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Optimization of preventive maintenance and spare part provision for machine tools based on variable operational conditions

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ABSTRACT

The reliability of machine components depends on their operational conditions. In order to maximize this reliability, the preventive maintenance intervals and the provision of spare parts have to be adapted to the individual load collectives. Up to now, there has been for different machine components no comprehensive approach to quantify the effect of load collectives and to adapt the respective actions accordingly. This paper presents a method which calculates the optimal time for preventive maintenance and spare part provision by a stochastic optimization algorithm based on a load-dependent reliability model.

1. Motivation and objectives

Operators of production facilities depend on the high reliability of their machines as one of the key factors for an efficient production. Thus, it is necessary to adopt appropriate and well-scheduled activities regarding maintenance or spare part strategies, for instance, to assure a specified reliability level throughout the machine's service-life. As a consequence, binding reliability predictions are demanded within the scope of reliability-based warranty or service contracts [1–3]. In order to determine the required key figures and optimize these activities, the best possible estimation of the remaining component service-life is necessary. Since the load profiles of machine tools vary considerably, this estimation needs to take into account the loads which a certain component has been subjected. Therefore, the paper at hand aims at presenting an approach which allows for a load-dependent reliability analysis and prediction at component level in order to calculate the optimal time for preventive maintenance and the provision of spare parts. Initially, the load-dependent reliability function is derived (Section 2.1). Then the necessary parameters are estimated based on complete (Section 2.2) and incomplete data (Section 2.3). The feasibility of the method is demonstrated by applications in field.

2. Derivation of a load-dependent reliability function

2.1. Generalized Log-Linear Model

Initially, the load-dependent reliability function has to be derived. The *Weibull Distribution* [4,5] is commonly used to describe the stochastic failure behavior of machine components and can therefore be applied to estimate their service-life for a certain probability [6]. But the *Weibull Distribution* was designed for failures occurring under similar loads. In the field however, load collectives can vary considerably for machines performing processes with, e.g. different materials or different cutting speeds. Since the commonly used form of the *Weibull Distribution* does not include load impacts, it cannot be used to estimate the remaining service-life under different time-varying loads. The model used in this approach is based on the *Weibull Cumulative Damage Model*. This model is an extension of the *Weibull Distribution* taking time-varying loads into account. In combination with the *Generalized Log-Linear Model* the model has been widely used in accelerated life testing [7]. In the *Weibull Cumulative Damage Model* the *Weibull Distribution* is related to a cumulative damage caused by different loads. The general form of the model is described by the following formula:

$$F(t; L) = 1 - e^{-(W(t;L))^{\beta}} \tag{1}$$

The shape parameter β is considered to be load-independent and, therefore, constant as a characteristic parameter for a specific type of failure [4]. The term $W(t;L)$ represents the normalized cumulated damage which is a function of time t and a load vector L. It replaces the normalized service-life t/η of the *Weibull Distribution* since the scale parameter η is considered to be load-dependent. In the *Generalized Log-Linear* form it is written as

$$W(t; L) = \int_0^t e^{a_0 + \sum_i a_i X_i(t')} dt' \tag{2}$$

In this formula a_0 and the a_i are model parameters, t is the variable for time and X_i is a transformation of the load levels L_i. The kind of transformation depends on the type of load. For example for mechanical stresses this is – according to the *Power-Law* – the natural logarithm [7]. Furthermore, this model allows for the calculation of the remaining service-life at any time for any probability using the conditional probability based on previous loads and a predicted future load profile.

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2.2. Estimation of reliability parameters with complete data

The statistical estimation of the parameters of the *Weibull Generalized Log-Linear Cumulative Damage Model* requires data about the component's lifetime and about the corresponding loads. For every single failure a corresponding load profile is necessary. In most cases, a functional description of the load profile over time is not available. There might be a continuous functional description of the frequency distribution $f_i(L_i)$. In this case a characteristic load level is calculated as the weighted expected value of the frequency distribution.

$$W(t;\, f_i(L_i)) = \left(e^{a_0} \cdot \prod_i \int_{-\infty}^{\infty} e^{a_i X_i(L_i)} \cdot f_i(L_i) \cdot dL_i\right) \cdot t \tag{3}$$

Storing the load collectives in load classes has proved to be applicable in practice. The load classes form a discrete frequency distribution of the occurring loads. The more classes are used, the more accurate the load collective can be described. Nevertheless, the classification always entails a data loss because the real loads are not stored. To analyze this data, the load classes can be transformed into a continuous frequency distribution for the loads. The parameters of this distribution can be obtained by Maximum Likelihood Estimation [7].

2.3. Estimation of reliability parameters with incomplete data

Analyses have shown that in the machine tool industry complete data, as used in Section 2.2, is not always at hand when dealing with reliability issues in practice. Therefore, an approach was developed which aims at the estimation of the necessary reliability parameters if data is incomplete. It distinguishes between two cases. Case one deals with the fact that some failure data is available but exact information about the load profile is missing, whereas case two aims at estimating the reliability parameters based solely on expert knowledge [6].

