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REMAINING USEFUL LIFE PREDICTION OF A TURBINE HOUSING USING A SOFT SENSOR APPROACH

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ABSTRACT

In this work a soft sensor and a stress analysis is used for the prediction of the remaining useful life of a turbine housing. Thereby the approach is based on the estimation of the load on the component during the operation using a soft sensor. Thus, a previously unknown load-time function is provided by a soft sensor, which can be used to predict the remaining useful life. The stress analysis and the life time model are used to calculate the damage and the state of health of the turbine housing depending on the specific usage. As corresponding lifetime model a S-N curve for high material temperatures is selected. Based on the previous load a prediction of the remaining useful life is carried out. Life data during field operation is used to characterise the uncertainty of the prediction.

Keywords: remaining useful life, Prognostics & Health Management, reliability, thermo-mechanical fatigue

INTRODUCTION

Turbochargers are commonly used to increase efficiency and thus reduce fuel consumption. As a result, internal combustion engines can become more environmentally friendly. In the case of large diesel engines, the increase in efficiency is an important sales criterion due to the high fuel consumption. The continuous development of internal combustion engines, also with regard to the reduction of exhaust gas emissions, leads to increasingly demanding requirements for the exhaust system. Since the turbocharger is one of the most complex and expensive parts of such a system, it will be investigated in further detail as it must meet requirements in terms of reliability.

Turbochargers are mainly damaged by varying operating conditions. For instance, the compressor and turbine wheels are failing due to changing rotational speed, whereas the turbine housing is damaged by the variation of the component temperature and the resulting expansion. Thermo-mechanical fatigue of the turbine housing has been identified the main failure mechanisms in previous work [1]. Therefore, thermo-mechanical fatigue is one of the main causes of failure of exhaust system components.

Unexpected or too early failures usually lead to high costs represent a risk for the operator. In order to prevent this, the considered system can be regularly maintained or replaced. However, this in turn leads to high cost for the manufacturer, since a large part of the remaining useful life of the components may remain unused. Therefore, the remaining useful life prediction depending on the operation-specific load offers many advantages for both the customer and the manufacturer. For instance, a maintenance interval of the component can be planned according to the remaining useful life prediction or the operational behaviour can be adjusted in order to extend lifetime of the component.

APPROACH

The approach to determine the remaining useful life of the turbine housing of the turbocharger is divided into two paths, see Figure 1. One path describes the estimation of the component load during operation using a soft sensor. Thereby a load-time signal is calculated, which is converted in a customer-specific load spectrum. Whereas the other path results in the component stress and strain under given conditions. In general, different approaches of lifetime modeling can be pursued. On the one hand, data-driven failure models can be applied by continuously recording degradation up to the end of life criterion. On the other hand, experiments can be carried out to determine the lifetime of the component, which in turn enables the application of a lifetime model. Finally, the lifetime can be determined by means of a stress analysis and the corresponding lifetime model. For this procedure, however, failures or usage data from the field are also necessary to validate the prediction. Lifetime tests for large diesel engines are neither practical nor cost efficient due to the high fuel consumption. So, in this paper a simulation is used to calculate the stress of the component. Therefore, a load cycle of the engine was specified in order to analyse the amplitude of the stress and strain. In addition, a transient temperature field of the turbine housing was determined as input for the structural mechanical calculation. The stress and strain amplitude are calculated through a FEM simulation.

