

Data Based Damage Prediction of Commercial Vehicles Using Bayesian Networks

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Abstract.

For the estimation of life expectancy and dynamic fatigue of a machine, the overall load configuration of the typical application is of major importance. Regarding commercial vehicles, the load spectrum differs with the variation of machine parameters which requires costly measurements for analysis of damage. This article presents robust methods for the computation of characteristic values for the damage to a certain component. The methods are based on a hypermodel, which represents the relation between different machine configurations and the resulting characteristic values. Therefore, fewer typical machine configurations have to be measured.

The statistical models of load and damage are made using the Rainflow counting algorithm and an extended version of Miner's Law. After the condensation into characteristic damage values, hypermodels for the relationship between these scalar values and the machine parameters are developed using Neural Networks. Due to the small amount of measurements and the high variance in the data, Bayesian regression is used to optimize performance and robustness. The method is validated using data from simulations and also tested on measured data of earth moving vehicles. Experimental results show that Bayesian techniques lead to a good prediction of the damage if the data quality is reliable, and they point out parameter configurations that should be measured additionally (Design of Experiment). Using the presented approach, the development procedure of commercial vehicles can be considerably economized by a drastic reduction of both time and measurement cost.

1 Introduction

For the design of commercial vehicles, individual customer requirements have to be satisfied. Furthermore, the demand on the machine's performance is increasing. Thus, an optimal adaptation of the machine parameters is necessary to get the best performance with the given operating conditions. One of the most important indicators for performance is the life expectancy of the machine and therefore the damage to its components.

For an estimation of damage, the knowledge of the overall load configuration of the specific application is of major importance. In general, the load oscillation with the maximum amplitude has to be considered for damage calculation (worst case). If the load spectrum is known, a different concept for strength computation can be used which takes into account, that loads with maximal amplitude do not permanently occur and thus, damage is lower as in the worst case scenario.

Due to the restriction of most commercial vehicles to a typical application with periodic operating cycles, the load spectra for different applications are similar, apart from the dependence on machine configurations and operating conditions. To get reliable information about this relation, usually costly measurements are necessary.

This article proposes a promising way to predict the damage of commercial vehicle components in dependence on machine parameters without the measurement of each configuration. Therefore, a hypermodel using Bayesian Networks for characteristic damage values based on statistic examination of measured data is built. Figure 1 illustrates the necessary steps to develop the hypermodel out of raw measurement data.

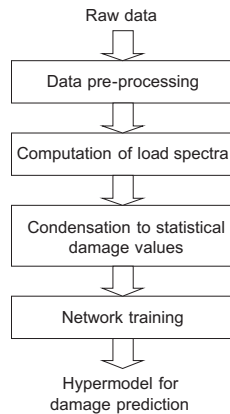


Figure 1: Modeling procedure

For the last step, the training of the Bayesian Network, the computed characteristic values for the damage to certain components are treated as output data to a regression problem with the machine parameters as input data. The resulting hypermodel is able to predict damage values for machine configurations that have not been measured yet, see figure 2.

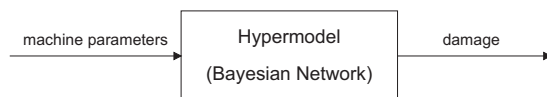


Figure 2: Model based prediction of damage depending on machine parameters

Starting with measurements of existing machine configurations, a growing data base and an improvement of the prediction with each new data set can be achieved. The presented method can be applied to all commercial vehicles that work in periodic operating cycles which are the basis for the statistical calculations. The application of the proposed procedure for the prediction of other design parameters is also possible. The prediction of complete load spectra, like in [1] or [2] is feasible as well. In contrast to those articles, which present methods for the modeling of load spectra under varying operating conditions, this paper analyzes the dependence of characteristic damage values on machine parameters. The paper is structured as follows: Section 2 starts with the description of data recording and preprocessing. Afterwards, the calculation of load spectra and the condensation into characteristic damage values is presented. Bayesian regularization techniques on Neural Networks are introduced in section 3. Section 4 proposes adequate methods for model validation. In section 5, simulation results are shown. Finally, the application of the pre-

sented methods on measured data of an earthmoving vehicle is shown and discussed in section 6. The paper is concluded by a short summary.

2 Statistical calculation of damage

The aim of this section is to generate a data set which can be used for the training of a Bayesian Network for damage prediction.

As a first step, measurements have to be planned and executed and the data must be prepared for further statistical examination. Design of Experiment (DoE) and data pre-processing are shown in subsection 2.1. Subsection 2.2, describes the determination of the load spectrum using the rainflow counting algorithm as well as the computation of the resulting stress spectrum. The calculation of damage including the condensation into statistical values is treated in subsection 2.3.

