VERIFICATION OF PREDICTION METHOD FOR ENERGY CONSUMPTION OF MACHINE TOOL FEED AXES

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Energy efficiency of electrical appliances is highly debated topic at present.This topic is transferred especially in industries where are the effects of savings much more significant due to higher energy consumption.In the case of machine tools is at present energy efficiency also a hot topic,basedon the Kyoto Protocol and the European Commission Regulation of energy appliances eco-design.Machine tool manufacturers already responses to this situation by using more efficient components (motors, pumps,etc...).This article focuses especially on determining the energy profile of the machine tool at the moment where the machine is not manufactured.It is used a method allows to simulate the energy profile of the machine tool. This is verified by measurement on the test device. Realized measurement was done under different loads of clamping table and under different feed rates. Average percentual error was achieved below ten percent limit.

KEYWORDS
energy efficiency, machine tool, feed axis, simulation, verification

1 INTRODUCTION

Energy efficiency and power consumption is currently one of the very discussed topic.It refers to a common population, and also all industry branches. The impacts caused by excessive energy consumption are reflected in the cost of production and processing of a given product, its final price and also to the environment. Same situation is also noticeable in processing and manufacturing.CNC machine tools are currently constituting the dominant market share of machine tools and at the same rate are represented in manufacturing companies engaged in chip machining.In order to allow these machines economically and efficiently operate, it is necessary to monitor their consumption[Augste 2013]to be able to predict certain phenomena which have demand on energy profile significant of given machine tool. It is thus necessary to have some available peripherals that allow the monitoring of energy consumption.Monitoring and assessment of the energy profile of a machine tool is possible only at the time when the machine is manufactured, assembled and put into operation.Methods of evaluation are different, for example, by life cycle assessment method [Krbalova 2015], [Iskandirova 2013].

The problem comes at the moment when the machine is already manufactured and does not meet the energy profile requirements that are requested.For this reason it is necessary to simulate and predict energy consumption of machine tool. Fairly frequently is a possible method of predicting energy consumption by realization of using previously measured characteristics[Hadas 2014] from which are formed polynoms, serving as a source of input data for simulation.This is based on the creation of libraries with power profiles[Guo 2015], [Lv 2016].One of the possible principles how to predict an energy-profile is for example using Generalized Stochastic Petri Nets [Xie 2016]or Artificial Neural Network[Kant 2015].An important element of determining the energy profile of the machine is its behavior during machining[Aluntas 2016].

2 METHOD

The way how are predicted values obtained in this paper is based on the methodology (Fig. 1)referred in the literature[Tuma 2014].The method is based on multi-body simulation of the main support structures of the machine tool. It consists in simulating a relative movement of structural parts during machining process of standardized workpiece.According to the specified G-code, it is possible to calculate the toolpaths, required feed rate and acceleration of feed mechanisms.Based on knowledge of the machine structure, especially the diameter, the number of threads and the thread pitch of the ball screw, it is possible to calculate the angular velocity and angular acceleration of each ball screwsdriving the feed axis.

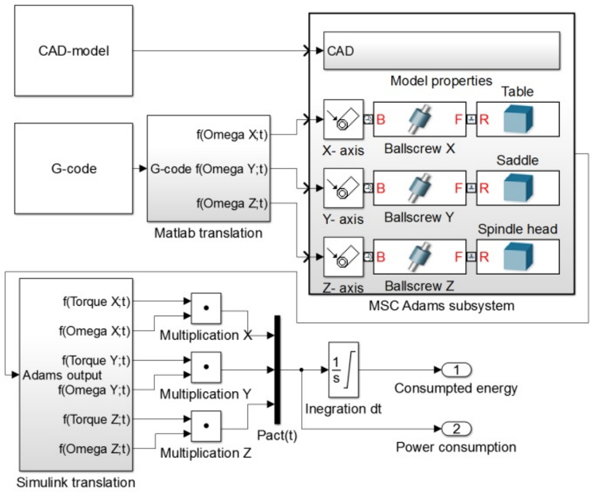


Figure 1. Scheme of simulation

The product of torque and angular velocity on the ball screw we obtain partial actual mechanical performance of single feed axis. Sum of the partial actual performance we get the actual mechanical power output of feed mechanisms shown in equation (1), where P_{Act} is actual power consumption, $M_{K(xyz)}$ are measured torques on ballscrew and ω_{xyz} are angular velocities of ballscrew.