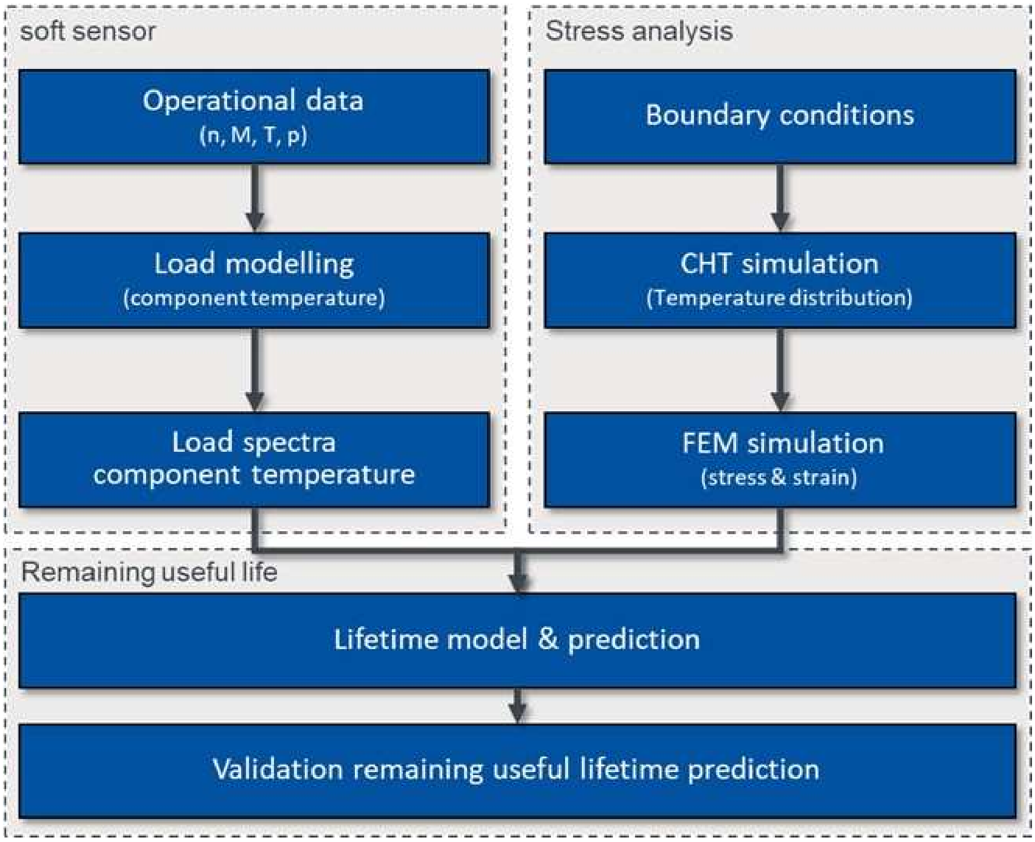

Fig. 1 - Approach for determining the remaining useful life

The load spectrum of the component temperature and the strain are then used in combination with a lifetime model in order to estimate the lifetime of the component. As the turbine housing is mainly damaged due to thermo-mechanical fatigue a S-N-curve is used as lifetime model in order to determine the cumulative damage of the turbine housing. Thus, the current state of health of the turbine housing is described. Based on the previous loads and the prognosis of the future loads the remaining useful life is predicted.

SOFT SENSOR

As the changing temperature of the turbine housing causes progressive cracks and thus its failure, the component temperature is considered as the relevant load. Due to the wide operating range of an internal combustion engine, a high number of different component temperature variations are possible. The measured variables recorded by the engine provide only a limited amount of information on the thermo-mechanical fatigue of the turbine housing. In addition, the attachment of a temperature sensors results in a notch in the component, which leads to an earlier failure or prior damage of the component. Therefore, the necessary temperature is determined using a soft sensor. A mathematical model which determined an unavailable variable using measured variables and parameters is referred to as soft sensor. As these models are designed for use during operation, a control unit must be able to solve them [2,4]. The modeling of the soft sensor for the destimation of the component temperature during operation is described in more detail in [5]. Thus, a load-time function is estimated during operation of the turbocharger, see Figure 2. In the upper half the two soft sensors models and the exhaust temperature of the engine are shown. In the lower half the one soft sensor and the engine power are displayed. The gradient of the component temperature is very low compared to the exhaust temperature and the engine power. This is due to the thermal inertia of the housing. When examining the engine power and the turbine housing temperature it is obvious that even in case of low corresponding power a high component temperature is possible and a rapid change of the power can result in a jump of the component temperature.

