LOAD CYCLE INVESTIGATION OF AXIAL PISTON UNITS INTEGRATED INTO A FORWARDER

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The consideration of the drivetrains behavior under real operating conditions is becoming increasingly important. While in the past decades it was good enough to have a rough knowledge about the operation conditions in field, a more accurate and detailed picture of the duty cycles is required today. Caused by specific and complex operation conditions the load deviation between different applications is significant. In many cases like e.g. lifetime calculation, a precise knowledge of field conditions leads to the more accurate calculated or simulated results. This paper covers the duty cycles investigation of a forwarder application in field including the measurement concept and implementation. Especially, the analysis of the load conditions, clustering algorithm and lifetime calculation is included. The load spectrum generation is consequently done based on comprehensive load cycle determination. The Aim of this work is to verify the calculation accuracy of the load spectrum by using the clustered and raw data. The outcome of the investigation gives an indicator for the load degree of the drivetrain. Here the developed method creates a new and fast possibility of data analysis and is applicable to most drivetrain applications. Furthermore, the collected data is used as reference for future investigation of the forwarder evolution.

KEYWORDS

axial piston unit, load cycles, clustering algorithm, measurement system, drivetrain, load assessment

1 INTRODUCTION

Comparison of the real operating conditions in field to the test lab evaluation of mobile machines leads to a clear recognition of a result deviation. While the test lab evaluation of axial piston units is done under standardized test conditions, the field use is very broad and the same type of units have to withstand many different conditions and load cycles [Stoll 2007, Lang 2002]. The standardized test conditions allow the evaluation of existing development progress of a product according to standards. But, on the other hand the suitability of a product to a specific application is possible as an approximation only. Therefore, different assessment approaches do exist. One approach is the additional cost- and time-consuming test lab evaluation according to field requirements. The other strategy can include simulation tools, but this would only yield theoretical results, whose quality is dependent on the used data and models [Häckh 2005]. Both procedures require a clear picture of the operation conditions

in field. Thus, a real load spectrum from the field leads to more accurate estimations of the expected system behavior. Many manufacturers of mobile machines have recognized that the real load spectra are important for product development [Mariutti 2003, Holländer 1998]. However, in the past it was not easy to get such data for the component suppliers of the drive system. Nevertheless, an assessment of a drive component based on a specific application requires extensive knowledge of the application. Especially, in the context of a drivetrain simulating of a real operating behavior, the presence of measured load data from a typical application is essential.

To illustrate the approach of the filed data analysis, a forwarder application is analyzed in this paper. The load cycles analysis of a forwarder application is motivated by the needs of stress level investigations and load spectrum determination concerning the lifetime prediction. Thus, a detailed overview and analysis of the load cycles will improve a subsequent phase like product development, drivetrain system sizing or analysis of lifetime prediction. It should be mentioned that this paper is a part of the work around the method improvement of the lifetime calculation for axial piston units. Hence, the goal is to increase the accuracy of calculation methods in comparison to the currently used method according to the field experience.

This work covers the representative load cycle investigation of forwarder applications and the development of a method for just-in-time-analysis. Thus, an automatic tool is able to sort the data immediately according to requirements and to process these directly after the receiving from the field. Therefore, the just-in-time expression is used for this specific procedure in this paper. The use of a measurement equipment in the field is included in this paper as well. Besides the definition of a measurement system and the data transfer via GSM-device (Global System for Mobile Communication), the analysis of relevant load cycle values is taken into account. Thus, an algorithm investigates the incoming data according to the relevant factors and synchronizes the data with a load cycle library. Parameters like pressure, pump displacement and speed are collected here and combined/clustered to a load spectrum form. The load cycles acquisition is consequently followed by a characteristic analysis of the forwarder conditions. The focus of the identification method includes the investigation of significant profile-influencing factors like: maximum drive speed, load and operation phases.