$$P_{Act} = M_{Kx} \times \omega_x + M_{Ky} \times \omega_y + M_{Kz} \times \omega_z \quad (1)$$

The total consumed mechanical energy is obtained by integration the course of mechanical power(2), where E_{total} is total energy consumption of the machine.

$$E_{total} = \int_{t1}^{t2} P_{act} dt \quad (2)$$

Another important parameter is the to determine the power loss, which is related to the energy consumption of passive components such as ball screws, linear guides and bearings.

2.1 *Passive components analysis*

For reasons of the measurement accuracy it is necessary to correctly define the passive resistances of the entire system.Among the passive resistances we classify the ball screws and linear guides. Schematically we proceed from the model mentioned in the methodology.

In the first phase of the measurement it is not possible to accurately determine the rate of loss of individual components, but it is possible to express the system as a whole.The aim is to

obtain a function whose shape is defined by a power function, and the variable will be feed rate, therefore the feed rate dependence on the size of multiplier losses.
The process of obtaining the final course of loss function will be as follows:

- **Measuring the actual power without a load for various feed rates**.
  In case that the passive resistances are equal to zero, the current power at the moment when the assembly moves steadily, will be also equal to zero. Nonzero power will be only in case of acceleration and braking. This is also due to the method of connection of the measuring system, which is inserted between the frequency converter and the motor.
- **Obtaining the average values of actual power**.
  The average value of actual power is understood a steady value of actual power obtained at a time when the system moves steadily. Acceleration and deceleration of system has resulted in power peak, the value and accuracy depends on sampling because it is a short-term action. With a set sampling period of 50ms, it is possible that it will not record the maximum value of the power peak.
- **Dividing the actual power of the corresponding feed rate.**
  Thus is obtained a loss coefficient, which is then multiplied by the feed rate so as to obtain more precise results and a difference between the simulation and the measurement was minimal.
- **Obtaining a trend line equation of power regression.**
  Power regression was chosen because of the absence of a coefficient that even if the feed rate is equal to zero causes a nonzero value of loss function. Loss function is then a function of speed and feed rate and via a signal in Matlab Simulink incorporated into the overall signal of force opposing the motion of system. An important result of the simulation is experimentally obtained loss function by using power regression in the form (3), where y is a value of power loss function and x is a value of feed rate:

$$y = 0{,}2505 \cdot x^{0{,}3471} \quad (3)$$

The course of this function can then be displayed as is shown in Fig.2:

