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Modeling of Passive Forces of Machine Tool Covers*

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Abstract
The passive forces acting against the drive force are phenomena that influence dynamical properties and precision of linear axes equipped with feed drives. Covers are one of important sources of passive forces in machine tools. The paper describes virtual evaluation of cover passive forces using the cover complex model. The model is able to compute interaction between flexible cover segments and sealing wiper. The result is deformation of cover segments and wipers which is used together with measured friction coefficient for computation of cover total passive force. This resulting passive force is dependent on cover position. Comparison of computational results and measurement on the real cover is presented in the paper.

Key words: Machine Tool Cover, Passive Force Modeling, Passive Force Compensation

1. Introduction

Mathematical modeling of machine tool main structures is nowadays in very advanced stage already. That is the reason why manufacturers also begin to focus on other machine tool components, e.g. telescopic covers.

The concept of virtual machine enables us to provide virtual testing of machine tool prototypes. Therefore the machine properties could be directly computed instead of properties prediction from indirect parameters like statical and dynamical stiffness. Complex modeling of feed drive axes [(1) (2)] is one of possible tools for prediction of movable axes accuracy. Better results of these models can be reached with results of models of other mechanical components. Especially modeling of covers is important for building more reliable models of feed axes.

Covers are very important parts of machine tools. They have direct impact on machine reliability and components lifetime. The most common design of modern covers is telescopic cover, which consists of sheet metal segments, polyurethane sealing wipers, guiding scissor mechanisms and other components. However, covers are also source of passive forces. Therefore they could influence feed drives and they could have significant impact on machine accuracy, especially during slow motion (stick-slip effect). They also increase power demand on drives.

Chapter 2 deals with experimental tests on existing machines. Influence of passive forces on machine tool will be demonstrated and discussed on examples of two different machines.

Chapter 3 deals with complex model of cover. Experiments on test bed described in chapter 4 are used for verification of computed results.

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2. Experimental Tests on Existing Machines

Measurement on Vertical Milling Machine

A measurement of passive resistance force of covers has been done on the 3-axes milling machine. This machine is a vertical milling centre with horizontal cross table (X and Y axes) and vertical spindle axis Z. The table axes are covered by 4 covers (2 covers per axis).

Figure 1: Tested vertical milling machine.

The total resistance force has been determined by measurement of motor current. The results are presented on Fig. 2 and Fig. 3. There is no inertial force during continuous motion with constant speed so the measured current shows the force necessary to deal with passive resistance mostly caused by friction.

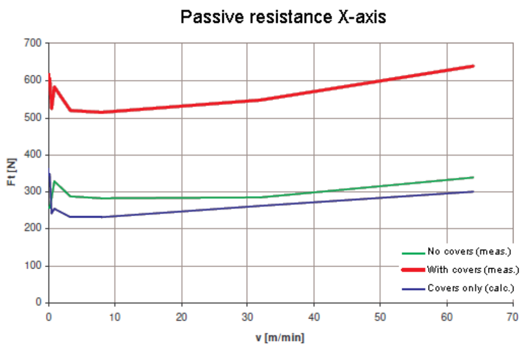

Figure 2: Results of measurement of X-axis.

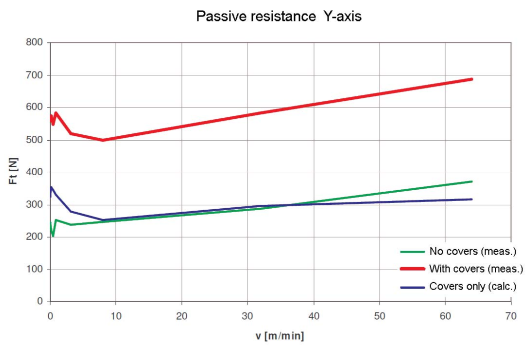

Figure 3: Results of measurement of Y-axis.

Subtracting resistance force of axis without covers from force of axis with covers mounted gives the value of force necessary to cope with covers. It can be seen on previous pictures, the cover passive force is responsible for approximately 50% of whole passive force in this case.

