S in Werra, Germany. The measurements were conducted as part of a European Union-funded project called ProMaschinenDaten run by various partners from academia and industry including Institute for Machine Elements and Systems Engineering (MSE) of RWTH Aachen University. The mine is located approx. 850 m underground and accessible via an elevator. A total of 6 days (including preparation and measurements) were used to carry out the experimental investigations on the entire test vehicle, GHH SLP-3H.

Figure 3. Vibration analysis for diagnosis of the cardan shaft bearing clearance fault methodology.

Figure 4. Test rig setup for a GHH SLP-3H wheel loader drivetrain.
During the field tests, various signals were recorded via external sensors and CAN bus. The external sensor data such as vibrations, pressure and shaft velocity of the main shaft were recorded at a high sampling rate. The operational data from the CAN bus was recorded at a low sampling rate due to the limitations of the CAN bus. Figure 5 shows a picture of the vehicle at K+S underground facilities together with sensor positions used for measurements. Figure 6 shows schematically the location of cardan shaft in the wheel loader GHH SLP-3H. The cardan shaft in the middle of the vehicle can transfer the drive torque when vehicle’s front and rear sides have a relative angle with respect to each other (i.e. when steering).

![Figure 5](image1.png)

**Figure 5.** A picture of the test wheel loader type GHH SLP-3H together with additional sensors for vibration monitoring of the cardan shaft.

In total, three sessions, healthy condition as reference, misaligned cardan shaft, and cardan shaft with bearing axial clearance, all using the same cardan shafts used for test rig investigations in Section 2, were measured. Each session has various parts ranging from wheel loader engine start to the end of measurement where vehicle arrives back at the mine workshop. In order to cover a wide gamut of operating conditions that may happen during the loading and unloading cycles of the vehicles, a few number of braking and accelerating manoeuvres together with steering conditions were carried out during the field measurements.

Figure 7 shows the time-frequency domain signal of an example session as the waterfall diagram alongside the vehicle’s velocity. The different parts of the measurement are marked and corresponding time periods are illustrated on the plots.

![Figure 6](image2.png)

**Figure 6.** Schematical illustration of a cardan joint shaft in a GHH SLP-3H wheel loader.
Figure 7. A complete operating cycles of the test wheel loader during the measurements.

5. Experimental results

The case studies described in Section 3 are used to perform the required analyses on the hypotheses for the damage types considered in this study.

5.1. Test rig experimental investigations

Figure 8 shows synchronised torque, vibration, and standard deviation signals for both bearing clearance and healthy states for comparison purposes. The vibration signal is captured by a sensor located near the cardan shaft on the test rig. As seen, the bearing clearance, as random impact-like excitation, gives a rise to energy level of the signal, hence an increase of the standard deviation in the time domain can be detected.

Similarly Figure 9 shows the test rig experimental results, but for angular misalignment investigations. As seen, while the energy level of first shaft harmonic remains more or less same for misaligned cardan shaft, this fault produces higher energy at shaft higher rotational velocity harmonics. This result verifies the findings using Equation (3).

Figure 8. Test rig experimental diagnostic results of a cardan shaft with a bearing clearance fault.
5.2. Field tests: cardan shaft with angular misalignment

As mentioned, while vibration signals were recorded using external accelerometers, the metadata, which includes the vehicle operational conditions, is recorded via CAN bus available on the machine. According to the hypotheses obtained in sections 2 and 3, the angular misalignment of a cardan shaft can be detected via vibration signals in the frequency domain when steering. Figure 10 shows 4 various spectrums obtained in different operating conditions and measuring directions.

**Figure 9.** Test rig experimental diagnostic results of a cardan shaft with angular misalignment fault.

**Figure 10.** Amplitude spectrum of the vibration signal captured from a sensor nearby the cardan shaft shown in Figure 5, when steering (upper left) and without steering (upper right) both in radial horizontal direction, and in axial (bottom left) and radial vertical (bottom right) both when steering.
As seen, while the spectrum obtained in the radial horizontal direction when steering can reveal the misalignment successfully, other spectrums, obtained for other directions, do not show any peak at shaft velocity harmonics. In addition, the spectrum obtained in radial horizontal direction does not reveal fault characteristics when there is no steering.

