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Mobile Automated Diagnostics of Stress State and Residual Life Prediction for a Component under Intensive Random Dynamic Loads

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Abstract

This article presents an approach developed for collecting and processing data about the actual stress state of a structural component of a technical product and to estimate its residual fatigue life in case random dynamic loadings. As input data sensor values are being used from which the operating loads acting on a component are calculated.

For the realization of the experiments a suitable mobile measuring device has been developed. The device is designed to digitize sensor signals at certain positions identified by simulation results, to collect this data in an internal memory, to mathematically analyze this data in real time, to process this data in parallel for the purpose of identifying characteristic information, to restore the stress state of the component and to estimate the residual fatigue life.

The created concept provides an opportunity to realize the "intellectualization" of structural components without radical changes in their construction and allows supplementing components with additional functions for collecting and analyzing data during the usage phase of the components life cycle, what is an integral part of an Industry 4.0 product.

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1. Introduction

Information and communication technologies form the basis on which future innovative solutions are developed. In the context of Industry 4.0, more and more modern products for the industrial sector and for the end users are created, taking into account the availability of regulatory, monitoring and tracking functions that support the collection, analysis and storage of various kinds of product data throughout its life cycle, including the phases of product manufacturing and usage [1, 2, 3].

The key features and differences of new industrial smart products are their modularity and the possibility of wireless communications between sensors, actuators and assembly units. Smart components can be considered as abstract objects with the following properties: they feature a standard interface for data exchange; can transmit and store information regarding their status and location; their functions are described by models; they can operate autonomously and universally.

Such functions can be provided by expanding existing product capabilities by implementing additional modules in the construction and product structure [4], for example, by using embedded systems or by developing compact mobile devices that ensure data collection and processing [5]. Such embedded systems or mobile devices can be intelligent central control units that are actively involved in the usage of technological systems and products. As a rule, they work within the established range of applications as information processing devices. Data collection and transmission is carried out by sensors and actuators, allowing embedded systems to be more interconnected with each other and with the network.

One of the main informative technical and economical characteristic of products which are subject to monitoring is the residual life. Under the condition of varying technical states components often have a potential operating time to failure, which can significantly differ from the one stated in the documentation or being considered for the maintenance periodicity. Thus, maintenance at a given periodicity can be untimely and cause additional costs. The advantage of maintenance tactics is the entire use of the potential resources of components.

The aim of this work is to create a methodological approach to analyze the current state of a component based on an analysis of its stress-strain state and implementing this approach by means of appropriate algorithms, software and a diagnostic device.

2. Approach to the analyze the stress state of a component and to predict its residual life

The term residual life refers to operating an object from the beginning or the resumption of operation until the onset of the limit state. Depending on the kind of a starting point in time and the considered units of measurement of the duration of operation, the concept of residual life receives different interpretation. Here, as a measure of duration, the number of loading cycles is chosen, and the residual life is predicted in percent, where 100 percent shall be the initial state of the component at the time of the first measurements and for its integration into the synthesis model of the identification of loads.

Most of the approaches developed to date to assess the residual life of components use statistical methods of data processing [6, 7, 8]. The presented approach is based on results of Lachmayer et al. [9] and applies a non-destructive method of current monitoring by measuring the strain condition of a component during its operation. By this method loads acting on the component can be identified considering the collected data from the strain sensors.

The general vision of an analysis including the main steps of how to conduct diagnostics is depicted in Fig. 1. At the first stage of the presented approach, the modeling and analysis of the stress-strain state of the component is performed to determine the location of the sensors for data collection and to create a synthesis model for recognizing the loads the component. The resulting reference matrices will be used subsequently to predict the residual life. The algorithm for calculating the remaining resources is briefly described in Section 2.1 and is contained in the computational unit of the device.

The calculation is carried out for the highly loaded regions of the component, in which the probability of fatigue failure is maximal. The quantity and location of these regions can be determined both from the experience of operating this component, and by analyzing the stress distribution pattern obtained, for example, by the finite element method. Analysis of the current state of the component is performed using a portable device that registers

analog signals of the strain gauge type sensors, digitizes them for a certain period of time, performs digital filtering, reduction and mathematical analysis of the obtained data.