The aim, verification of the calculation accuracy of the load spectrum in comparison to the accuracy by using the raw data, is addressed in this work. The outcome of the identification method gives a first picture of the propel load. Here, the developed just-in-time method creates a new and fast possibility of data analysis and is applicable to most drivetrain applications. The algorithm-performed reduction of raw data is an additional positive outcome of this work, which increases the data quality and leads to improvement of the lifetime prediction as well. Additionally, the offline clustering method is compared to a field connected system. Moreover, the collected and clustered data will be used as reference for future investigation of the drivetrain evolution.

2 FORWARDER APPLICATION

A forwarder is a forestry vehicle that carries felled trees from the sawed position to a roadside landing area. This application type belongs to the most complex drivetrains in the off-road market, caused by hard transport and operation use in most challenging terrain. Typically, a forwarder picks up the logs from the ground and transports them to the stock. This

application does reduce soil impacts like erosion. Forwarders are typically used together with harvesters.
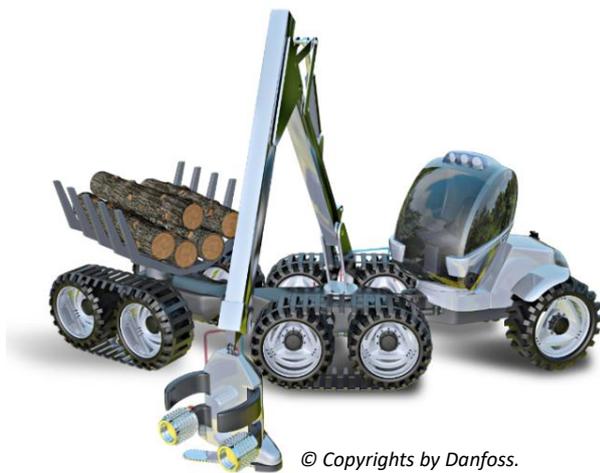
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Figure 2. Forwarder application

A forwarder is designed for extremely demanding conditions. An illustrative example of a forwarder is shown in Figure 1. The characteristic of a forwarder includes powerful engine, load independent drivetrain and ability to transport heavy loads. Furthermore, the forwarder application has to be robust, terrain- and situation-adoptable. During a typical operation procedure, the vehicle can operate on extremely steep slopes. This often brings the drive system to the limit. Hence, the high system pressure, vibration and temperatures do have an additional impact to the drivetrain. Therefore, the highest safety and technical demands have to be fulfilled. While the drive axles have a very high degree of freedom to the ground, the drivetrain ability of the load independency provides the needed level of safety standards. In case of high safety standards, special requirements are set on the maintenance management, which is connected to the reliability of the drivetrain components as well [Fusko 2018]. Furthermore, the drivetrain system has to have high off-road grip and at the same time to avoid the destruction of the paved roads. Hence, weather conditions and effects play an important role. Therefore, the operation of the forwarder is typically seasonal in the most global fields of use. The must-have of the seasonal availability brings additional requirements on the calculated lifetime accuracy, like other seasonal application e.g. harvester or combine [Shepelev 2015].

3 EXPERIMENTAL SETUP & DATA MANAGEMENT

This chapter covers the generic measurement concept based on the forwarder application. The measurement concept includes the hardware implementation, software of the different transmission levels and data transfer to the database. A forwarder drivetrain includes a simple setup of two main components (pump and motor). Here, a generic hydraulic and sensorics diagram of a forwarder drivetrain is shown in Figure 2.

The measurement equipment is flexible and adjustable to different vehicles due to fact that this concept is used for different application types. Furthermore, the design of the measurement equipment is built independent from the size and form of the system. The measurement system includes among sensors (pressure, speed, temperature, etc.) a microcontroller unit (signal processing unit) and an integrated wireless device (GSM-device). Different load-affected values are measured by sensors or transferred via CAN-BUS-Message. In this example, the command currents of pump and motor coils are transferred via CAN. The displacement value of the pump is obtained by an angle sensor or can be calculated by coil commands with sufficient accuracy. It is recommended to measure the displacement by an additional sensor, due to possible case of power supply losses, see position 4 in Figure 2. The system delta pressure can be calculated by measured pressure at port A and B. The detection of the shaft speed of both pump and motor is implemented by analog sensors, as well as the integration of two temperature sensors, see sensor positions 8 and 9 Figure 2.

