Extended Evaluation of Pitting Degradation Tests to Increase the Remaining Useful Life of Gear Wheels

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Abstract. Within this work, the potential of an operating strategy is analysed based on test runs in laboratory environment, field tests as well as simulations. The operating strategy is used to increase the remaining useful life of gear wheel pitting by reducing the local stress at the weakened tooth. The local stress reduction is achieved by applying an adapted periodic input torque to the transmission and shift the minimum in the area of the weakened tooth. All the other teeth undergo a higher stress and therefore compensate the reduction. To analyse the potential of this strategy, the evaluation of pitting degradation tests has to be extended to all teeth using data from test runs as well as field tests. Both analyses show great potential as many teeth are totally intact. Finally, a simulative approach was carried out to quantify the potential and to show a reference value for the accuracy of the measuring system. As a result, for an increase in lifetime of 10 %, the measurement system has to locate pitting with a size smaller than 1 % based on the total tooth flank. If the pitting is located even earlier, a maximum of 38 % increase in lifetime is possible.

1. Introduction

Many transmissions fail due to pitting at the gear wheels. This flank spalling is caused by material fatigue and is normally located below the pitch circle [1]. If the gear wheel is case hardened, usually one tooth is responsible for the failure of the whole system of the gear wheel only and thus for the whole transmission. Sometimes there are few other small pittings at the circumference, but most of the teeth are still intact at the standardized end of life criterion of 4 % pitting area based on the total tooth flank [2]. The possible service life of these teeth is therefore not used which is why the system gear wheel is well suited for a Prognostics and Health Management (PHM) approach.

There are five basic areas within a PHM approach, the system, data, diagnosis, prognostics and optimization. First of all, the system has to be analysed and different data has to be collected, e.g. with sensors. This data can then be used to analyse the actual state of the product within the diagnosis. In the prognostics, the current state of the system is forecasted to the future under assumed usage scenarios. With these scenarios, the end of life (EOL) can be calculated and following this the remaining useful life (RUL) which is defined as difference between EOL and the current time. In the last step, this information can be used to optimize the service life of the system. Exemplarily, the stress of the system can be reduced and therefore an increase in service life is possible. This is why this last step is also called Health Management. [3]
In the field of automotive transmission, such a PHM approach is presented by Foulard [4]. The input torque and speed are measured and an online simulation performs a linear damage accumulation of the gear wheels. If a defined sum of damage is reached, the total input torque of the transmission and therefore the stress at the weakest tooth is reduced. With this torque reduction an increase in service life is possible. Unfortunately, the transmission loses the maximum transferable power due to the reduced torque. Moreover, the defect within the gearing is not measured directly, the reduction of the input torque is only based on a simulation.

Within this work, an operating strategy is presented that reduces the torque specifically at the weakest and therefore previously damaged tooth. The total power remains the same as the other intact teeth undergo a higher torque. The operating strategy is consequently based on the principle that the strength of the individual tooth is scattering in a certain range because of the material and production. So, the main target of this paper is the examination of the potential of the operating strategy. This potential is divided into two parts. In a first step, the statistical potential is analysed by means of extended evaluations of pitting tests. Here, the scattering in tooth strength at the circumference is examined in two test environments with different conditions and requirements, a laboratory test bench (chapter 3) and a field test (chapter 4). In a second step, based on the findings, the potential of the operating strategy is quantified within a simulative approach (chapter 5).

2. Operating Strategy
In practice, gears are usually loaded by a constant torque, which can change due to a specific load spectrum. But concerning one revolution of the gear wheel, the torque remains nearly constant. The operation of the gear with the specific load spectrum continues until system failure that is defined as 4 % pitting area related to the active tooth flank. Shortly before the failure, the damage can be detected by accelerometers at the transmission housing. This information is used to take the transmission out of service but not to influence the input torque, as seen in figure 1.

![Figure 1. Schematic diagram of the operating strategy.](image)

In contrast, the information about an upcoming failure is used in the presented operating strategy to gain a local stress reduction at the weakened tooth. Here, a small pitting (< 4 %) is detected and localized at the circumference. Within a PHM-Control Loop, this information is used to influence the input torque, see figure 1. An adapted periodic input torque is applied and the minimum is shifted in the area of the pre-damaged and therefore weakened tooth. For example, the input torque can follow a sine signal or a jump function. As an advantage of this operating strategy it should be mentioned, that the overall power of the transmission remains the same. This is possible due to a higher torque/stress at the intact tooth at the circumference.