The fact that power consumed by cover movement may achieve very high percentage of total power implies the necessity of prediction of passive resistance prior drive design. This prediction can be made by mathematical model in case of development of a new machine.

Measurement on horizontal milling machine

A simulation of circular interpolation has been verified on XY vertical table of horizontal milling centre.

This milling centre is equipped by two-axis cover that is able to move in two directions simultaneously. That means the cover is moved by lighter Y axis which is positioned by heavier X axis.

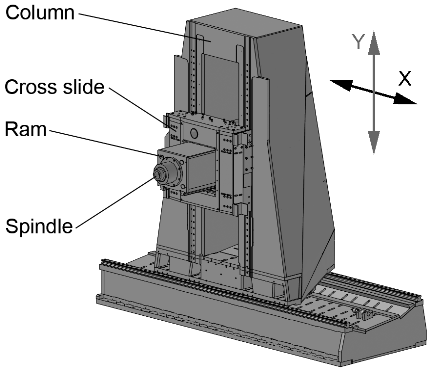

Figure 4: Horizontal milling centre

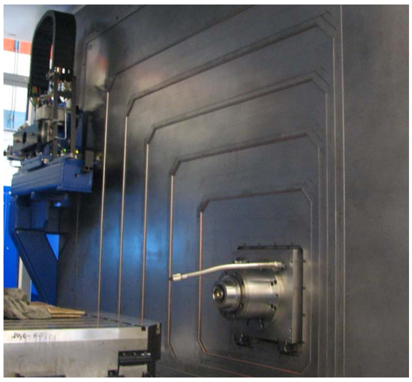

Figure 5: Two-axis cover on horizontal milling machine

A model with linear force increase has been developed to simulate frictional behavior of axes. This model substitutes the discontinuity between static and dynamic friction by two linear curves. First steep curve represents growth of friction up to value of Coulomb friction. The second curve respects the effect of viscous friction (Fig. 6).

This friction model and model of movable axes [(2)] have been implemented into simulation model of circular interpolation.

The model parameters have been set up according to previous measurement to allow result comparison.

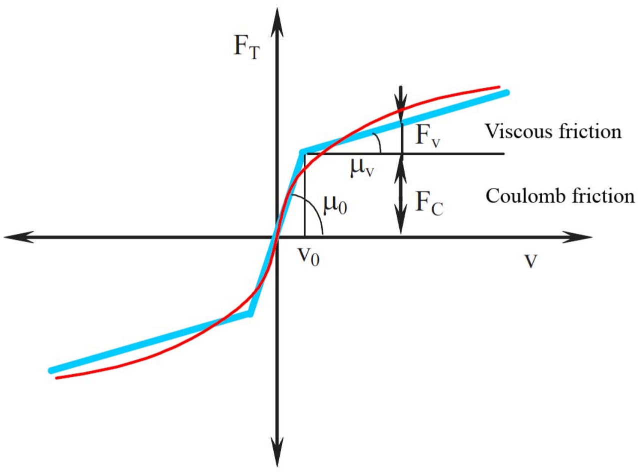

Figure 6: Friction model

Friction force is applied to a place of ball nut mounting interface. Simulated circle diameter is 50 mm; velocity is 7 m.min^{-1}.

Comparison between measured and computed results is shown on Fig. 7. The peaks in diagram show Coulomb friction values. Coulomb friction of X-axis is 4790 N, in case of Y-axis it is 1830N. We can also see bigger differences between both data sets in Y axis (vertical axis). The reason is, models of both axes used the same friction model. However, the cover has rectangular shape, therefore both movement directions have different total length of sealing wipers. This is not respected in the friction model, so the Y axis has worse concordance between simulation and model. It shows need of more accurate modeling of cover passive forces.