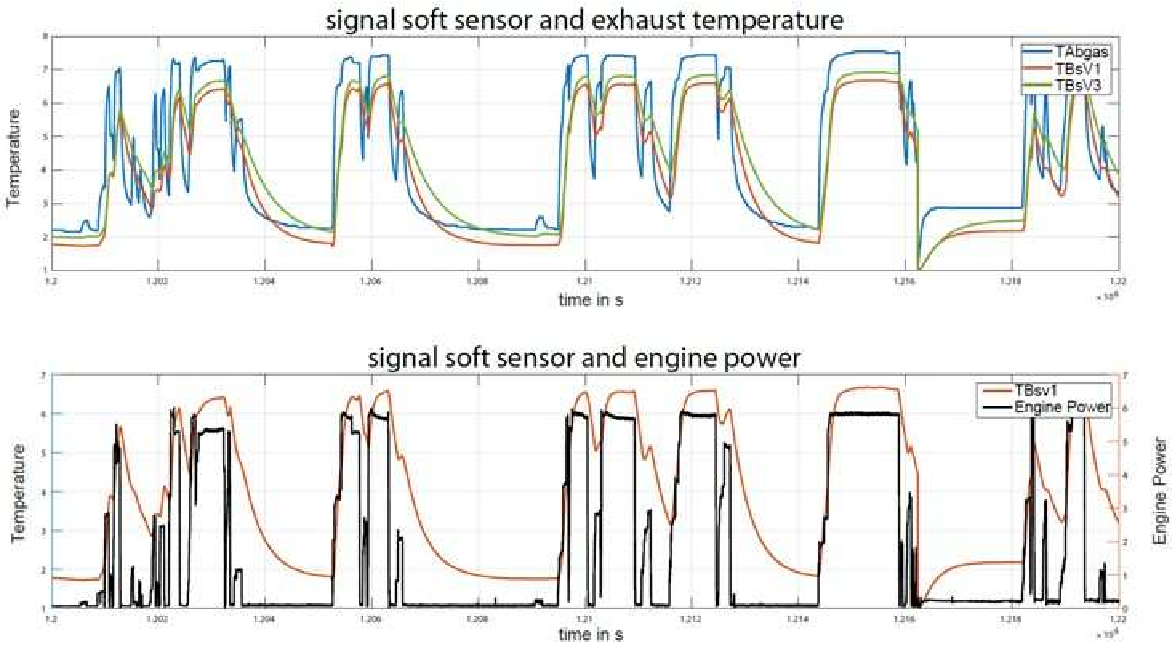

Fig. 2 - load time signal using a soft sensor approach

In the third step of the approach a load spectrum is determined using the load-time function. Since thermo-mechanical fatigue is the failure mechanism, Rainflow counting is used in order to calculate the number of cycles at the specified load amplitudes [3]. Thereby the algorithm detects extrema in the load-time-function and compares them with each other in order to identify a closed loop. If a cycle is detected, the two corresponding extrema are deleted from the temporary memory and the total number of cycles is increased by one. This avoids the need to store the entire load signal during operation. Thus, a load spectrum of the turbine housing temperature is determined, which can be used in combination with the stress for the remaining useful life prognosis. Figure 3 shows a load spectrum for a specific engine.