All measured values are device-intern transferred via a second CAN, which is drivetrain-separated. The raw data are temporary stored in a ring buffer. As soon as the GSM-module has the connectivity to the GSM-signal, the data can be transmitted to the database. Additionally, it is possible to exchange the GSM-device by a data logger with a "big" memory. But, the disadvantage is that a data logger requires a manual procedure
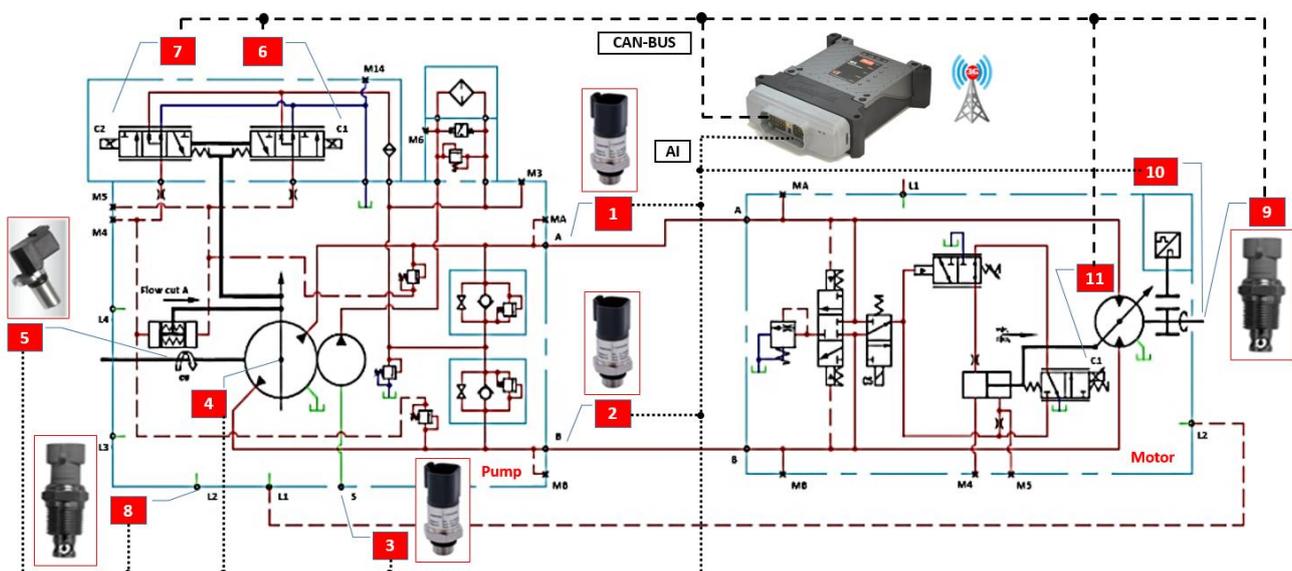

Figure 1. Schematic of a generic experimental setup

to restore the data from the measurement system to the database. The data handling is much faster, easier and resources-saving if the GSM transfer is in use.

Today many different data management concepts exist. Here, the distinction between "online" and "offline" methods are in focus. While an online method processes the data on-board of the drivetrain control unit, the offline method transfers the data "into the cloud". The advantage of the online concept is the "real-time" analysis of the operation conditions. A typical field application for an online system could be a condition monitoring of field data for a real-time maintenance procedure [Fusko 2018]. An online system is however very cost- and resources-intensive [Kunze 2005]. Due to the hardware limitation of memory space, the data management has to reduce the data amount significantly [Martin 1994]. On the other hand, the disadvantage of the offline system is the high amount of the data transfer versus data resolution. The

experiences in this specific field of use. In some cases, the duty cycles are measured as a shortcut of typical operation. Thus, the scenarios ratio is typically equally divided and is recorded at maximum load condition to get all limits of the application behavior. The equal ratio (50/50 > drive profile to work profile) is one factor of the accuracy losses of the currently used calculation method. Thus, the experience shows the deviation between vehicles of the same application and not only between different applications. The duty cycle deviation of same vehicle types is caused by the area of use [Krüger 1992].