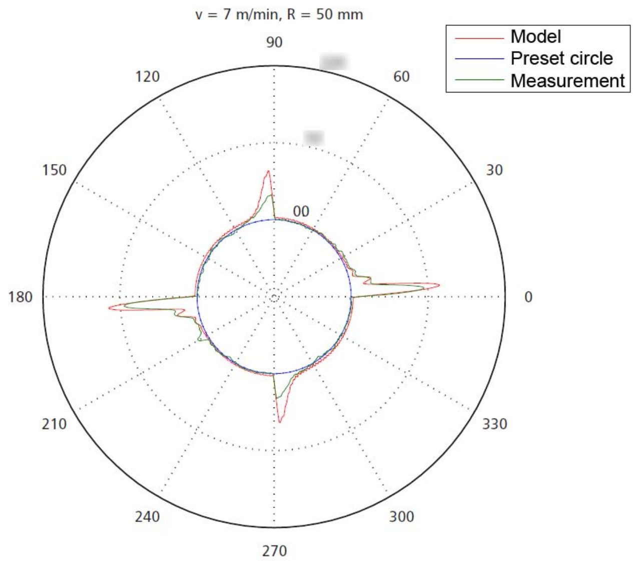

Figure 7: Circular interpolation plot

3. Structure of complex model

In order to compensate friction or / and inertial forces it is necessary to know the passive resistance of the axis and cover. For this and many other reasons a complex model of telescopic cover has been developed (Fig. 8).

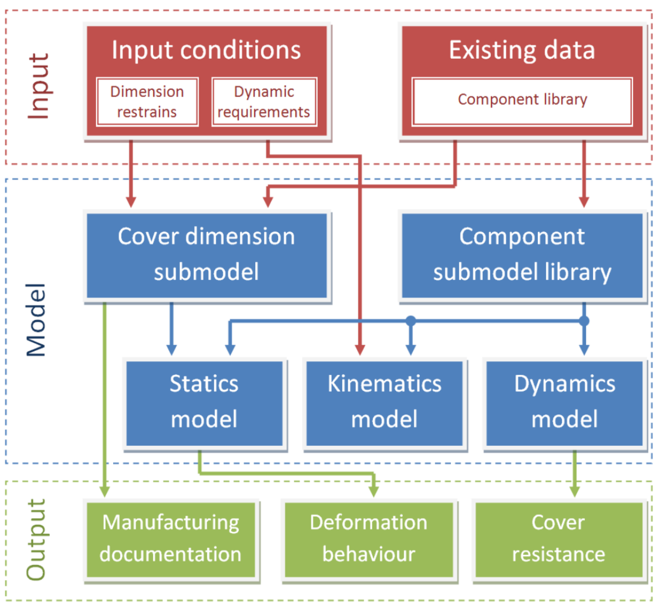

Figure 8: Complex model scheme

The complex model consists of three basic layers: input data layer, model layer and output data layer [(3)].

Input data

Input data layer acts as database of model settings. It consists of two main elements – input conditions and existing data.

Input conditions are information containing dimensional and dynamic restrains specified by the customer in the inquiry form. The existing data is a database of cover components – its physical properties and capabilities.

Model layer

The model layer contains mathematical models calculating physical behavior and interactions of parts according to specified input parameters and component properties.

This layer consists of several models and submodels.

The cover dimension submodel suggests all dimensions of cover optimized for required travel. Optimization is based on dimensional restrains of customer machine tool and dimensional parameters of used components. This assures minimal reasonable proportions for reduction of material consumption, inertial forces and costs.

The component submodel contains mathematical description of components behavior based on its specific properties (mass, stiffness). These characteristics are used in superior interaction models.

Very important submodel is submodel of sealing wiper (Fig. 12). The wiper submodel is based on Neo-Hookean hyperelastic constitutive model that is used for wiper mechanical response modeling. A 2D model was created for simulation of wiper interaction between cover segments. Plane strain conditions were assumed. Computational model includes PU wiper, clamping steel profile and interacting adjacent metal sheet. To simulate large deformation effects eight-node element PLANE 183 was used. Wiper interaction with clamping profile and metal sheet was represented by CONTA172/TARGE169 contact element. Example of wiper deformed shape is on Fig. 9. Stiffness characteristic of the wiper is bilinear – see Fig. 10. The model results have been successfully verified with experimental measurement.

