Sensorless automated condition monitoring for the control of the predictive maintenance of machine tools

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1. Introduction

The operational availability of machine tools is an essential prerequisite for the profitability of the manufacturing industry. Maintenance is driven by increasing cost effectiveness. It is state-of-the-art to use accessory measurement systems to analyse bearing failure or shaft unbalance conditions. This paper presents experimental results and specific SACM algorithms for signal analyses on the wear of feed drives.

A common characteristic of the components examined is the rolling contact. Rolling contacts show wear in a typical sequence. When used in the Hertzian contact stress range a micro-damage is caused in the metallic structure. Due to many load cycles and roll-overs pitting or peeling occurs eventually. If the surfaces of the rolling pairing are damaged, failure, caused by wear, is due within a short period of time. Surface damages can be caused by different loads or environmental influences. Loads and environmental influences, such as overload, corrosion and dirt, often cannot be fully taken into account for the design and can partly change during operation. The change of the surface or the geometry of the counter parts is ultimately the cause of failure.

Generally, damages release energy, which is converted into vibrations. It is therefore possible to record and describe damages by examining the signal energy and signal power [1]. The damage types have different effects. They cause measurable physical phenomena, the signal characteristics of which permit a classification into damage types [2].

1.1. Periodical damages

Periodical damages produce signals, which are caused by periodical impulse-like excitation. The cycle period depends on the relative speed of the components. Hence a characteristic frequency is generated, which can be clearly assigned to the components involved. It can be observed that the impulse sequences show modulations [3]. Periodical damages cause impulses with a speed-dependent frequency. This frequency excites the resonance frequencies of the components. Increasing wear causes a rise of the amplitudes of the excitation frequency and the resonance frequencies. At the same time the resonance frequencies shift down. The shift is caused by non-periodical damages, e.g. loss of stiffness and change in friction [4].

1.2. Non-periodical damages

Non-periodical damages do not appear in a cyclic manner. They can occur spontaneously in time and place, discretely, in irregular sequence or for an indefinite period or length. Their signal aspects do not show any specific, speed-proportional frequencies. This damage type is, for example, caused by a change in friction or stiffness of a component [5]. For the modelling of mechanical components non-periodical damages are described by linear and non-linear variables. Non-periodical damages can be recognized by means of physical parameter estimation procedures or state observers [6].

1.3. Characteristic wear parameter

Spectra of damage-free components, which are caused by constant excitation, are mainly determined by mechanical imperfections, such as pitch errors and unbalances. If wear is to be described by a characteristic parameter, three effects need to be taken into account:

1. Damages produce impulse-like excitations
2. Resonance frequencies move due to increasing wear
3. Interferences of excitation and resonance can occur due to shift

Measurements are taken at constant speed so that vibrations are excited uniformly and transient excitation is avoided. Therefore it
should be possible to interpret the position and or the speed signal to 
detect wear.

2. Test bench

In order to examine the wear on components of a feed drive, 
such as coupling, fixed bearing, floating bearing, ball screw drive 
and linear motion guides, a test bench was set up with standard 
components which were assembled on a machine bed. The 
machine table had a working range of 800 mm. During the tests 
there was always at least one component that was worn out under 
real conditions. In this paper we will focus on the example of a ball 
screw drive.

2.1. Test procedure

Time-accelerated but wear-equivalent tests were conducted on 
the test bench. Their goal was to record and quantify signal 
characteristics, which were caused by wear, and to assign them to 
different wear conditions, taking only the physical values which 
are used in the machine control. Control-internal signals are 
recorded, out of which a characteristic parameter based on 
vibration energy is calculated. The velocity values from the rotary 
encoder and the linear encoder were recorded at 4 kHz. For other 
parameters which are based on positioning accuracy a laser 
interferometer was used for the linear position measurement.