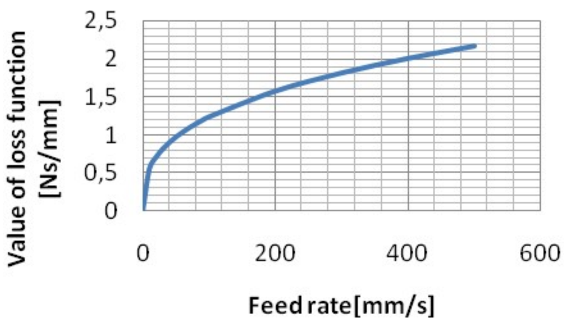


Figure 2. Course of the loss function

During the preparation of the physical (Fig. 3) model has been neglected several important phenomena, which to some rate may affect the energy profile of the machine.The first is the stiffness of the whole system.In case of simulation, it is not about checking the operation accuracy of the machine, or about finding achievable cutting parameters while keeping stability of the cutting process.Admittedly vibrations of the whole system is also involved in the energy profile of the machine, because the absorption of vibration also occurs the conversion of the kinetic energy into heat and thus losses of energy, however, the resulting losses are negligible due to the complexity of solving of such system, and due to the parameters of analyzed machines.Furthermore, in this physical model are not incorporated frictional forces and rolling resistance of bearings or ball screws, because it is a relatively complicated issue which cannot be solved by simply entering constants into the software.Also entering the friction in this software is quite complicated and unsuitable for this application.It is necessary to take into account a wide range of components arranged in series with specific passive losses.For the simplification of adjustment of these parameters is added next input variable, which takes into account passive resistances and enters the physical model in the form of force acting against the direction of movement, which is due to increased mechanical power required for the operation of the system with given parameters.For rolling bearings or roller guideways it will be a function of two variables, so that the dependence of speed and load.For such input variable it is possible to affect an impact of passive components, whose function is generated a force that acts against the direction of the linear axis.This way also allows a to compute a generated cutting force dependent on technological parameters, which are also reflected in the total course of actual power.

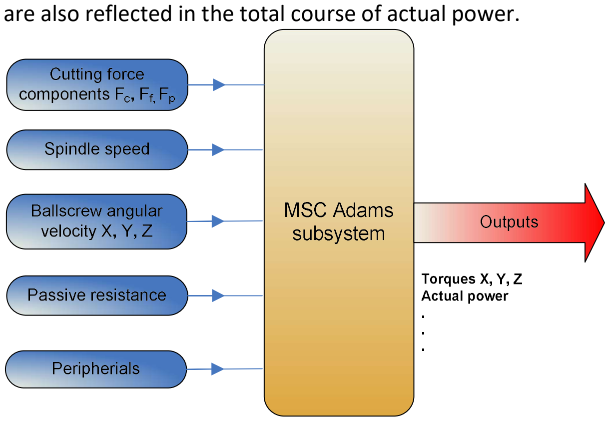


Figure 3. Input and output values of the simulation

2.2 *Demonstrator*

The base part of the stand is made of extruded aluminum alloy profile.On top of this they are bolted plates to which are attached the engine flange and ball screw bearing houses.Attachment of the ball screw is made at both ends of the ball screw, wherein one end is radially and axially fixed and at the other end of the ball screw is mounted only in the radial ball bearing, which can move axially in the house.This is in order to avoid buckling deformation caused due to thermal load condition of the ball screw system - nut and bearing, formed during their functions (Fig. 4).Ball screw is used with a diameter of 20 mm and 10 mm pitch. The motor is connected via backlash-free couplings.Linear guideways HGH20CA from Hiwin are used to hedge a linear motion of the clamping table.Applied linear guideway is at backlash-free design.Measurement of the position is possible to realize three ways.One of them is the indirect measurement using encoders in synchronous servomotors.It is also possible to use direct magnetic incremental measurement, which is part of the linear guideway.The guide rail is screwed to the base part from the underside and the upper side of the rail is equipped with a magnetic strip.Magnetic sensor of measurement is part of the linear guideway carriage.Another way is a direct absolute optical measuring system, which is realized by strap with a mask and a optical sensor.The strap is fastened in a groove designed for this purpose and the sensor is attached to the table.Stand is controlled and driven by electronics of the Beckhoff Company. Here are applied frequency converters which allow to drive a variety of drive configurations of this stand.Frequency converters also enable the electricity recovery.

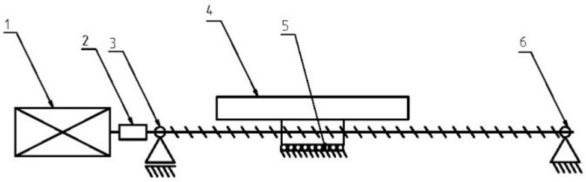


Figure 4. Kinematic scheme of the demonstrator. 1) AC servo drive, 2) backlash-free coupling, 3) axial-radial bearings, 4) clamping table, 5) ballscrew system, 6) radial bearing

Linear measuring stand is located on the clamping table with T-slots.By using brackets is the stand attached to the table to prevent unwanted movement.On the clamping table of the linear of the measuring stand is screwed a machine vice in which it is possible to clamp various loads.For the purpose of measurement was used a steel blank burden 60x60mm with varying lengths, the individual loads and vice were weighed before measurement to allow the weight to enter into the simulation.Next to this workplace is placed a table with a frame to which is fastened the frequency converter and PLC to enable control of the servo drive (Fig. 5).

