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

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ABSTRACT

Modern manufacturing systems are characterized by numerous interacting machine tools each with sophisticated maintenance. In order to be competitive, it is possible to reduce the system downtime by applying sensorless automated condition monitoring (SACM). This paper presents newly developed and tested SACM-algorithms based only on signals which are available in position controlled drives such as position, speed and motor current. The algorithm is based on comparing current characteristic parameters with those which were taken when the machine was new.

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

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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 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:

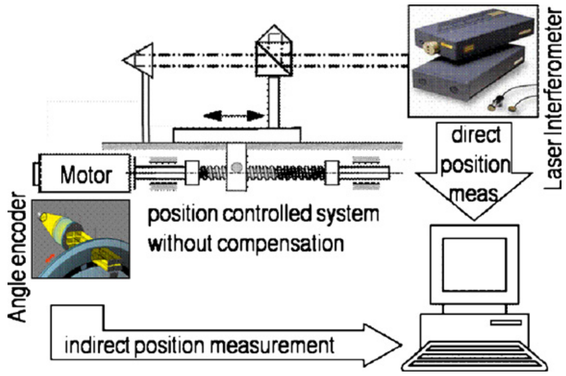

Fig. 1. Measurement setup.

$$\text{Mean deviation}: \bar{x}_{ij}\uparrow = \frac{1}{n}\sum_{j=1}^{n} x_{ij}\uparrow \tag{1}$$

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.

$$\text{Reversal error}: B_i = \bar{x}_i\uparrow - \bar{x}_i\downarrow \tag{2}$$

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.

$$\text{Repeatability}: R_i = \bar{x}_i\uparrow \pm 2s_i\uparrow \tag{3}$$

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 measurement 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 hence an extension of the methods for recording the positioning accuracy suggested in [7]. The method 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