Another substantial submodel describes polyurethane guiding slider. Sliders are guiding elements supporting cover segments (Fig. 13). Its frictional behavior has been measured and implemented into complex model. This submodel calculates frictional force according to overall slider length, specific frictional force (force per 1 mm of slider length), slider load and travel speed (Fig. 11).

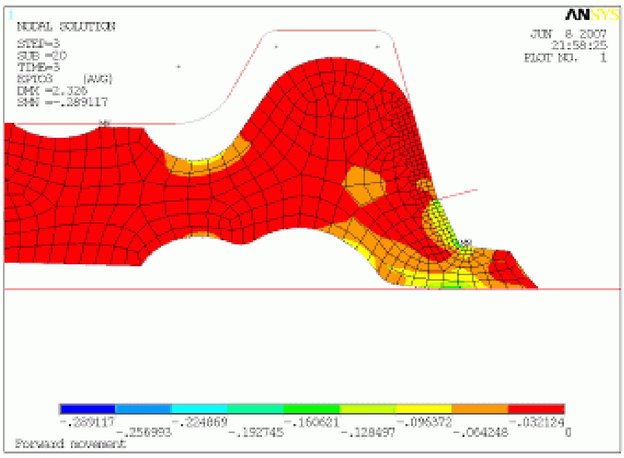

Figure 9: FEM model of deformed wiper

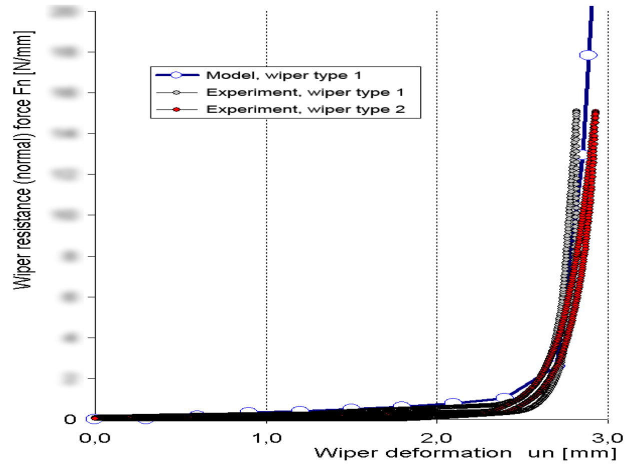

Figure 10: Bilinear stiffness characteristic

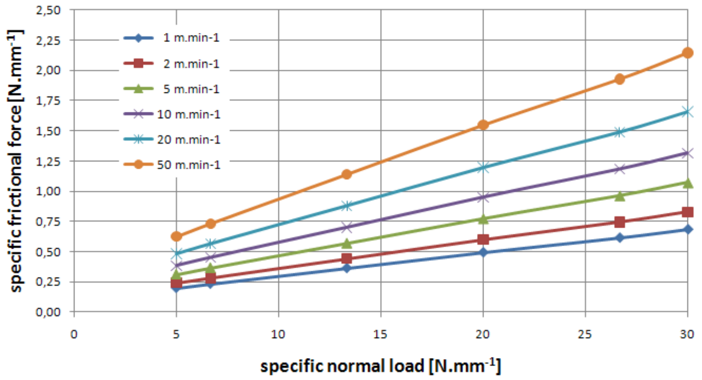

Figure 11: PU slider resistance – travel speed and load dependency

The statics model of cover calculates strain and deformation of particular components. It is possible to predict behavior of operational covers when function and life is concerned. This prevents unacceptable deformations and excessive loads of components.

The kinematics model describes motion of movable parts and mechanisms dependent on axes movement to reveal necessary space and possible collisions. It is also a data source for dynamics model of covers.

The dynamics model determines actual accelerations and dynamic effect on particular parts of a cover. Along with resistance forces (inertial and friction), these effects represent overall resistance against movement. Resistance is an error value important for axis drive dimensioning.