Pitting degradation is a soft failure that begins with a very small area. This small pitting grows with operating time and the speed of growth depends on the applied torque, as shown in figure 1. This leads to an increase in service life, if the operating strategy is used.
3. Evaluation of pitting degradation tests in laboratory environment

The increase in service life due to the operating strategy is only possible if the strength of each individual tooth is varying within a certain range. For this reason, a phenomenological investigation of the failure mechanism pitting is necessary and the evaluation of pitting tests must be extended to all teeth.

3.1. Electrical Stress Test Bench and Specimen

In previous work [5], the degradation of gear wheel pitting was investigated on a test bench. Here, the focus of the analysis was based on the weakest tooth of the gear wheel only. The following test setup was used:

- Electrical stress test bench with two electrical machines
- Single stage test transmission with serial gear wheels with 21 teeth (pinion) and 41 teeth (gear)
- Helical gearing
- Constant stress level: 200 Nm
- Constant output speed: 1300 rpm
- Oil temperature: 90 °C
- Number of specimens: 8

As the aim of the prior work was the analysis of the degradation path of pitting, the test was interrupted at a constant interval of 0.25 million cycles. The flanks of the pinion were visually analysed and a negative imprint of some of the biggest pittings were made. The pitting areas were measured afterwards and the test was terminated as soon as one pitting achieved the standardized end of life criterion of 4% pitting area. Only this pitting was used for further investigations. Smaller pittings were not considered because they are not relevant for the system failure.

3.2. Results concerning all teeth in laboratory environment

The available data of the mentioned test runs are now used to analyse all teeth at the circumference. Therefore, the investigations are expanded concerning the location of the pittings at the circumference and the degradation path of all pittings. In a downstream step, the degradation paths are used to extrapolate all pittings to the end of life (EOL) criterion of 4% pitting area and thus, the failure distribution can be extended.

3.2.1. Localization of the pittings at the circumference

A total of eight pinions are examined concerning pitting failure. For each pinion, the location and the size of the pittings are determined in a radar chart, see figure 2. The radii are the 21 tooth and the drawn black line represents the pitting size at the individual tooth. In the example of pinion I, there are four pittings at the circumference with a range of size between 1.7% and 6.0%. Moreover, it turns out that many pittings occur at neighbouring tooth flanks, as it can be seen in figure 2 at tooth number three and four.

This observation was further investigated, see figure 3. As the number of teeth is 21, the total sum of teeth is 168 for the eight pinions. First, the probability of the appearance of a pitting at the individual tooth is 31%. At 116 teeth and therefore 69% no pitting occur and the teeth are totally intact. Second, all teeth with pitting (in total 52) are analysed. Here, the probability of a direct neighbouring pitting is very high with 88%. So, there are 17 pittings without neighbour, eleven pairs of pitting, three trios and even one quartet. For more information about the depending and competing failure modes of pittings see [6].
Figure 2. Radar chart of pinion I.

Figure 3. Pie chart of all investigated teeth.

It can be concluded that the analysis of the location of the pittings at the circumference of the pinions show a great potential of the presented operating strategy. Most of the teeth do not have a pitting or preliminary stage of pitting (see figure 3) at the termination of the test run although the gear wheel counts as failure. Therefore, these teeth can undergo a higher stress and compensate the power of the transmission. As these teeth did not show any sign of a pitting, their strength must be very high. The initiation of the pitting lies in the future and even then, a certain time of pitting growth is available until these teeth fail. The potential of these teeth is therefore enormous. Furthermore, the neighbouring pittings are advantageous for the operating strategy. If a sinusoidal input torque is implemented, these neighbouring teeth also undergo a reduced stress and therefore the degradation speed is automatically reduced due to the lower loads. This advantage also applies to the jump function. Neither the measurement nor the control of the torque is ideal. Consequently, the reduced torque is always at a certain angle of the gear wheel so that the neighbouring teeth are in the reduced area as well.