4 FORWARDER PROFILING

A forwarder application does not have standard recurrent cycles due to the arbitrary complex operation conditions of off-road operation. Only operation profiles like drive (transport) or work (creep & pick up) modes can be defined. Thus, the quasi-steady-state conditions are analyzed and lead to the profile
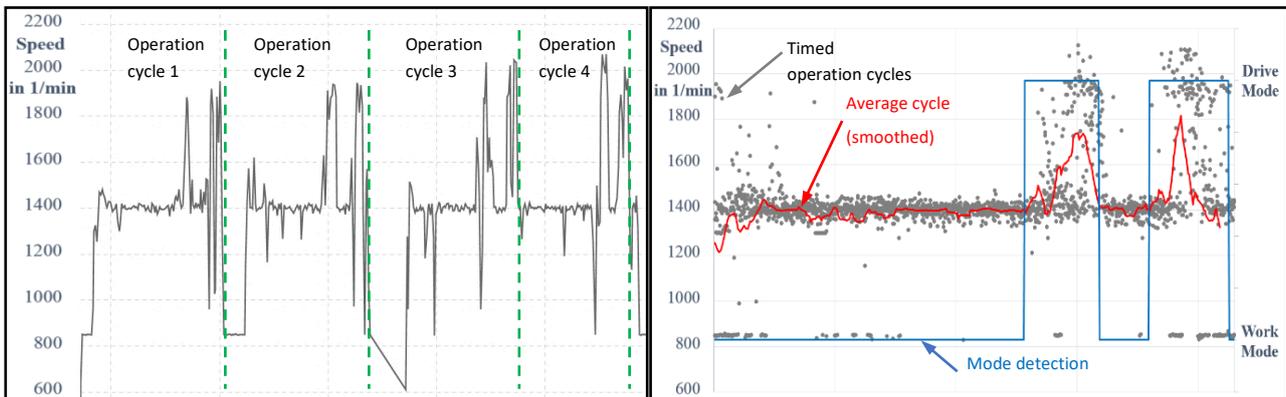

Figure 3. Illustrative example of 4 synchronized operation shortcuts

strength of the offline data handling includes the possibility of secondary data investigation. Thus, among the lifetime calculation e.g. the efficiency or economical aspects can be analyzed at later stage [Buxbaum 1992, Jardine 2005]. Already in the stage of raw data, the first analysis delivers a good picture of operation conditions. Hence, load spectrum can be visualized to verify the application conditions like pressure limitation. As well as the operating points (profiling investigation) are identified through trigger procedures (threshold values) and thereby consider the status/mode of a mobile machine. However, a deep analysis of the drivetrain behavior at this point requires additional activities. Hence, the data "quality" of continuous record must be improved. In this specific case the data quality was improved by time stamp alignment, threshold filtering of non-operation status, division in modes by specific conditions, etc. Generally speaking, the data have to be structured, filtered or specified by significant factors of interests before analysis [Bertsche 2004]. Thus, analysis methods like: clustering and lifetime calculation or rain flow analysis are only few examples for subsequent steps [Amzallag 1994].

The procedure of the lifetime calculation requires the analysis of duty cycles. Hence, the raw data are split in predefined sectors (Clustering). A simple clustering includes the "pressure over speed" overview. The third dimension is a count number of the occurrence in this sector. In a typical situation of lifetime calculation, the vehicle manufacturer delivers characteristic duty cycles, which include the application-specific operation behavior. In case of the forwarder application, it may be the worst-case scenarios of a work and/or a transport mode. If the ratio of drive profile scenarios is unknown, some assumptions have to be done. The assumptions are typically based on

separation. For the purpose of profile analysis, the time record of know operation conditions is split and timed. Followed by the analysis of the standard deviation and RPM-thresholds of the axial piston units, the drivetrain profiles are verified, see Figure 3 [Deiters 2009]. The derivative values of the mode ratio were confirmed by the clustering matrix as well, see Figure 4. This paper includes a real data example of a forwarder, used in working mode of 88% and drive mode of 12% of the whole record duration.