Output data

Output data layer contains information crucial for actual production and successful implementation of covers into machine tool. This information sets are the basis for automatically generated manufacturing documentation.

It also allows checking the behavior of operational covers – load, wear and deformation of components. That is important for designers to verify the sufficiency of their solution (Fig. 18).

The last output is overall cover resistance. This data are important for determination of drive axis load caused by covers. That is the very important information for customer.

Cover is usually one of the last parts mounted to the machine because it is requested when all parts of the machine (including drives) are specified for order or designed and ready for production.

Problem could happen if the cover was not taken into account during drive dimensioning. There is a significant difference in machine drive dynamics when cover is mounted to the machine. Drive positioning is less responsive and power consumption is 10-30 % higher in case of two axis covers.

Producer is usually unable to provide such an information, definitely not before the cover is produced. This model can estimate cover resistance during the price offer process before the cover is designed. These are parameters important for compensation.

That is the added value of the complex model.

Passive resistance by model

One of the complex model output is calculation of cover deflection used for estimation of normal force generated by wiper preload. This force can be transformed into friction force of wipers.

4. Verification

Results of friction force calculated by the complex model have been verified by an experiment.

Test setup and test conditions

Tested telescopic one-axis cover is mounted on a testing bed. The cover is supported by guiding rails and its rear side is actuated by movable table driven by a ball screw with Baumueller servomotor. The motor power is 2 kW and torque is 10 Nm. Ball screw diameter is 32 mm and the pitch is 32 mm. The feed drive axis is controlled by Baumueller drive controller in velocity loop. The value of current is recorded for further analysis by dSpace 1104 signal processor controlled by ControlDesk (Matlab/Simulink interface).

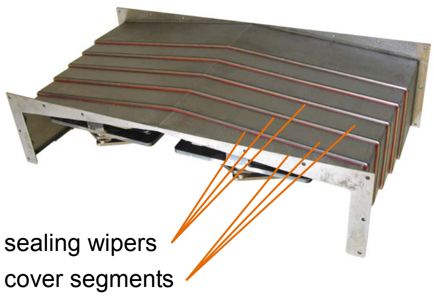

Figure 12: Tested telescopic cover

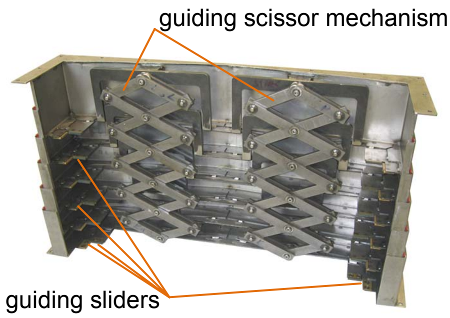

Figure 13: Bottom view of cover

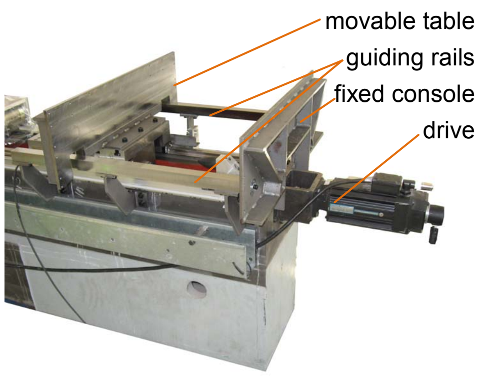

Figure 14: Testing bed

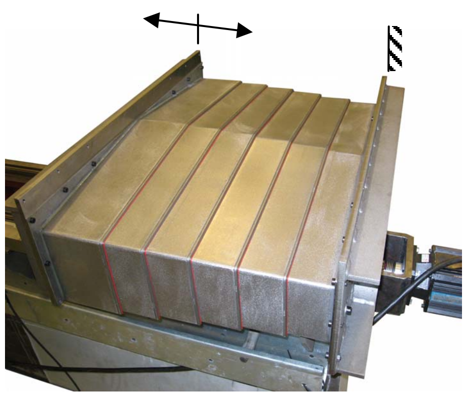

Figure 15: The testing bed setup with cover

The testing cycle has been set to extend the cover by 400 mm, remain stopped for 0.5 sec, return, stop and repeat the cycle. The extension / contraction velocity was 30 m.min^{-1}, acceleration / deceleration was 6.7 m.s^{-2}. The cover was running dry.