It is hard to achieve a natural wear of the feed unit, caused by 
fatigue, in adequate time. For the experimental analysis the wear 
progress was purposefully accelerated through contamination of the 
lubricant with abrasive materials. Nonetheless a damage type 
was caused which is close to reality. The signals gained are hence a 
suitable basis for the application and assessment of the developed 
algorithms.

The machine table is moved in double phases. During the first 
phase the table is moved back and forth twenty-two times 
twice between 200 mm and 400 mm at a speed of 10 metres per minute. 
Because of the contamination of the lubricant with abrasive materials a zone of increased wear is created. During the second 
phase the data is collected. In order to achieve a statistically 
reliable data basis, the table is reversed eight times. This occurs at a 
speed of three metres per minute. The whole cycle hence consists 
of thirty back and forth-movements.

2.2. Enhanced positioning accuracy

The data of the indirect position sensor (rotary encoder), which is 
built in the feed motor, and the data of a direct position 
measurement system (laser interferometer or linear encoder) are 
used for analyses. Fig. 1 illustrates the principle measurement setup.

The data of the indirect measurement system and the data of the 
direct measurement system are recorded synchronously. The 
control system does not compensate any position errors resulting 
from spindle pitch errors, thermal drift or wear. The indirect 
position is being controlled according to the reference value. The 
direct actual position measurement of the laser interferometer shows 
all mechanical imprecisions.

While the table is moving at steady speed, the measuring 
system continuously records both values. The collection and 
interpretation of the data was implemented in the hard- and 
software of the CNC-control.

3. Data analysis

3.1. Positioning accuracy based data analysis

In the course of the experiments drive- and operation-specific 
characteristic parameters of wear have been derived and tested. 
The analysis has been done by comparing the signals of direct and 
the indirect measurement system. Model based analyses were 
not involved. The following characteristic parameters were 
considered:

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\text{Mean deviation} : R_i = \frac{1}{n} \sum_{j=1}^{n} x_{ij} \\
\text{Reversal error : } B_i = \bar{x}_i - \bar{x}_i \\
\text{Repeatability : } R_i = |R_i| \pm 2s_i
\]

The reference position is being approached several times from 
positive and from negative direction. The difference between set 
value and actual value is calculated. This is done for several runs. 
The arithmetic mean is determined for each direction.

It indicates how great the difference is when a target position is 
first reached from one and then from the other direction. The mean 
values from one direction are deducted from the mean values 
of the other direction.

It indicates how strongly the measured values of the runs fluctuate 
around their mean value. The positional deviation and the reversal 
error record systematic errors. The repeatability records stochastic 
errors in the form of standard uncertainties $s_i$.

The collection of the measurement data is different from the 
procedure suggested in [7]. In order to understand wear 
phenomena more precisely, it is necessary to process measure- 
ment values continuously instead of processing measurement 
values only at certain positions. While the table moves at steady 
speed, the measurement values are collected continuously with a 
high sample rate. The implemented data collection algorithm is 
therefore called “enhanced positioning accuracy measurement”.

3.2. Vibration energy parameter

The vibration energy parameter $P_{vib}$ describes the changes of 
the energy which is converted into vibrations. The difference 
between the current condition and the initial condition of the 
machine is considered.

This evaluation is generally possible both in the time and 
frequency domain. The phase shift of the signals of the initial 
condition does, however, represent an almost irresolvable 
problem. In order to make a direct comparison of time-based 
signals, the signals need to be recorded in an exactly reproducible 
manner. The kinematics of a ball screw drive do not permit that. It 
is required that, at the trigger moment, all moved elements 
(spindle and balls) have to be in the same position each time. It 
even has to be assumed that this is generally not possible due to 
slip. In the frequency domain, however, amplitude and phase 
position can be separated. Hence the effect of signal extinction due 
to interference caused by phase-shifting can be avoided.

The auto correlation spectrum after a discrete Fourier- 
transformation (DFT) permits the separation of amplitude and 
phase. For the interpretation of the vibrational energy only the 
amplitudes are considered. Therefore the analyses takes place in
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