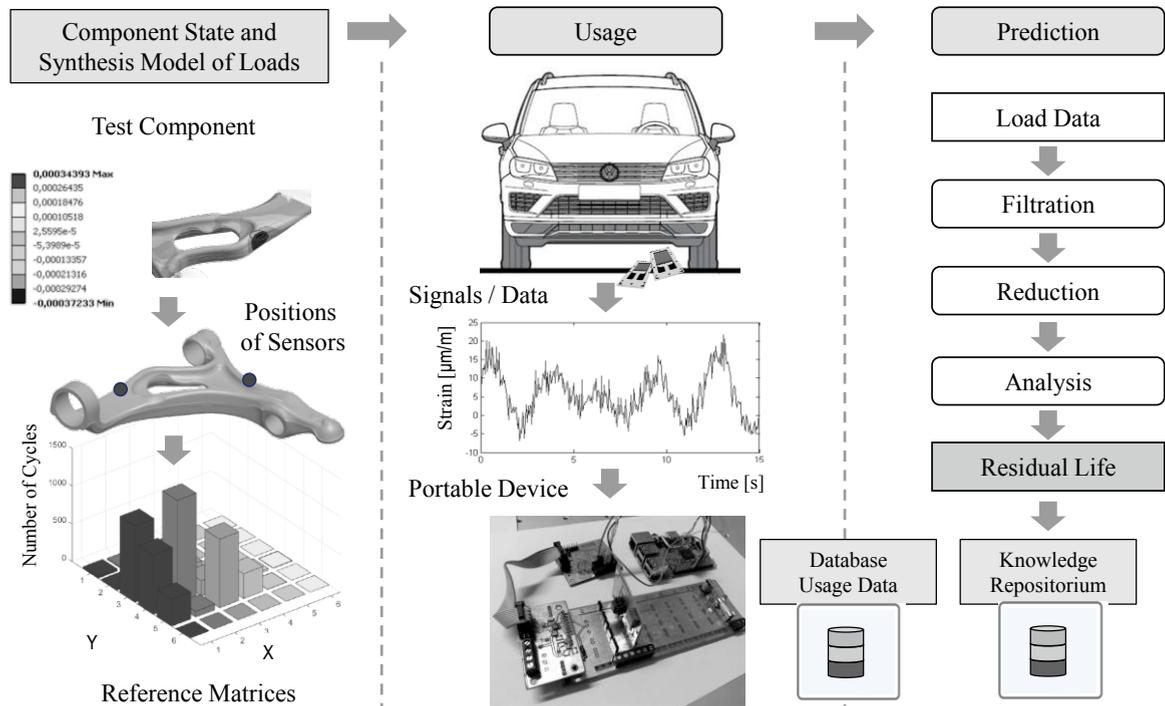


Fig. 1. General description of the methodological approach.

2.1. Residual life prediction for repeated loads

The approach is based on calculating the measure of accumulated fatigue micro damage and is carried out for a component whose geometry, material characteristics, attachment variant and the positions R of applied external forces $F_r(t)$ ($r=1, R$; t - time) are given. These forces as function on time are not known, but can be computed from the readings of the data from S strain sensors.

The classical methodology for calculating multi-cycle fatigue of a component subject to random, irregular loading assumes that the entire load history is a collection of identical blocks within which the external force's influence functions $F_r(t)$ are known.

If the measure of damage in the material of a component in the calculation area for a single loading block is designated as a dimensionless quantity ΔD , then the approximate number of blocks before appearance of fatigue failure is determined by the ratio $\lambda=1/\Delta D$. The residual life of the component can be determined by the residual life of the most "damaged" area with the minimum value of λ .

The calculation ΔD for a particular region is carried out by means of the history of the change of the equivalent stress $\sigma_e(t)$ the time block with duration ΔT , which is due to the action of the external loads $F_r(t)$. The function $\sigma_e(t)$ can be calculated using the FEM. Using the rainflow counting method [10], a reference matrix containing detailed information about the allocated blocks will be obtained.

2.2. Residual life prediction for random dynamic loads

In the case when time variation of load cannot be represented as a set of periodically repeating identical blocks, the calculation of residual life is often performed by means of the probabilistic laws of distribution of the loading maxima. The present approach assumes a direct identification of the values of these loads by the indications from the corresponding sensors. In accordance with the approach described by Lachmayer et al. [9], identification of the

system from R unknown loads can be realized in real time by the indications of sensors whose values are an indirect manifestation of the sought loads.