2.1 Data recording and pre-processing

An important factor for the calculation of damage - and thus for the prediction - is the quality of measurements. To get both representative and reproducible data, DoE is used. The following steps are of major importance:

1. Definition of precise types of damage as target variables.
2. Definition of a sufficient set of measured variables in order to guarantee the unique computation of the target variables.
3. Selection of the determining factors on damage prediction. As mentioned above, different machine parameters and operating conditions are possible choices. Preliminary measurements or expert knowledge of the developers can facilitate the procedure. Factors are input variables to the modeling procedure which means that each factor increases the dimensionality of the regression problem. Therefore, the number of possible factors is limited.
4. Variation of each factor. Number and distribution of factor variations determine the quality of the possible model. E.g. if only 2 variations are measured, the estimated model can only have linear characteristics in that dimension.
5. Determination of the remaining parameters and operating conditions. To enable a reliable detection of dependence on the chosen factors, all other

influence variables have to be kept as constant as possible. Furthermore, the chosen operating conditions have a great influence on representability and reproducibility of the measurements. Attention should be paid at least to location and duration of measurements, covered distance, bulk material, ground quality and weather.

6. Design of the measurement campaign including all above defined machine configurations.

Because DoE is an iterative process, the measurement campaign should be adapted with the knowledge of the result of each new experiment.

To prepare data for a statistical examination, it is necessary to separate the operation cycles of each measured variable. Furthermore, measurement errors as well as cycles with outlying characteristics should be eliminated. A proper procedure coping with this challenge has been presented in [3], including data pre-processing, cycle border detection and cycle selection. With the application of these methods, the basis for the calculation of damage for each operation cycle has been established. The next subsection deals with the calculation of the load spectrum using rainflow counting.

2.2 Calculation of load spectra

The frequency distribution of the load is called load spectrum. In most cases, the time function of the load, for example a force or torque signal, is measured. To calculate the load spectrum from the given load-time function, an exact definition for the counted loading cycle is needed. In literature, several counting algorithms are given to determine the load spectrum, see for example [4], [5]. Mostly, the load-time function is discretized into equally spaced classes, maxima and minima are determined and counted in some way. There are algorithms that only count amplitudes of oscillations and so called two-parametric methods, that additionally take into account the mean values of the oscillation [4]. The resulting loading spectrum depends on the selected counting algorithm and therefore, the method should be chosen with respect to the specific application.

One of the most popular methods is the rainflow counting algorithm, which is chosen for this application. The rainflow counting algorithm is a two-parametric method which does not count single oscillations, but complete hysteresis loops, see [4]. As a result, the distribution of maxima and minima is known, and the distribution of amplitudes and mean values can easily be computed.

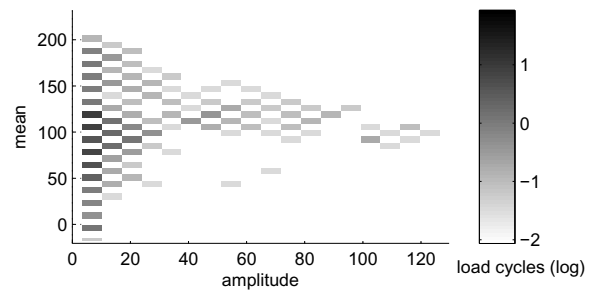


Figure 3: Histogram of load cycles

To avoid residual uncomplete loops, the counting can be started at a global extremum.

Considering commercial vehicles, the load spectrum of each operation cycle can be calculated separately. Figure 3 shows a histogram of the average number of load cycles per operating cycle calculated with the rainflow method. The color represents the logarithmically scaled number of cycles.

The next step in damage calculation is the computation of stress spectra out of the loading spectra. Therefore, the critical location of the component has to be taken into account as well as the combination of additive loads. Furthermore, multiaxial states of stress have to be reduced to uniaxial ones. The calculations differ with the application and can be taken from literature, e.g. [5].

2.3 Damage accumulation

To calculate the damage to a machine component, the endurable stresses have to be determined. Basis of this procedure are the Wöhler curves (S-N-curves) for the certain material and conditions. Because a Wöhler curve only shows the endurable number of load cycles with a constant amplitude, the damage due to all amplitudes have to be combined to a cumulative damage. A number of hypotheses are known for this procedure, which is called damage accumulation [4], [5].

The most simple and most popular one is Miner's Law, which is a linear hypothesis and assumes that oscillations with the same amplitude lead to the same damage, and all fractions of damage are simply accumulated. Therefore, an abstract damage function D is designed, which starts at 0 and increases to 1 which is equivalent to fracture. With n_i as the number of oscillations with an amplitude of the i -th class and N_i as the endurable oscillations with the same amplitude, the cu-