Test results

The recorded data of current values have been processed to plot corresponding force behavior. Fig. 16 shows the force behavior with and without the cover mounted.

The extension period consists of acceleration, constant speed movement and deceleration. The constant speed movement is the period for determination of cover friction resistance without influence of inertial forces.

There is also opposing force acting during idle period. This is due to drive tendency to keep the table still in desired position, while the decelerated movable table tends to overshoot this position by its inertia and causes constant preload of the drive when it stops. This effect becomes more significant in case of mounted cover.

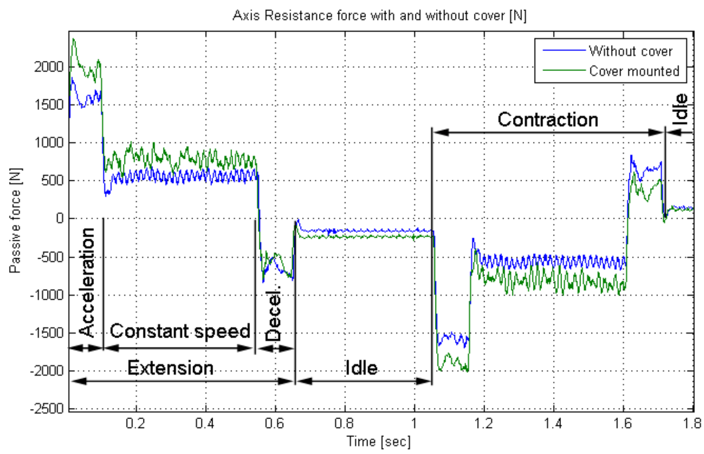

Figure 16: Resistance force of the whole axis with (green) and without cover (blue).

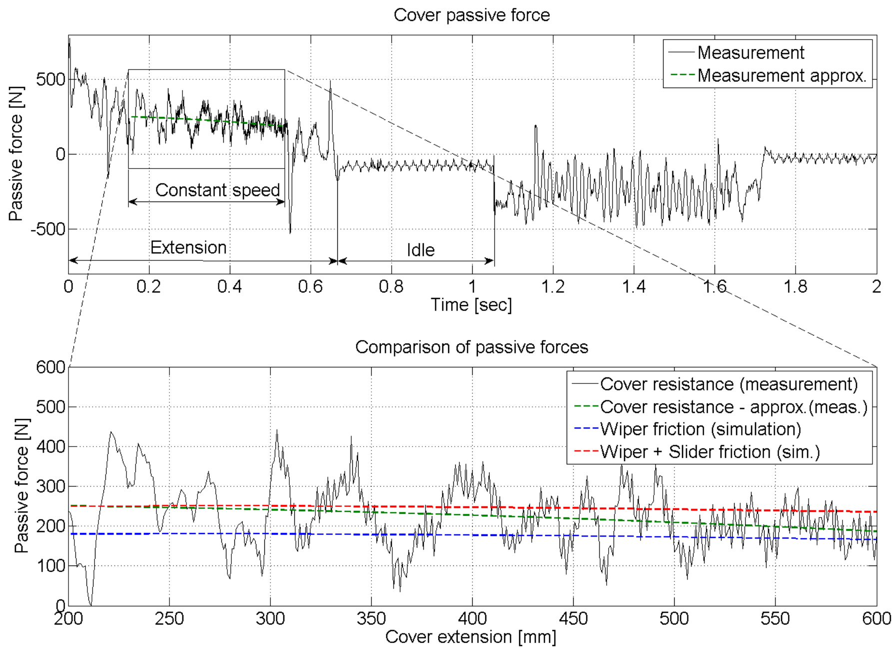

Figure 17: Comparison of measured and simulated passive resistance forces during cover extension.