The transformation formula for each time step $m=1, \overline{M}; M = \Delta T_j / \Delta t$ in the matrix form can be written as follows:

$$F_m = (A^T A + \alpha C)^{-1} A^T \cdot E_m \quad (1)$$

The index T denotes the transpose operation, F_m and E_m are matrices of height S and R , respectively, containing the indication values from the sensors; $A(S \times R)$ is a matrix of coefficients of sensitivity, which reflects the response of the s -th sensor to a unit r -th action; $\alpha \geq 0$ is the parameter of regularization, C is the unit matrix with size $R \times R$.

The procedure for calculating the fatigue strength for such a random, non-periodic external loading is based on the idea that the operation process of the component is divided into finite time intervals with a duration ΔT_j , after which the history of the stress changes σ_{ej} is formed for the calculated region of the component. The method described in Section 2.1 is implemented to evaluate the measure of fatigue damage ΔD_j accumulated exclusively in the j -th time interval ΔT_j .

The measure of the total fatigue damage D in the investigated area of the component for the current time of operation of the component $T = \sum_j \Delta T_j$ will be equal to the sum of computed ΔD_j at the previous stages: $D = \sum_j \Delta D_j$.

As a result, the residual life of the part can be indirectly estimated by the minimum value of the difference $1 - D$.

3. Functional diagram of the device

Within the framework of the presented methodology, a reliable portable device that performs registration, digitization and analysis of data [11, 12] obtained from sensors of a strain-resistive type has been developed. Therefore, an electrical circuit of the tuned amplifier of the analog signals received from the strain gages, a hardware platform for a discrete recording of the signals for a certain period of time and a software for filtering and the initial processing of analog signals have been created. The functional diagram of the device is depicted in Fig. 2.

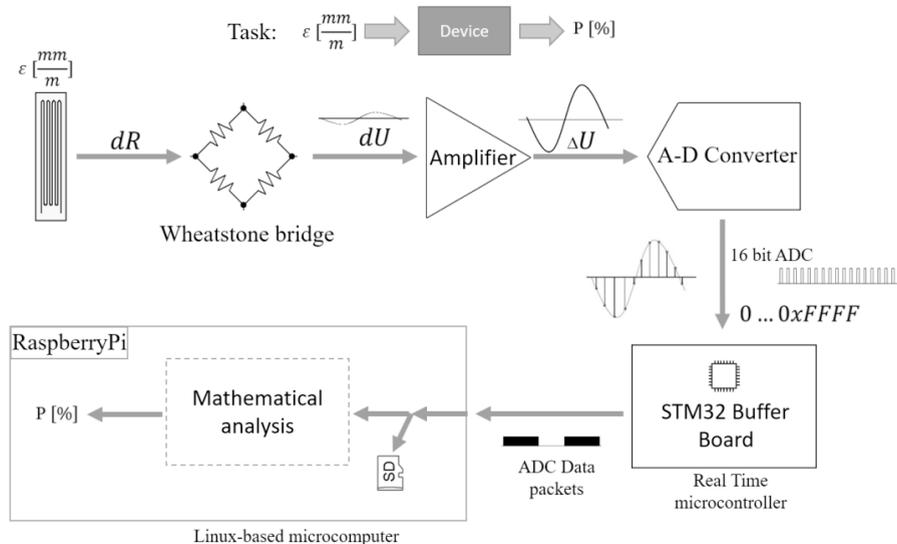


Fig. 2. Functional diagram of the device.

The functional diagram shows all stages of signal conversion. The strain gauge is included in the Wheatstone bridge. Schematic solutions are designed taking into account the influence of parasitic noise and temperature

compensation. The signal from the bridge output has a low amplitude and requires amplification. For amplification a system of two operational amplifiers is used, thus at the output a bipolar signal with offset is ready for digitization. The signal is digitized using a precision 16-bit 8-channel analog-to-digital converter (ADC). The microcontroller controls the ADC in hard real-time mode, stores the data in internal buffers and sends these to the Raspberry PI microcomputer in asynchronous mode. The received data is stored on the internal SD card, undergoing preliminary compression and digital frequency filtering.