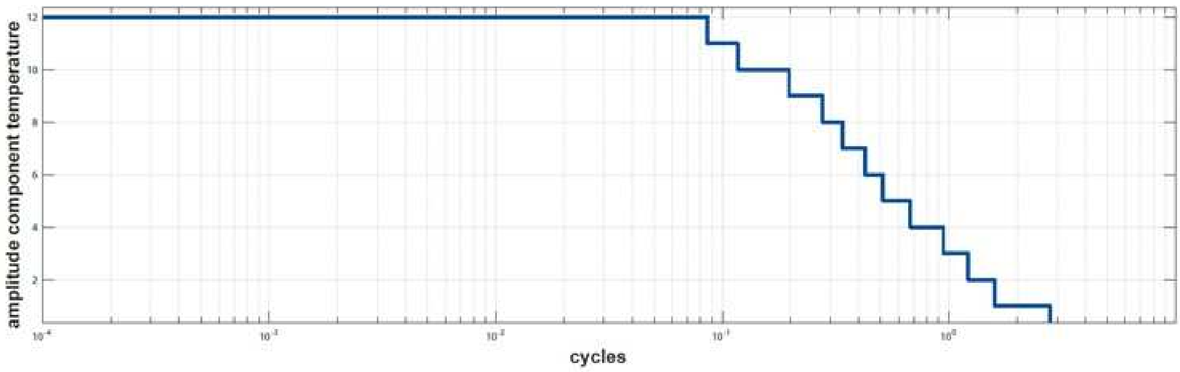

Fig. 3 - load time signal using a soft sensor approach

STRESS ANALYSIS

In order to determine the remaining useful life, the stress and strain of the component have to be determined. Since high absolute temperatures and a wide variety of temperature gradients can occur in the turbine housing, the temperature distribution of the housing and surrounding parts must be used as a boundary condition for the stress simulation. However, for the calculation of the temperature distribution further information regarding the mass flow within the components is necessary. Due to the complex geometry and flow conditions, damage to the turbine housing is mainly caused by the variation of the operating points. Therefore, a transient simulation of a load cycle has to be performed in order to identify the relevant stress and strain amplitudes. Thus, the first step is to define a load cycle for which the boundary conditions are provided and the different simulation steps are performed. The load cycle is derived from the maximum power amplitude of the diesel engine, which represents the highest load amplitude for most failure mechanisms. The load cycle is divided into 6 sections, Figure 4. The first section describes the start from the defined ambient conditions of the engine. The next step is characterised as stationary operation at idle until the gradient of the component temperature can be neglected. A slope for changing the operation points is defined in section 3, since there is a limit of what is physically possible for the diesel engine. Furthermore, if the slope is to steep, errors will occur in the simulation. Section 4 is specified as stationary operation at rated power. A slope from nominal power to idle is defined for section 5 following the operation until a stationary temperature distribution is achieved for section 6.

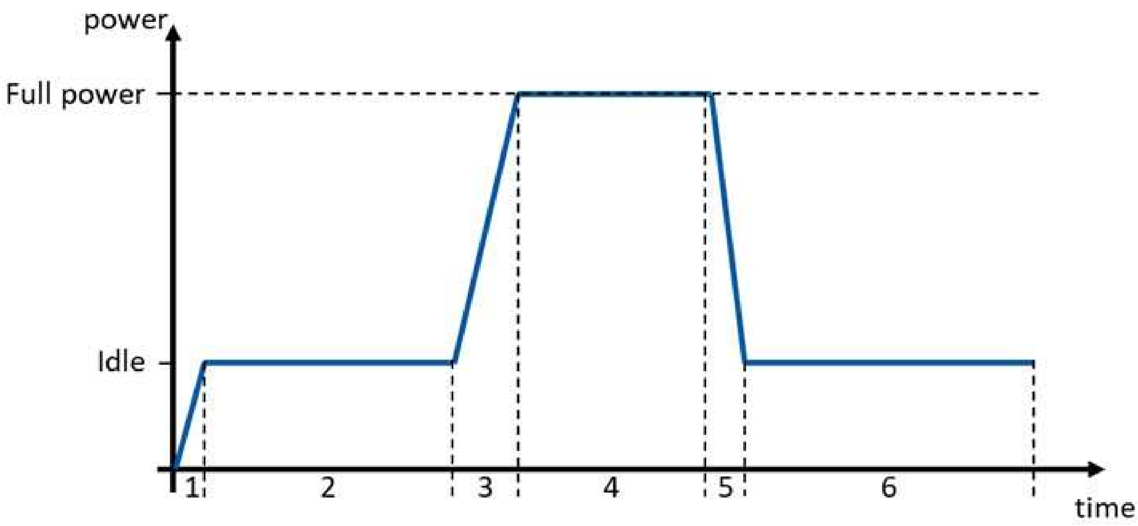

Fig. 4 - load cycle transient simulation

First the environmental conditions regarding the different sections, the boundary conditions of the exhaust gas, the interfaces between the components and the material properties are specified. In order to calculate the transient temperature distribution, the exhaust gas flow must be determined in a previous step. For this purpose, the inlets $\dot{m}_5$ and outlets $\dot{m}_6$ of the turbocharger are defined and characterised by the mass flow, temperature and pressure, Figure 5. In addition, the flow within the turbine housing is divided into inlet, turbine and outlet. This simulation provides the heat transfer coefficients and the gas temperature for the following steps.