It is worth mentioning that all these spectrums are calculated for a short time period where the vehicle has constant and comparable velocity of 0.3 Hz as tire rotational speed for all these cases. In addition, by further analysing the upper left spectrum in Figure 10, despite the high external noise, the excitation caused by the misalignment is high enough to be detected in the spectra.

5.3. Field tests: cardan shaft with bearing clearance

In this subsection, the bearing clearance fault using the same sensor and CAN bus data discussed in section 4.2 is investigated. For comparison purposes, the measurement with defective cardan shaft is analysed and studied relative to the healthy condition of the vehicle as reference. According to hypotheses mentioned in sections 2 and 3, depending on torque and shaft velocity conditions, the bearing clearance fault can either be detected by parameter trend analysis in the time domain or by shaft harmonics in the frequency domain. Figure 11 shows the complete vibration measurements for healthy and defective cases. In order to compare healthy and defective states, two signal segments, each of which in one case with similar operating conditions, are selected for detailed investigations.

**Figure 11.** Signals corresponding to the complete cycles of measurements for healthy and defective cardan shafts (left), waterfall illustrations of short signal segments with similar torque and speed selected for further analyses (right).

Figure 12 (upper side) shows spectrums for the short signal segments selected and shown in Figure 11. According to CAN bus signals, since the velocity and torque directions of shaft remain unchanged, the bearing clearance should be detectable as a peak at shaft harmonics. Therefore, as seen in Figure
12, standard deviation trends corresponding to the short signal segments selected and shown in Figure 11, do not reveal any explicit energy level difference between healthy (reference) and defective cases. The frequency domain analyses results shown in Figure 12, however, indicate an increase at second harmonic of the shaft rotational frequency. The amplitude order spectra in Figure 12 suggest that the periodic dynamic force is applied in one direction only, which can be due to unbalance originating from bearing shift. Nevertheless, this may not be considered as a sharp and explicit indication of the bearing clearance fault due to uncertainties originating from field measurements.

![Figure 12. Amplitude order spectrum of the vibration signal captured from a sensor nearby the cardan shaft shown in Figure 8 in radial horizontal direction (upper left) and radial vertical direction (upper right) both for the short time signal segments in Figure 12, and corresponding standard deviations.](image)

Using case studies in subsections 5.2 and 5.3, the great importance and role of metadata in CAN bus on the improvement of vibration analysis is highlighted. While analysis of vibration signals alone without information of vehicle driving condition may not be reliable way to detect the damage type considered here, a multi-dimension analysis using CAN bus and vibration signals can lead to a successful diagnosis of damage.

6. Conclusion
In this current study, cardan joint shaft, as one of the commonly failing components in the drivetrain of wheel loaders, is investigated in the context of vibration-based damage diagnosis.

In order to do that, two common cardan shaft failure types and their effects on the vibration signals are theoretically reviewed. Then, hypotheses for two various damage cases are derived. It is shown and discussed that how metadata, that is available in the machine CAN bus, can improve the fault detectability of a vibration-based diagnosis procedure. According to the derived hypotheses, a methodology based on combination of vibration, operational condition, and machine condition signals
are proposed in the current study. The proposed methodology is then analysed and investigated using test rig measurements, as benchmark investigations, and field measurements under real-world operating conditions in an underground mine environment. The experimental results for the test wheel loader considered in this study confirm that CAN bus data can significantly improve the fault detectability of the on-board vibration-based diagnosis system, and are necessary for mobile work machine applications. It is shown that by merging the data from CAN bus and vibration signals, both angular misalignment and bearing clearance fault types on the cardan shaft are diagnosed even under harsh and non-stationary operating conditions of a wheel-loader in field scenario.

Finally, it can be concluded that in addition to stationary applications, vibration monitoring can also result in reliable diagnosis of non-stationary cases, providing that a deep insight into the target component and machine is available.

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