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Friction Variances of Linear Machine Tool Axes

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Abstract

Friction and damping have a wide influence on machine tools’ dynamics. The statistical spread of identical machine tools’ friction and components’ influence on it are marginally known. In order to reduce this lack of knowledge, measurements of friction in linear axes of identical machine tools were performed.

In the course of this paper the variance of friction in a single axis is determined as well as the difference between several machine tools. Different types of feed drive systems, ball screw and linear motor driven, are measured and compared. The measured friction curves are used to estimate parameters of an extended Stribeck friction model.

As a result, a method of measuring and analyzing friction in machine tools is developed and the evaluated parameters can be used for observing the assembly process, for condition monitoring, for on-board diagnostics and for scatter based parameterization of simulation models.

1. Introduction

Decreasing lifecycle, increasing number of functionalities and further increase of achievement potential in machine tools enforce computer-aided construction and simulation tools. The mechanical behavior of components except damping is available either in libraries or can be measured easily. However, the behavior after assembly is marginally known. That means due to the high effort to measure as well as the availability of machine tools, the parameters needed for simulation of machines of such a high complexity are often validated with measurement of an unique machine. From this it is obvious that mounting errors and tolerances are not observable. Furthermore the variation of parameters during machine life is hardly evaluated. Therefore validity of simulation models and value of their results are disputable.

This paper describes examination of friction in equal machine tools by using automatically generated NC-programs. These measurements are performed on two different types of machine tools. In each case three linear axis either ball screw or linear motor driven are examined. These are produced by two machine tool makers. Measurements of nearly identical ball screw and linear motor driven axes are described. It is shown even with a single measurement mounting errors are be observable and by comparison of several measurements mechanical properties can be determined. These can be used for quality management as well as condition monitoring. Furthermore machine tools’ mechanical behavior is comprehended better and the validity of simulation models is improved.

2. Measuring method and signal processing

2.1. Measuring method

A machine tool is a complex mechatronic system. It is combined of CNC control unit, controller, electronics and mechanical system, as shown in Fig. 1. It is nearly impossible to integrate external sensors or analyze devices separately in machine tools produced in serial
production. Therefore the internal measuring devices must be used.

![Fig. 1. Schema of machine tool as mechatronic system](image)

Measurements were taken on new metal cutting machine tools during start-up direct before shipment to customers and machine tools at the producer’s own shop floor. To measuring trace-functionalities provided by the NC-controller were used. Thereby the effort of measuring with regard to costs of external sensors and measurement computers as well as the duration and the needed operators for installing these can be reduced tremendously. Automatically generated NC-programs are used to generate velocity and position as input signal. Since machine tools are expensive industrial goods with high machine hour rates, it is necessary to keep the duration for measurement as short as possible. Especially for low velocities which are needed for identification of sticktion and mixed friction are time-consuming if measured over the complete stroke length. Furthermore the data volume which must be buffered in the NC-controller is correlated with the duration. To solve this challenge a procedure was developed which only measures friction at certain ranges. In between these the carriage is moved with rapid traverse. In Fig. 2 the measuring procedure is shown schematically. The continuous curve shows a measurement with constant velocity over the complete stroke and the dotted curve the here developed measuring method. The friction curve is measured at the first range. Afterwards it is moved with rapid traverse to the second measuring range. Between the measuring and the rapid traverse the axis is stopped to avoid influences of acceleration on the armature current. The reduction of time effort is obvious.

![Fig. 2. Scheme of measurement process (a) velocity over measuring positions 1-3 (top); (b) time saving during the measurement (down)](image)

To generating such a NC-program only few parameters like end positions of the axis, minimum and maximum velocity, number of velocity steps and number of measuring points have to be set. Thus reduces the possibility of programming errors which might cause collisions as well as time effort for programming.

The main advantage of using trace-functionalities provided by the NC-controller and NC-programs is measurements can be done at customer’s facilities with equal conditions within distinct maintenance intervals. Thus changes can be observed. That means these results can be used for condition monitoring and preventive maintenance, [1, 2]. However it is impossible to observe the friction force respectively torque directly but it can be calculated with the torque constant $K_r$ of the motor and the steady state of armature current $I_A$, as described in equation (1). Here thermal and magnetic dissipation of identic servomotors are assumed to be equal.

$$M_{Motor} = K_r I_A$$

Using trace-functionalities and automatically generated NC-programs permit to collect a set of parameters with minor effort.

### 2.2. Static friction model

Friction behavior of machine tools is discussed in several articles, e.g. [3-6]. However mostly Strubeck friction which is a combination of three different friction characteristics is used for description. These three characteristics are the constant coulomb friction $F_C$, the
velocity proportional viscous friction $f_v$ and the exponential decreasing mixed friction containing Stribeck coefficient $f_s$ and an exponent $v_s$ observable. The mixed friction is exponentially decreasing and only measurable at slow velocities. The resulting friction force $F_R$ is described by following equation (2), [4, 5].

$$F_R = F_C + f_vv + f_s \exp\left(-\frac{v}{v_s}\right)$$ (2)

However it turned out this friction model doesn’t satisfy axes driven by ball screws with small pitch and big diameter. That means having many rolling contacts leads to divergences between the model and the measurement. This kind of rolling friction causes a digressive characteristic at high velocities, Albrecht [6]. To solve this modeling issue one more friction component is introduced, containing a rolling friction coefficient $f_w$ and an exponent $k$.

$$F_R = F_C + f_vv + f_s \exp\left(-\frac{v}{v_s}\right) + f_wv^k$$ (3)

### 2.3. Parameter estimation

For fitting friction model described with equation (3) to measured curves parameters have to be estimated. Therefore least square method an often used operation for parameter estimation which minimizes the squared distance between measurement and model is used. For certain kinds of objective functions it also becomes possible to estimate nonlinear functions like friction [7, 8].