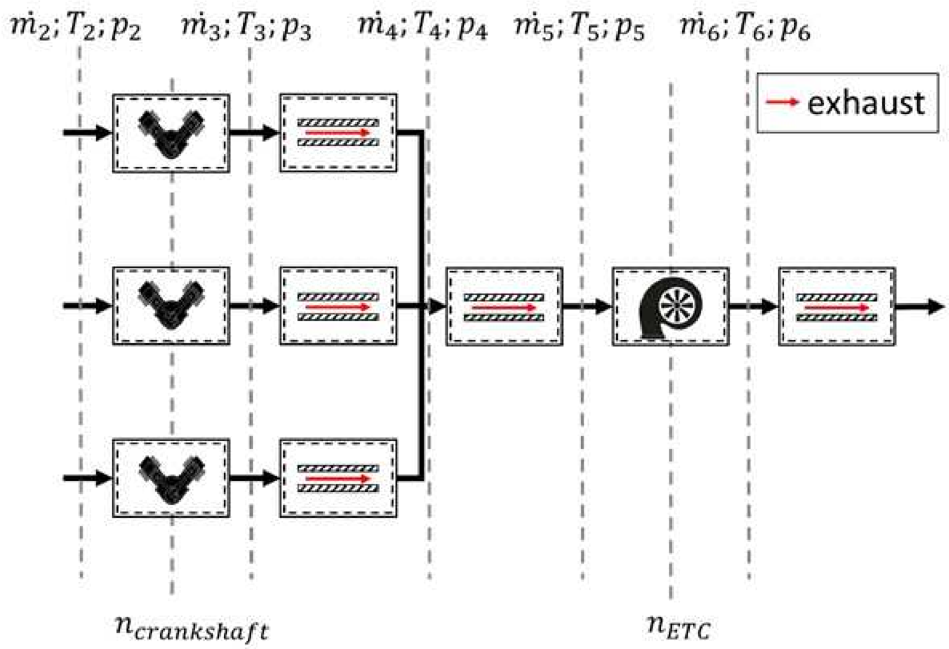

Fig. 5 - Exhaust system of a diesel engine

The material properties and the boundary conditions to the environment at the different operating points are necessary in addition to the heat transfer coefficients of the exhaust gas to estimate the transient temperature distribution. Once all heat-transferring surfaces have been defined, the CHT calculation can be performed. As a result, the three-dimensional transient temperature distribution of the turbocharger is obtained, see Figure 6.

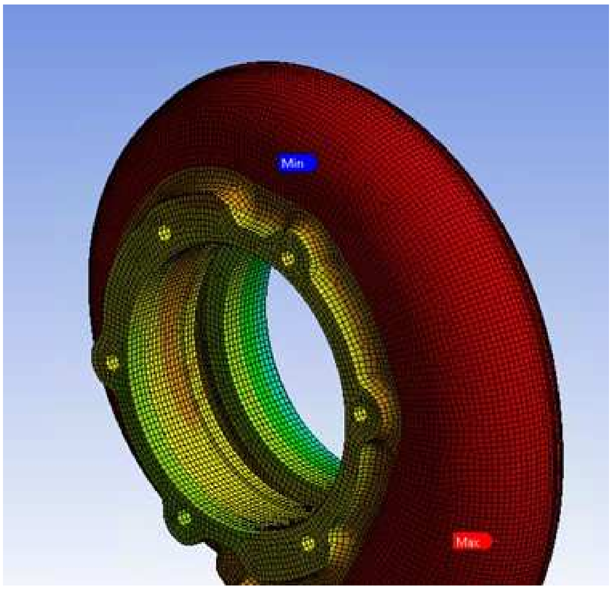

Fig. 6 - Temperature distribution turbine housing

The temperature simulation serves as a boundary condition for stress analysis together with the contact regions and the attachment of the components. The FEM simulation provides the stress and strain information for the derived load steps of the specified load cycle. It is obvious that the stress analysis of the turbine housing is very complex due to the geometry, fluid dynamics and mechanical boundary conditions and requires a considerable effort for modeling. Therefore, only one load cycle has been used in order to calculate the stress and strain of the turbine housing. In order to calculate the stress and strain, external loads on the components are applied the first step following the implementation of the temperature distribution of the individual steps of the load cycle. Thus, the structural-mechanical state of the components is calculated for every load step. This information about of the individual calculation steps is used to derive the stress and strain amplitudes of the load cycle.

REMAINING USEFUL LIFE

In the step of remaining useful life prediction, the load spectrum of the component temperature, the stress and strain amplitude and the lifetime model are used to determine the current health state of the component depending on the customer-specific operation. The strain can be applied to the S-N-curve in order to estimate the number of cycles to failure, see Figure 7. The probability of failure of the S-N-curve at the corresponding temperature must also be taken into account. Since only a very small amount of data from the field is available, the median of the failure probability of the S-N curve is used. This is also influenced by the large dispersion of the failure times at different failure probabilities. Thus, the location of the failure is estimated for validation.