3.2.2. Degradation of gear wheel pitting and failure distribution

Pitting damage usually develops progressively after an incubation period [7]. This was also observed in the available measurements of the eight pinions. As an example, figure 4 shows the degradation path of a pitting that did not lead to failure. The black circles mark the measured pitting size at different load cycles and the grey line represents the progressive curve fit. The initial pitting occurs at 6.25 million load cycles and at the termination of the test (11 million load cycles), its size is 2.15 %. With this degradation path an extrapolation to the EOL criterion 4 % pitting area is possible. In total, the initial pittings were only visible after more than 70 % of the total test run. The initial pitting size is round about 0.45 %.

The eight pinions have 52 pittings at the end of the test run, but the focus was on the weakest tooth only. Therefore, the smaller pittings were not considered in the test runs and the degradation path is only available for 23 pittings. Equation 1 was used for the curve fitting of all degradation paths:

\[ f(x) = a \cdot e^{bx} + c \]  

(1)
After the regressions, an extrapolation to the EOL criterion was carried out and the pittings were classified in three groups:

- group 1: pittings that lead to failure,
- group 2: pittings that did not lead to failure,
- group 3: all pittings together.

The failure distributions of those groups were analysed, which is shown in figure 5 in the form of the density function. An adaption test shows a lognormal distribution function for all groups. The dashed black line represents the state of the art with group 1, the pittings that lead to failure. The solid black curve are all the other pittings that did not lead to failure. The median values of the two groups show a quite large offset. For group 1 the median value is 8.59 million load cycles and for group 2 14.18. Hence, the difference between the two groups is 5.59 million load cycles. Furthermore, the density function of group 1 is narrower and therefore higher than the density function of group 2. That means the scattering of group 1 is smaller than the scattering of group 2 and from this, the very different strength of the individual teeth can be read off directly. The scattering of the strength is very advantageous for the operating strategy as the stress at the pre-damaged tooth is local reduced and all the other teeth undergo a higher stress. It is obvious, that the strategy only works if those teeth with higher load do not fail earlier than the pre-damaged tooth with the reduced stress. At this point it must be emphasized once again that in group 2 only the smaller pittings with degradation paths are collected. The many teeth that are totally intact and do not have any pitting are not considered here, compare figure 3. Therefore, they cannot be included in the evaluation. But nevertheless, it can be concluded that the distribution of all other teeth at the circumference is much broader and the offset of the median values is therefore much higher.

Up to this point, the two groups have been considered separately to show the difference between failure pitting and other pittings at the circumference. But the density functions of group 1 and 2 are overlapping to a large extent and moreover, the failure mechanism is the same which indicates that the pittings follow one distribution. Therefore, a hypothesis test was done to clarify if there is a significance between the two distributions. As expected, no significance was observed and the pittings were analysed all together in the third group (dashed grey line). Compared to group 1, there is a higher scatter and therefore a broader distribution. The median value is 11.8 million load cycles and thus the high potential of the operating strategy is obvious. Therefore, the feasibility of the operating strategy could be demonstrated by means of the laboratory test as a high difference in the strength of the individual teeth was shown.
4. Evaluation of field tests
The previously described investigations were performed in a laboratory environment and at a constant load. For this reason, it was investigated whether the phenomena can also be observed in the field. Only then, the statistical potential of the operating strategy can be confirmed.

First, the transmissions were described and the method to determine the real field loads of a single use case of the individual transmissions. Afterwards, the diagnosis of the gear wheels is presented and compared to the results of the laboratory tests.

4.1. Transmissions of the field tests
For the investigation of the field data an automotive transmission from a large series was selected. An automatic transmission has been chosen because it minimizes the operator's influence on the shifting process and thus, on possible load peaks that can occur during fast clutch engagements. The automotive sector has extremely high quantities and the production process as well as the geometry of the gearing is optimized. Therefore, only a marginal influence of the manufacturing on the pitting degradation is expected. Finally, a 9-speed planetary gearbox was selected, see figure 6. This transmission is used for vehicles with Standard drive and their all-wheel drive derivatives.