Each block of the device was modeled with various mathematical packages. Testing showed that the operation parameters of each block are within the modelled range. The device is completely autonomous and uses an external computer only at the calibration stage, for which the corresponding software has been developed.

4. Testing of the mobile device

Each block of the device was modeled with various mathematical packages. Testing showed that the operation parameters of each block are within the modelled range. The device is completely autonomous and uses an external computer only at the calibration stage, for which the corresponding software has been developed.

The application of the described approach of an automated condition diagnostic was studied at the example of a part of the front suspension of the WV Touareq. As a demonstration part the lower wishbones were used due to its functionality and complex free form geometry. The CAD model of the investigated part is depicted in Fig. 3, a). Data is collected using two sensors (Fig. 3, b) located at critical positions regarding the stress-strain state of the part. Measuring positions are determined by computing the stress-strain state where the results of the simulation are shown in Fig. 3, c) and d). The stress-strain state of the component is calculated with a maximum load of 1,400 kg on the front axle of the car.

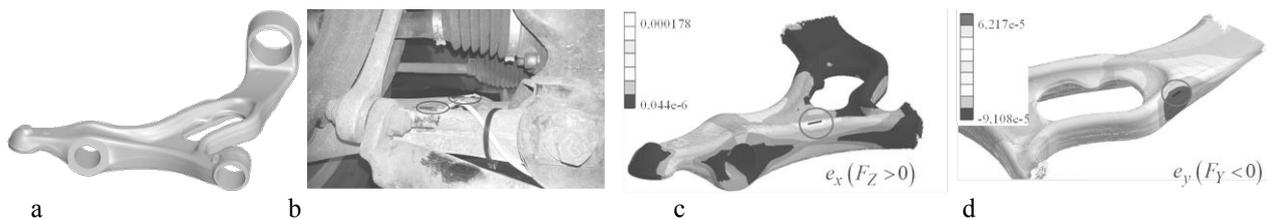


Fig. 3. Lower wishbones: (a) CAD Model; (b) sensors applied to the component surface; (c)-(d) calculated stress-strain states of the component.

To validate the working prototype of the mobile device, static and dynamic experiments were conducted to determine the correctness of the development of the boards for a customized analog signal amplifier and a hardware platform for recording of discrete signals. The results of the static experiment are depicted in Fig. 4.

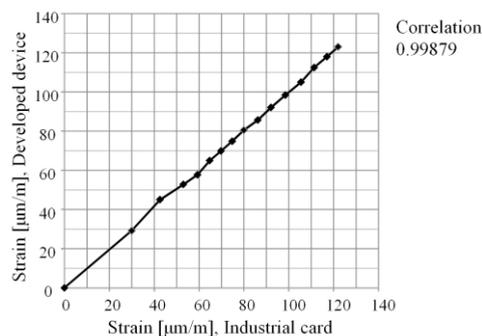


Fig. 4. Results of the comparative static experiment.

Experiments were carried out for the developed device and the industrial measuring card GSV-2MSD-DI DMS-Data Logger. During the static experiment a beam with an active strain gage was loaded with loads from 0 till

15 kN, and another beam with compensating strain gauges was at rest, which corresponds to the actual operating conditions. Comparison of the results showed the character of the change in the force development, which allows to draw a conclusion about the correctness of operation of the developed device. Dynamic experiments were conducted on a lower wishbones of a Volkswagen Touareg in urban conditions as well as at a test rig. The experiments included a comparative analysis of the signals from the measuring devices for a test run along a test course around obstacles as well as over several obstacles of a specified height. Comparison of the experimental results from the developed mobile device and the industrial measuring card shows the correctness of the developed device.

5. Conclusion

An approach to analyze the real stress state of a component is described to forecast its residual life based on collected actual load data. The proposed approach includes a method to calculate the accumulated fatigue damage for a structural component under intensive random dynamic loads. As initial data the readings of sensors are applied; based on these a restoration of the loads acting on the component is realizable.

The first prototype of a measuring device was manufactured, its debugging was carried out and a number of experiments, which confirmed the correctness of the operation of this device, were performed.

Further steps are an improvement of the algorithm for converting the ADC raw data to the necessary magnitudes of mechanical effects, as well as developing software for an advanced signal analysis and user-friendly interface for connecting the device to a personal computer and a smartphone.

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