Forwarder characteristic analysis shows a fixed operation point of 1400 RPM (pump) during the working procedure. In that case, the driver/operator set an individual fix point of the operation conditions, which is optimal for the working phase like pick up of the tree logs. On the other hand, the drive mode is clearly detectable by RPM rising of pump and motor. Based on the RPM, gear stage and the transmission, the maximum vehicle speed was calculated at 7,5 km/h. Thus, it is obvious that used the test vehicle is operating in the forest only, during the time record phase. The typical maximum vehicle speed for a forwarder can be up to 25 km/h.

5 PROFILE RATIO VS. ACCURACY LOSS

In this chapter, the evaluation of lifetime calculation regarding the accuracy loss caused by supposed profile ration is addressed. In this case, the expectation is a significant deviation by using of wrong profile ratio. A real data of a forwarder from the field build the calculation base for the evaluation. The calculation covers bearing example for demonstration purpose of the accuracy loss.

A review of state-of-the-art methods for lifetime calculation may be found in [Baus 2018]. The calculation example which is
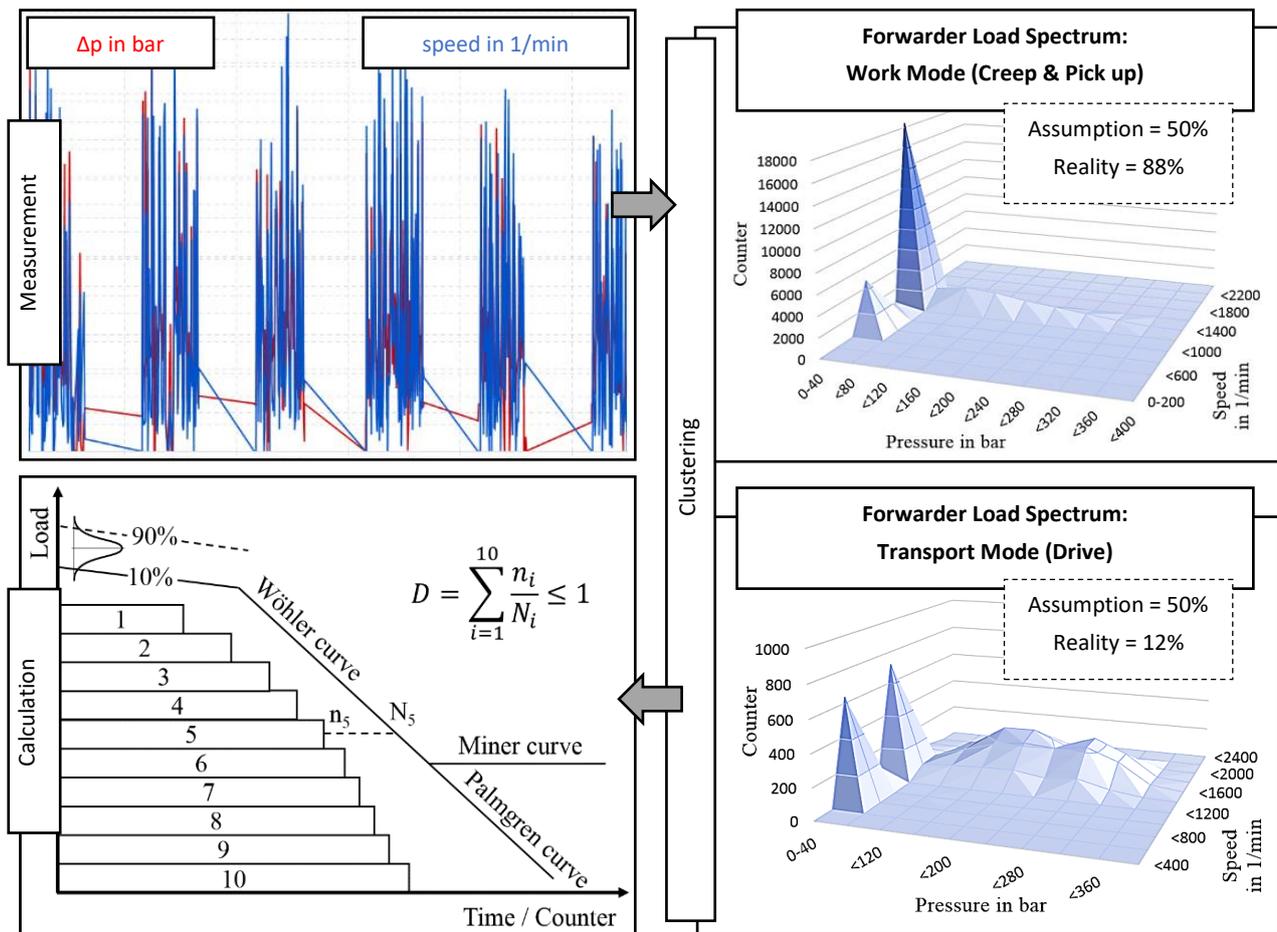
Figure 4. Clustering & Calculation