This section focuses on case one with input information at component level consisting of failure modes, failure causes and the times to failure. Initially, this approach focuses on fatigue failures. Fatigue failures occur when components are subjected to a large number of cycles of an applied stress. With fatigue, components fail under stress values which are much below the ultimate strength of the material. Those failures are estimated to be responsible for 90% of all mechanical failures since loads on the components usually are not constant but vary with time [6,8]. However, the main methodology can be applied with some modifications to other failure modes as well. Often the problem is that the type of stress is known but its absolute value is unknown. In order to estimate the load-dependent reliability parameters the approach is divided into the following steps:

1. Realization of a *Weibull* analysis to estimate the shape parameter β of the distribution function.
2. Substitution of the scale parameter η by a suitable life-stress transformation.
3. Estimation of the load-dependent parameters using the *Generalized Log-Linear Model* in combination with a component *Wöhler Curve* (also known as *S–N Curve*).

The shape parameter β is determined to be load-independent whereas the scale parameter η is load-dependent [4]. Since the approach focuses on non-thermal and mechanical stresses in particular, the application of the *Power-Law* was proven to be the suitable life-stress transformation given by

$$\eta(L) = \frac{1}{KL^n} \tag{4}$$

By using the *Power-Law* the scale parameter η, often referred to as the characteristic lifetime, is estimated depending on a constant load L and two constant model parameters K and n which have to be estimated and kept constant [7]. By analyzing the load profile it is possible to determine those parameters. If this load profile is not available, the theory of the integrity of operation is used to integrate mechanical load aspects by using the *Component Wöhler Curves*, also known as *S–N Curves,* to close this information gap. This is possible since the failure modes and causes, in this case fatigue failures, are known. The curves describe the relation between the number of cycles t and the stress amplitude σ_a up to the point where a specific failure (e.g. a crack) occurs with a certain probability [9].

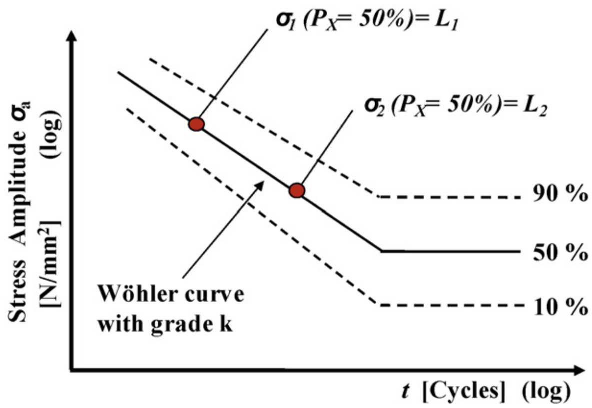

Fig. 1. Usage of the Component Wöhler Curve (S–N Curve).

As shown in Fig. 1 it is necessary to choose two load levels L_1 and L_2 of the *Component Wöhler Curve* characterized by a stress amplitude σ_a, a probability of failure x (e.g. 50%) and the number of cycles to failure t in order to set up a system of equations to solve for the parameters K and n. The parameters can then be calculated by

1. Definition of a reliability function for two load levels:

$$\text{load level } 1: x = 1 - e^{-(K L_1{}^n t_1)^\beta} \tag{5}$$
$$\text{load level } 2: x = 1 - e^{-(K L_2{}^n t_2)^\beta} \tag{6}$$

2. Set up of a system of equations:

$$1 - e^{-(K L_1{}^n t_1)^\beta} = 1 - e^{-(K L_2{}^n t_2)^\beta} \tag{7}$$

3. Solution for the parameters (note that the parameter n is equal to the grade k of the *Wöhler Curve*):

$$n = \frac{\ln(t_2/t_1)}{\ln(L_1/L_2)} = k \text{ and } K = \frac{\sqrt[\beta]{-\ln 0,5}}{L_1^n t_1} \tag{8}$$

At this point, all parameters of the load-dependent reliability function are determined and can be used for prediction purposes. But in practice specific *Wöhler Curves* for all components do not exist since the process of determination can be very complex and expensive, depending on the type of component that is to be analyzed. The results obtained from using the basic *Material Wöhler Curves* instead, which are available for most materials, are not sufficient. In this case the so-called *FKM guideline* allows for the arithmetical derivation of a *Component Wöhler Curve* [9,10]. This guideline helps to set up *Component Wöhler Curves* taking into account information about the component such as roughness or tensile strength. Fig. 2 shows the general derivation of a *Component Wöhler Curve*.

Component Wöhler Curves can be determined by using the functional relationship of Eq. (9). The calculation of the single parameters is carried out according to the *FKM guideline*.

$$N = N_D \left(\frac{\sigma_a}{\sigma_D}\right)^{-k} \tag{9}$$

The number of cycles at fatigue limit N_D depend on the type of material and on the component. It can be derived from parameter