For the estimation negative and positive velocities are observed separately, to realize direction dependencies. Furthermore to avoid influence of the controller and inertia measurements were taken after arriving steady state. The look-ahead functionality and friction compensation were deactivated.

### 3. Friction in linear axes

#### 3.1. Comparison of ball screw and linear motor driven axes

Typical systems for generation feed in machine tool axis are ball screws and linear motors. Linear motor driven axes have a simpler mechanical construction than ball screw driven axes. This means there are fewer mechanical contacts, especially in the spindle nut, generating friction. Schematic constructions of these axes are shown in Fig. 3.

The differences in the mechanical construction can be observed in the measured friction force, too. In Fig. 4 are typical measured curves of axes with similar carriage mass and covers and equal linear guides. The figures are representative results of measurements of several equal machine tools.

The friction of axes driven by linear motor, Fig. 4(a), confirms the friction behavior of linear guides described by Ispaylar [3] with a small nearly constant friction coefficient. Compared with ball screw driven axes there is a deviation. It is caused by not compensated cogging effect of linear motors and the measuring method.

As expected is the friction in the ball screw drive Fig. 4(b), higher than in the linear motor driven axis. This can be explained by the higher number of surfaces in
contact. Furthermore the variance as sum of variances of each contact becomes higher. The different friction behavior especially the digressive roller friction can be explained with additional roller contacts in spindle nut and bearings. This digressive character is correlated with the number of roller contacts which can be seen by comparison of different types of ball screws. The velocity depending increase of friction coefficient depends on an increase of pretension at higher velocities described by Frey [9].

3.2. Identification of mounting errors due to one measurement

Horizontal axes have an almost constant friction. Hanging axes or quills have a strongly position depending friction. This position dependency is caused by counter mass or displacement of center of gravity. It can be shown under equal conditions the friction behavior of feed axes is repeatable. Horizontal axes are more comparable and discussed in the following.

Fig. 5(a) shows a position depending steadily changing friction force. It is caused by nonparallel linear guidances.

In Fig. 5(b) there are two measurements of the same axis. For low velocities the friction showed in the dotted line is much higher than the other. This is caused by a gripping of the splash guards and releases abrupt. The continuous curve is a measurement after that problem has been solved.

This shows it is possible to recognize mounting errors and problems even by measuring only a single machine.

Comparing several machine tools it becomes possible to define quality features and remedy failures.

3.3. Statistical spread and changing during machine life

Identical machine tools have similar friction characteristic. Assuming this friction behavior is normally distributed the mean value \( \mu \) and the standard deviation \( \sigma \) can be calculated from a set of measurements \( x_i \) as shown in equation (4) and (5). These can be used to calculate a confidence region \( \mu \pm 3\sigma \) within about 99.7%.

\[
\mu = \frac{1}{n} \sum_{i=1}^{n} x_i \quad (4)
\]

\[
\sigma = \frac{1}{n-1} \sum_{i=1}^{n} (x_i - \mu)^2 \quad (5)
\]

In Fig. 6 mean value and confidence region of friction of seven factory-new machine tools are compared with two in operation for several years. It is obvious the friction, especially viscous and roller friction, is decreasing during machine live. Run in processes in bearings and seals and wear cause this decrease. Certainly the decrease of roller friction is affected by wear caused diameter reduction of rolling elements. Friction measurement offers easily observable parameters which can be used for condition monitoring.

This means it is possible to determine parameters during start-up. Due to measure with NC-programs and trace functionalities, the same parameters can be measured automatically in certain intervals. Hence these parameters can be compared and used for condition monitoring.
4. Conclusion

Friction behavior is observable by NC-programs and trace functions. Therefore it is possible to estimate parameters for condition monitoring and quality management automatically. This measurement can be repeated in certain maintenance intervals and allows several significant improvements.

The confidence region can be determined by statistical methods. With its upper and lower boundary simulation models can be parameterized and the influence on dynamical behavior can be observed.

Furthermore with characteristics measured during start-up it becomes possible to identify problems and correct them purposeful. Here it is shown only by measuring a single machine problems like gripping of splash guards or errors in parallelism of guidances can be detected. By comparison of several measurements the correlation between component and effect should become better.

Last but not least there is the possibility to get information about machine’s condition by continuous observation for parameter changes. This is useable for condition based maintenance planning.

In further work the database should be increased. This means further measurements of new machine tools as well as during machine life are necessary. Furthermore other kinds of machine tools should be measured to receive a more general statement.

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