![Figure 6. Gearbox diagram and gearshift pattern of the 9-speed automatic transmission. SCC: slip-controlled torque converter lock-up clutch, T: turbine, R: reactor, P: pump, PS: planetary gear set, S: speed, i: ratio [1]](image)

| S      | Brake | Clutch | i     | Gear step |
|--------|-------|--------|-------|-----------|
| A      | B     | C      |       |           |
| 1      | •     | •      | 5,35  | 1,65      |
| 2      | •     | •      | 3,24  | 1,44      |
| 3      | •     | •      | 2,25  | 1,37      |
| 4      | •     | •      | 1,64  | 1,36      |
| 5      | •     | •      | 1,21  | 1,21      |
| 6      | •     | •      | 1,00  | 1,15      |
| 7      | •     | •      | 0,87  | 1,21      |
| 8      | •     | •      | 0,72  | 1,20      |
| 9      | •     | •      | 0,60  | -4,80     |
| R1     | •     | •      | 8,91  |           |

Table 1. Number of teeth of the four planetary gear sets

|                  | planet gear set 1 | planet gear set 2 | planet gear set 3 | planet gear set 4 |
|------------------|-------------------|-------------------|-------------------|-------------------|
| sun              | 46                | 44                | 37                | 34                |
| planet           | 26                | 27                | 23                | 26                |
| ring gear        | 98                | 100               | 83                | 86                |

The chosen transmission is made up of four planetary gear sets, three brakes and three clutches. Advantage of the planetary transmission is that in general all planetary gear sets are used for the nine forward and one reverse speed of the transmission. Therefore, they are all under load and the amount of specimen is very high although only some transmissions have to be analysed. Each planetary gear set
has three or four planets, depending on the maximum input torque. For this reason, the planets are chosen for further investigations as the number of specimens is the highest. Moreover, the number of teeth of the different planets is in the same range as the pinion of the laboratory tests, which makes a comparison very easy. All numbers of teeth of the four planetary gear sets are listed in table 1.

4.2. Determination of the real field load on the transmissions

Automatic car transmissions like the 9-speed automatic transmission have an electronic control unit (ECU) which is integrated into the vehicle network. Information and requirements of the complete powertrain can be exchanged for example by the controller network (CAN) signals like the engine torque, the engine output speed and the current gear-speed, which is achieved by an interconnection of the four planetary gears sets. Based on the damage accumulation approach, the transmission ECU is able to determine an operating point dependent damage value for each gear-speed. This value is calculated based on the information on the drivetrain-CAN like the engine output torque and speed, compare [4]. At the time of the analysis of the transmission, the obtained gear-speed dependent damage values of the real field loads can be used to do a reverse calculation to the loads of each planetary gear set. For this purpose, the geometric data and the gear ratio of the transmission is used to calculate a damage value depending on the different planetary gear sets. Further information such as the deposited mileage and ECU operating time are used to estimate and assign the field load spectra. In a last step it is necessary to normalize the calculated damage values to known loads. For this purpose, damage values generated from success run tests are defined as reference value. From this, percentage damage values can be derived. The back calculation and scaling of this approach is presented in detail in [8].

4.3. Diagnosis of the gear wheels

The examined transmissions are mainly early failures and the failure cause is varying, for example the mechatronic control unit with the integrated ECU and sensors are failed. Therefore, the mileage is relatively low concerning the design point and the gearing is not failed in the examined transmissions. Consequently, the tooth flanks do not show any pitting, but there is a pre-stage visible, namely micropitting. This observation corresponds with the results from the test bench. The first pitting outbreak was visually observed at about 6 million load cycles. The termination of the test was at about 8.5 million load cycles. Therefore, the pitting grows in the last third of the lifetime. It is obvious, that there are no pittings visible in the determined field tests.

Micropitting is indicated by grey zones on the tooth flank as fine surface pittings break out due to mixed friction as a result of the oil viscosity and the surface structure [1]. The effect of micropitting on macropitting was investigated in literature, for example [9-11]. Micropitting affects the location of the beginning pitting on the tooth flank. As the micropittings mostly emerge in the area of the tooth root, pittings occur preferably at the border between micropitting and the micropitting free area. However, the direction of growth is determined exclusively by the sliding conditions. [10] The greater the micropitting area, the greater the probability of pitting [9].