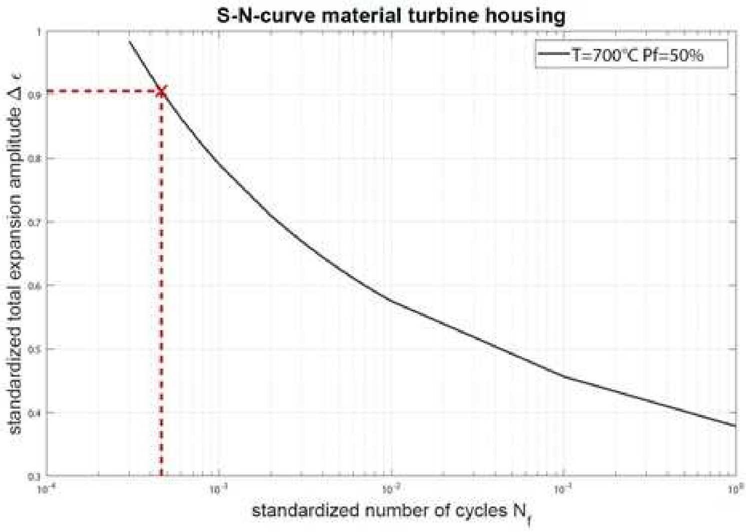

Fig. 7 - lifetime prediction using an S-N-curve

Thus, the number of cycles to component failure is known. In order to predict the time of failure during operation, the number of load cycles are extrapolated until they reach the threshold. The prediction is based on the past load on the component as well as its current state. Therefore, the remaining operating time can be estimated and the predicted time of failure is against the real time of failure, Figure 8. In comparison, the predicted lifetime is estimated to be lower than the real failure.

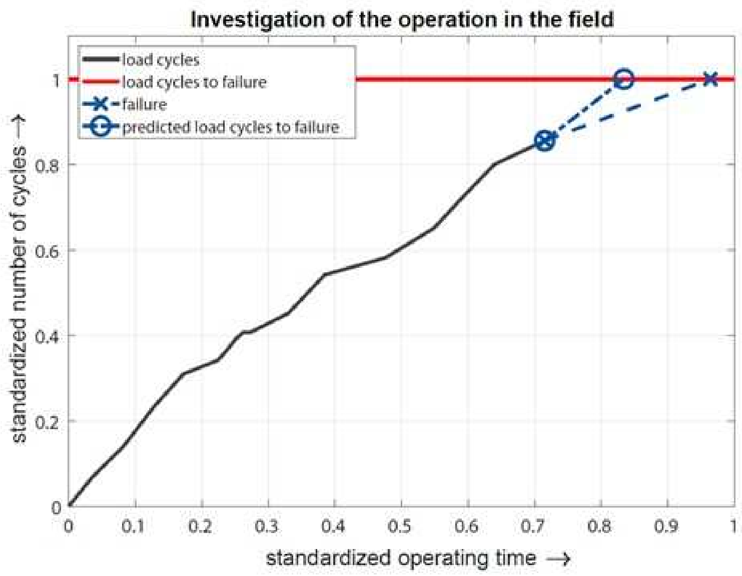

Fig. 8 - predicted number of cycles

CONCLUSION

In this paper, a soft sensor is applied in order to estimate the load-time function of the turbine housing. Thereby the model calculates the temperature signal of the component and converts it into a load spectrum. The stress was calculated using FEM-simulation and as lifetime model an S-N-curve was used, as the turbine housing mainly fails due to thermomechanical fatigue. The remaining useful life was predicted and compared to the real time of failure during operation.

Failures during operation due to thermomechanical fatigue can only be detected, if a certain crack length is reached. Therefore, the real time of failure and detected failure can vary from each other. In addition, a simplified load cycle is used in order to calculate the stress and strain of the turbine housing. This cycle deviates from those detected in the field and therefore represents a conservative assumption.

Future optimization steps can be to further increase the accuracy of the soft sensor, the consideration of other stress and strain amplitudes and the modification of the load cycle used for the simulation.

In this paper a sift sensor was used to estimate a previously unknown load in the field. Thus, a load spectrum can be determined, which can be used for the interpretation of the usage behaviour. The simulation of the stress and strain of a specific load cycle is performed. The load spectrum, the stress, strain and the lifetime model can be used to predict a remaining lifetime during operation. Thus, the lifetime of the component can be made better of and the maintenance of the component can be planned according to its usage. Furthermore, an increase in the lifetime of the component is possible through active control in the system behaviour.

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