mentioned here, was proceeded on Palmgren & Miner method only. Already in 1924, Palmgren presented a simple method for the lifetime calculation of the mechanical components for the example of a bearing [Palmgren 1924]. With this first approach a simple calculation possibility was built, which allowed to make conclusions about the load on a bearing over its entire service life. For this purpose, the number of cycles in a certain load class n_i was recorded in field. This value represents the actual load occurring, which is given by measurement. Afterwards, this load is checked in relation to the maximum number of duty cycles for the respective load class N_i before a failure occurs. This value represents the load capacity of the component in relation to the respective load class. The relations are shown in Figure 4 (Calculation subpart). The resulting quotient:

$$D_i = \frac{n_i}{N_i} \qquad (5.1)$$

is the partial damage of the rolling bearing for the considered load class. Thus, Palmgren assumes a linear behavior in damage with the number of cycles in the respective load class N_i. If the partial damage D_i is summed up for the different load classes of the bearing, the theoretical life of the bearing can be calculated. If the sum exceeds 1, the lifetime of the bearing is exceeded. Different to Palmgren, the Miner's curve does behave according to the Wöhler line. Thus, the curve runs with a slope of zero, which is equal to fatigue strength. All load classes below the fatigue strength do not have any effect on the lifetime duration, when dealing with iron/steel alloys. Consequently, these stresses do not play a role in the lifetime calculation, according to Miner below the fatigue strength [Miner 1945].

As mentioned above, it is important to have the field data of a considered application to be able to calculate the lifetime with high accuracy. Normally, it is difficult to get the right duty cycles before a development process due to the pre-study phase of vehicle or subcomponents. Therefore, some estimations regarding the duty cycles have to be done. In that case, it is helpful to have a rough picture of the application and the field of use. A library with load spectra of different applications and their profiles/modes can help to avoid mismatching of the development goals or support the product sizing.

The clustering and calculation tool does include an automatic algorithm. The algorithm downloads the data from the database. Specific load values have to be preselected by the user, based on the decision focus of affected load values. This first tool generation has a matrix resolution of 15x15 cells, see a reduced overview in **Chyba! Nenalezen zdroj odkazů.** (Clustering). Thus, a value like pressure or speed can be divided and clustered. The issue during the clustering is the decision of resolution and/or the calculation value of the cells (median, average, etc.). In the next process phase the matrix is reordered due to the calculation equation needs.