In the following, micropitting is regarded as preliminary stage to pittings and is therefore evaluated in the same way as in chapter 3.2.1. In total, four transmissions were analysed concerning micropitting. As the planetary gear set 4 has the highest damage value, only those planets were determined concerning all teeth. Therefore, four planets per transmission with 26 teeth each were examined. The pie charts for the four transmissions are shown in figure 7.
Figure 7. Pie chart of the four planetary gear sets. a) transmission A (damage value 38%) b) transmission B (damage value 53%) c) transmission C (damage value 59%) and d) transmission D (damage value 63%)

In all pie charts of figure 7 it is visible that most of the teeth do not have any damage. Furthermore, the amount of damage at neighbouring teeth is higher than the amount of single damage. The observations within the laboratory tests could therefore be confirmed.

Within this chapter, the four transmissions were evaluated separately as the mileage and the damage value vary in a wide range. The total number of teeth examined in each transmission is 104, four planets with a number of teeth of 26. Transmission A has a high mileage with above 200 000 km and nevertheless the percentage of the intact teeth is 54 % and therefore very high. With a medium mileage of about 150 000 km at transmission B and C the proportion of intact teeth increases to 80 %. The very small mileage of transmission D with less than 19 000 km shows an extremely high number of intact teeth with 88 %. But despite the low mileage of only 6 % of the design goal, 12 % of the teeth already show micropitting, which was not expected. For the analysis, however, the damage value must also be considered since this allows a statement about the field load of the individual transmission. Transmission D has with 63 % the highest damage value of the four transmissions although the mileage is the lowest. Therefore, the customized stress of transmission D was very high and far above the average. With this point of view, the visible micropittings are obvious.

Transmission A shows a contrary user profile. The mileage is very high with above 70 % of the expected mileage whereas the damage value is very low with 37 %. Although the mileage suggests that pitting is beginning to occur, only preliminary stages can be seen. The damage value indicates a very weak load of the transmission during the customized load spectra. Therefore, it is obvious that there are no pittings visible. Those two transmissions (A and D) show the difficulty in designing new transmissions as the field load spectrum varies in a wide range with passenger cars. More information about the stress and strength of different transmissions can be found in previous work [8].

The transmissions B and C are also analysed further. The mileage as well as the damage value are nearly the same, above 150 000 km and 50 %. Those two transmissions can therefore be treated together and as expected, the pie charts in figure 7 look nearly the same. Slight differences always occur due to scattering in the material, the manufacturing process of the transmission and the customized load spectra.

Last but not least, the percentage of the micropitting at neighbouring teeth was analysed. The four pie charts in figure 7 show that the percentage increases with the mileage. At the same time, the total number of micropitting rises so that the probability of neighbouring is statistically increased. In addition to the statistical approach, the neighbouring can be explained phenomenologically. In practice, more than one tooth is in contact within meshing. For example, the contact ratio of the spur gear pair of the laboratory investigations is 2.7. Thus, two or three teeth are simultaneously in mesh. If one tooth has a
defect, the load capacity is reduced and therefore the two neighbouring teeth have to compensate the load. Consequently, the load rises and the probability of a defect increases [6].

During the analysis of the individual tooth flanks, it was also noticed that the zone of micropitting moves along the tooth flank. Transmission D has a relatively high damage value, but the mileage is very small with almost 19 000 km which indicates a high torque. The photo from the microscope in figure 8 shows a micropitting area at the tooth root. In contrast, the transmission B has a relatively low damage value, but the mileage is with about 150000 km significantly higher. Here, the photo in figure 9 shows micropitting above the pitch circle and the input torque is expected to be lower.

These images suggest that the highest load point on the flank moves with different input torque. It is assumed that this effect occurs due to the tooth stiffness. At the addendum, the stiffness is lower than at the dedendum. Therefore, the tooth is bending with higher load and the highest load point moves to the tooth root. With lower input torque the bending stress is lower and the highest load point is higher at the tooth flank. This effect shows additional potential for the operating strategy as the highest load point is moved away with the adapted input torque. With regard to a local damage accumulation on the tooth flank this effect has advantages on both the pre-damaged flank and the intact flank.