Subtraction of characteristics with and without cover mounted gives behavior of the telescopic cover itself. Peaks show inertial forces during acceleration and stable parts of curves show value of the passive resistance during motion. Fig. 17 compares simulated and measured passive resistance of covers. The average value of measured friction force is approx. 220 N.

The high frequency fluctuation of measured force is caused by fluctuation of current of the motor during its rotation due to pole pitch. The low frequency fluctuation of measured force was not unfortunately identified. Because this fluctuation occurs also during movement without covers, it is probably problem of the test bed design.

Results discussion

The simulated values contain friction caused by wipers and sliders. The average value of simulated wiper frictional force is approx. 170 N. Slider frictional force calculated by model is 70 N.

The measured values contain overall passive resistance of the whole cover including sealing wiper and guiding parts. This measured values show dynamic friction. The average value of measured frictional force is approx. 220 N. The difference between model and measurement (Fig. 17) can be caused by factors described below.

Measurement	Simulation		Simulation
Overall cover resistance (wipers and sliders)	Slider frictional force	+	Wiper frictional force
220 N	70 N		170 N

According to the measurement, the friction force slightly weakens (Fig. 17). This phenomenon respects higher rigidity of the cover when contracted, because wipers are located above each other supporting each other. In this situation the metal segment cannot be bended by the wiper preload like it is when the cover is extended. When the preload is not released by segment deformation it applies more force to the cover generating more friction.

This confirms simulation of friction force and cover deformation caused by wiper preload – one of complex model results. [(4)] (Fig. 18)

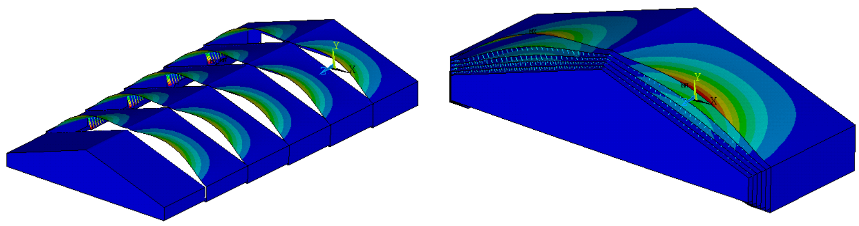

Figure 18: Deformation of contracted cover is higher than deformation of extended cover.

Factors affecting model accuracy

Unfortunately there are plenty of factors having substantial influence to result of the simulated value of passive resistance.

One unpredictable factor is the assembly process. The best assembly tolerance of wiper preload is +/- 0.2 mm. This can affect the result by 5 – 50% [(5)].

Under ideal conditions the friction is also dependent on its current extension of the cover as mentioned in previous chapter; and it is dependent on the current direction of movement as the sealing wiper produces more friction in one direction than in the other. These factors however seem insignificant in real situation.

Current version of complex model estimate static friction only. Real friction during movement is dynamic and is speed-dependent.

Other factors are temperature, age of material, friction contact conditions (oil, cutting fluid, dry friction).

Factors affecting machine axis dynamics related to covers

Inertial forces of cover are responsible for significant reduction of drive parameters during acceleration and deceleration of drive.

Frictional resistance and its changes is another factor limiting drive positioning precision. This paper describes methods of frictional resistance prediction in order to give information for its compensation.

Ratio of axis and cover weights is also very important. There is very often problem on cross table structures: one drive is weaker, because it accelerates just a table. Another drive is stronger, because it accelerates the whole cross slide and the table. But covers are similar on both axes, therefore the lighter axis positioning results are more afflicted.

5. Conclusion

This paper describes current stage of passive resistance model of covers. This model is a part of virtual machine concept.

Results of passive force measurement of machine axes and covers are presented as well as methods of their prediction. The differences between computed and measured average values can be caused by factors described in previous chapter.

The predicted value of cover passive forces can be used for more precise choice of drives during development process. The model is also able to predict cover passive forces in dependence on cover position and velocity. This data could be used as feedforward signal for quadrant error compensation. This application will be the next work.

Acknowledgement

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