The result accuracy is suspected without the exact knowledge of the application conditions and modes/profiles ratio. A general assumption of the equal impact of different modes can lead to wrong results. In this assumed example, the rolling bearing lifetime was equal to **1191 cycle of the assumed 50/50 load spectrum**.:

$$L_{10,50/50} = \left(\sum_{i=1}^{n} \frac{c_i}{\sum_{i=1}^{n} c_i} \times \frac{\Delta p_{ref}}{\Delta p_i} \right)^{\kappa} = 1191 \qquad (5.2)$$

where $L_{10,50/50}$ is the calculated lifetime based on assumed cluster with 50/50 ratio, c_i is a cluster cell, Δp_{ref} the reference pressure, Δp_i the effected pressure and n is the sum of the cluster cells. While the real situation is different, as seen in the results of the real ration from the field, see equation (5.3) below. The calculation of the real (clustered) value from the field shows a longer lifetime than assumed before the measurement. Here **the lifetime is equal to 2547**, which generally strengthens the experience gained from field lifetime in the past.

$$L_{10,88/12} = \left(\sum_{i=1}^{n} \frac{c_i}{\sum_{i=1}^{n} c_i} \times \frac{\Delta p_{ref}}{\Delta p_i} \right)^{\kappa} = 2547 \qquad (5.3)$$

where $L_{10,88/12}$ is the calculated lifetime based on cluster with real ratio of 88/12.

6 CLUSTERING VERSUS RAW DATA

This chapter covers the verification of the accuracy loss of the lifetime calculation caused by discretization of the load spectrum. The comparison of the clustering versus raw data calculation is done here. The assumption of the accuracy loss is confirmed by using of field generated data of a forwarder. Due to simplification reasons, the calculation was done with one influencing factor (pressure) only.

The acquisition of field data by the measurement concept and the automatic proceeding by the calculation tool allows the simple and fast possibility of lifetime calculation or verification. The direct (field to desk) calculation method of field data (alias: just-in-time-Calculation) has clear benefits in case of condition

The forwarder example with the given data leads to following results: The calculation example is applied to a rolling bearing and pressure only. The results show that a 6,7%-higher lifetime is calculated based on the raw data:

$$L_{10,Cluster} = \left(\sum_{i=1}^{n} \frac{c_i}{\sum_{i=1}^{n} c_i} \times \frac{\Delta p_{ref}}{\Delta p_i} \right)^{\kappa} = 2547 \qquad (6.1)$$

$$L_{10,Raw\_Data} = \left(\sum_{i=1}^{m} t_s \times \frac{\Delta p_{ref}}{\Delta p_i} \right)^{\kappa} = 2717 \qquad (6.2)$$

where $L_{10,Cluster}$ is the calculated lifetime based on the cluster, L_{10,Raw_Data} is the lifetime based on the raw data, c_i is a cluster cell, Δp_{ref} the reference pressure, Δp_i the effected pressure, n is the sum of the cluster cells, m is the sampling sum and t_s is the sampling time of the raw data.

On the other hand, this concept can be used as a verification method of the lifetime exponent k, of the Wöhler curve. This idea requires the long-term use of a measurement system in a big vehicle fleet[Hosnedl 2014]. The claimed situation can be used in a positive way. Thus, the lifetime exponent can be extrapolated by the feedback from the field. If the load spectrum, the failure mode and the failed component is known, the load spectrum can also be used for the backward-calculation to get the lifetime exponent:

$$k = \frac{ln\left(\frac{C}{P}\right)}{ln\,L_D} = \frac{10}{3} \rightarrow for\,rolling\,bearings \qquad (6.3)$$