In summary, it can be said that the qualitative potential of the operating strategy has been demonstrated within the extended evaluations. The strength of the individual teeth is scattering in a wide range as most of the teeth do not have any pitting. Furthermore, it is advantageous for the operating strategy that the pittings occur preferably at neighbouring teeth and therefore the local reduction at these teeth is done automatically. Within the analysis of the field tests, an additional potential concerning the tooth flank was detected. All these results show the feasibility of the operating strategy. Therefore, the quantitative potential of the strategy is analysed in the next chapter by means of a simulation.

5. Simulative results
Within the simulation study the influence of a load shift on the percentage lifetime extension is investigated. For this purpose, the failure behaviour is simulated by means of a model, which is then run through in several iterations according to the Monte Carlo principle. The initiated failure behaviour is defined by the initial values (pitting size \(a_0\), load cycle \(n_0\), damage \(d=0\)), the EOL values (pitting size \(a_{EOL}=4\%\), load cycle \(n_{EOL}\), damage \(d=1\)), as well as pitting growth \(a=f(n)\) and damage \(d=g(n)\). The initiated failure behaviour corresponds to the actual failure behaviour if all teeth are loaded with a constant moment without the strategy. If the moment is varied, the damage increment following from the moment is calculated by means of a linear damage accumulation.

Furthermore, the Wöhler Curve of the spur gear pair from chapter 3 is used to get the new failure time with the adapted input torque of the operating strategy. This is done by a parallel shift of the Wöhler Curve in the failure time without the operating strategy. Linear damage accumulation and a load-independent relationship \(a = f(g^{-1}(d))\) are assumed, whereby the corresponding pitting size can be calculated for each damage.
Finally, a two-stage load spectrum is calculated for each tooth and the difference of the failure time with and without operating strategy is considered. The boundary conditions of the simulation are the following:

- Failure distribution ($n_{EOL}$): Normal with mean 11.39 million load cycles and standard deviation 1.053e6
- Distribution of pitting initiation time ($n_0$): Normal with mean 6.875 million load cycles and standard deviation 1.053e6
- Distribution of pitting initiation size ($a_0$): Normal with mean 0.45 % and standard deviation 0.205
- Wöhler exponent: 10.5
- Adapted torque function: ideal jump function with reduction only at the weakest tooth
- Standard torque: 200 Nm
- Reduced torque at the weakest tooth: 190 Nm
- Increased torque at the other teeth: 200,5 Nm
- Only weakest tooth is considered
- Iterations: 100
- Variation: startpoint (direct at pitting initiation, 7, 8, 9, 10 million load cycles)

The starting point of the operating strategy is varied within the simulation and the results are collected in Table 2. In the first simulation, the starting point was directly the initiation of the pitting that is drawn from the distribution. This initiation is simulated as a normal distribution. After that, the starting point was varied between 7 and 10 million load cycles, which corresponds to an average pitting size of 0.49 % and 2.28 %.

| Starting point               | With pitting initiation | 7 million load cycles | 8 million load cycles | 9 million load cycles | 10 million load cycles |
|-----------------------------|-------------------------|-----------------------|-----------------------|-----------------------|------------------------|
| Medium pitting size         | 0.45 %                  | 0.49 %                | 0.87 %                | 1.44 %                | 2.28 %                 |
| Median of lifetime extension| 20.46 %                 | 19.61 %               | 11.83 %               | 4.21 %                | 1.14 %                 |
| Maximum of lifetime extension| 38.11 %              | 25.99 %               | 17.88 %               | 11.50 %               | 5.68 %                 |

The greatest potential is presented when the operating strategy is started directly at the pitting initiation. Here, the reduced torque is applied to the weakest tooth for the longest and a maximum extension of 38 % lifetime could be achieved. Moreover, the median of the lifetime extension is reduced to only 1.1 % if the operating strategy is started at 10 million load cycles. From Table 2 it can be concluded that the detection of the pitting has to be very sensitive. If a lifetime extension of 10 % should be reached, a pitting size smaller than 1 % has to be detected. The later the operating strategy starts, the less extension can be achieved. But the potential of the operating strategy could be proven definitively by simulation and further consideration is recommended.

Within this simulation, the weakest tooth only is considered. This is sufficient for this simulation, because the input torque at all the other teeth is only increased by 0.5 Nm and those teeth do have a higher strength (compare to chapter 3 and 4). Additionally, for all starting points 100 iterations were calculated with a percentage error in the median value lower than 5 % in the Monte Carlo simulation. In further work, the number of iterations should be increased, to get a more accurate result. Moreover, the simulation should be extended to more teeth at the circumference compared to chapter 3 and 4 and it should be validated within laboratory test runs.
6. Conclusions and outlook

Based on the results of the extended pitting evaluation of laboratory and field tests and the simulative approach, several conclusions can be drawn:

- There are some pittings at the circumference, but only one pitting causes the failure of the system
- In 88% of pitting failure, a neighbouring flank has a pitting as well
- 70% of the tooth flanks of the test runs do not have any pitting
- The pitting degradation paths show an exponential growth and therefore a failure distribution of all teeth could be extrapolated
- The evaluation of all pittings results in a significantly higher scattering whereas the totally intact tooth should be included in further work
- The field tests also show a great potential as the same observations as in the laboratory test runs could be examined although only a pre-stage of pitting was visible, namely micropitting.
- The field tests show an additional potential for the operating strategy as the micropitting moves on the flank with different input torque. It is therefore expected that the highest load point on the tooth flank moves as well.
- The simulative approach shows a maximum increase of service life of 38%
- The later the strategy starts the lesser the potential is. Therefore, the measurement of the pitting location has to be very accurate and should detect pitting with a size smaller than 1% pitting area.

In further work, the simulation has to be extended to more pittings at the circumference. Additionally, the adapted input torque should be analysed as it is an ideal jump function in this simulation. A verification in an experimental test run is also still pending.

References

[1] Naunheimer H, Bertsche B, Ryborz J and Novak W 2011 Automotive Transmissions – Fundamentals, Selection, Design and Application 2nd edition Springer-Verlag Berlin Heidelberg

[2] ISO 6336-2 2006 Calculation of load capacity of spur and helical gears - Calculation of surface durability (pitting). International Standard

[3] Henß M and Bertsche B 2019 AutoEncoder basierte automatisierte Zustandsdiagnose von Wälzlagern Tagung Technische Zuverlässigkeit, Nürtingen, Germany

[4] Foulard S, Rinderknecht S and Ichchou M 2015 Real-time and online lifetime monitoring system for automotive transmissions The 14th IFToMM Word Congress, Taipei, Taiwan (Oct.)

[5] Beslic Z, Mueller P, Yan S and Bertsche B 2017 Planning optimal degradation tests in consideration of budget and statistic accuracy on different stress levels Proc. ISSAT 2017 Conference, 3rd – 5th August 2017, Chicago, USA, ISBN 978-0-9910576-4-1, pp. 108-115

[6] Gretzinger Y, Dazer M and Bertsche B 2020 Using life data of competing failure modes to increase the remaining useful life of gear wheels Proc. RAMS 2020-Conference, 27th – 30th January 2020, Palm Springs, USA.

[7] Sommer K, Heinz R and Schöfer J 2018 Verschleiß metallischer Werkstoffe - Erscheinungsformen sicher beurteilen 3rd edition Springer Vieweg

[8] Kroner A, Luo Z and Bertsche B 2020 Prediction of the Remaining Useful Life of Transmission Components within a Remanufacturing Process to Ensure the Second Product Life Proc. IRF2020: 7th International Conference Integrity-Reliability-Failure, 6th – 10th September 2020, Funchal, Portugal

[9] Felbermaier M 2016 Untersuchungen zur Graufleckenbildung und deren Einfluss auf die Grübchentragfähigkeit einsatzgehärteter Stirnräder Dissertation TU München

[10] Radev T 2005 Einfluss des Schmierstoffes auf die Grübchentragfähigkeit einsatzgehärteter Zahnrad Dissertation TU München

[11] Bartz W J 1999 Schäden an geschmierten Maschinenelementen 3rd edition expert verlag