where, L_D is the lifetime until damage, C is the basic dynamic load rating according load spectrum (time record), P is the equivalent dynamic load and k is the specific lifetime exponent of rolling bearing [ISO 281].
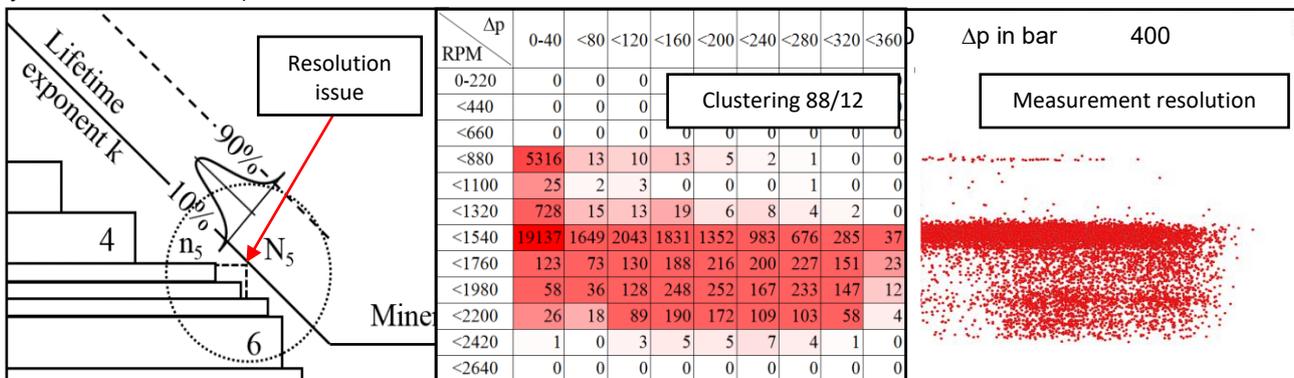

Δp RPM	0-40	<80	<120	<160	<200	<240	<280	<320	<360
0-220	0	0	0						
<440	0	0	0						
<660	0	0	0	0	0	0	0	0	0
<880	5316	13	10	13	5	2	1	0	0
<1100	25	2	3	0	0	0	1	0	0
<1320	728	15	13	19	6	8	4	2	0
<1540	19137	1649	2043	1831	1352	983	676	285	37
<1760	123	73	130	188	216	200	227	151	23
<1980	58	36	128	248	252	167	233	147	12
<2200	26	18	89	190	172	109	103	58	4
<2420	1	0	3	5	5	7	4	1	0
<2640	0	0	0	0	0	0	0	0	0

Figure 5. Clustering issue of a load matrix

monitoring. Also, the vehicle specific calculation accuracy increased by using of field data.

In case of calculation algorithm, two different aspects are analyzed. At first the resolution of the clustering matrix is investigated. Thus, the expectation is confirmed that an accuracy loss exists due to the matrix resolution of load clustering, see the encircled area in Figure 5. The cluster steps are the main issue. The cell specific load is inaccurately calculated with assumed value. Here, different approximation methods like load-average or -median can be used. If the load distribution of a cell is unknown only cell average can be used, which can increase the deviation to reality even more. While the raw data considers every single point of the time record, which avoids data loss. This is confirmed by the result of equation (6.2).

7 CONCLUSION & OUTLOOK

The real/raw data from the field delivers a more complete picture of the duty cycles, than the clustered data. Thus, the clustering causes a certain loss of accuracy, which is analyzed and confirmed in this paper. The load spectrum is partly assumed in profile ratio and that leads to an additional calculation failure. Therefore, the lifetime calculation is done more accurate with time record data of a long period in field. Thus, a direct analysis of the raw field data leads to a more accurate result. The outcome of the identification method gives a first picture of the propel load. The algorithm-performed reduction of raw data is an additional positive outcome of this work, which increases the data quality and leads to improvement of the lifetime prediction as well. Moreover, the collected and clustered data will be used as reference for future

investigation of a forwarder evolution. Finally, the load spectrum of the real field data and the just-in-time-calculation is the right direction and is one of the first factors to reach the high accuracy method of the lifetime calculation. This is confirmed by the mentioned example of the forwarder based on the comprehensive load determination.

In the next stage, the lifetime calculation approach of the method improvement will cover the separated investigation of subcomponents regarding the lifetime exponent and reliability. Thus, future wok will cover the analysis of the load chain of the axial piston unit as an assembly system. In case of the verification of the improved method a testing concept is required as well. At the later stage a reconstruction of the field duty cycles in the test lab will be under investigation. Thus, the data reconstruction over a period of time, with a large similarity of the original data record and also a nearly identical damage effect will be addressed as well.

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