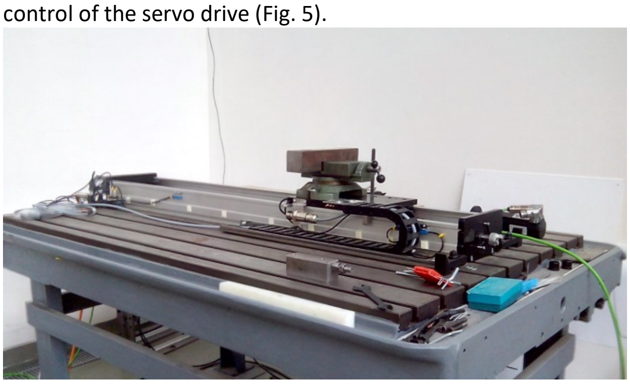


Figure 5. View of demonstrator's workplace

In order to compare the simulated data with real conditions, or if necessary to refine it is important the simulated technological process to compare with the real case.For relevant measurement of electrical energy consumption it is necessary that the measuring instrument is satisfying the following criteria:

- Possible long-term operation of the measuring device
- Necessity of collecting and recording of measured data
- Measurements during a defined time period or specific time periods
- Possibility to compare the measured values with the measured values relating to the functions of the machine
- Protection against electromagnetic interferences in the machine

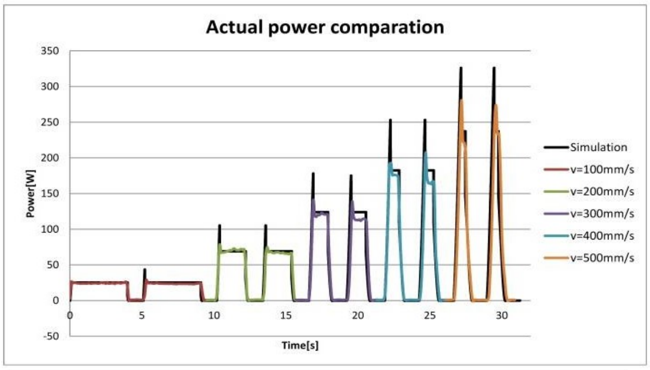
To meet these requirements was selected measuring instrument [Huzlik 2013]developed by the project FR-TI3 / 655 - Eco-design in the construction of machine tools. Measurements carried out both on the heel of the machine, and directly between the frequency converter and motor of linear axes or spindle. By this way it can be achieved relatively complex view of consumption of measured machine. We can compare partial results of each linear axis and spindle with measured results on the heel of the machine.

Here can be seen the influence of the peripheral devices that are necessary to participate indirectly in the primary function of the machine, but are important to achieve the required machining accuracy, surface quality, achieving safety, or are important for functionality of the machine.

3 RESULTS AND DISCUSSION

Within the verification of simulation was carried out a measurement at various feed rates and loads. The measurement was carried out at loads of the clamping table 0 kg, 17,336kg and 22,711kg and at feed rates of 100, 200, 300, 400 and 500 mm/s.The outputs are courses compared to the actual power of the measured and simulated data, the comparison of energy consumption and for each measurement differential and percentual error. Measurements on the test device were carried out by repeated sequences of movement of worktable by linear reciprocating movement of 400 mm with a delay of 1 second because of a potential separation of individual measurements.Same applies to simulated course of measurements.After evaluating the measurement was then necessary to extract relevant patterns of simulation and to unify them chronologically with the simulation.This may be the reason for increased mismatches between the simulated and measured data.The results are then presented in the following charts.The first part shows the results of measurements at zero load (Fig.6, Fig. 7, Fig. 8) of the clamping table, therefore driving mechanisms are loaded only by the weight of the table and components attached to it.

Figure 6. Comparison of actual power course while zero load



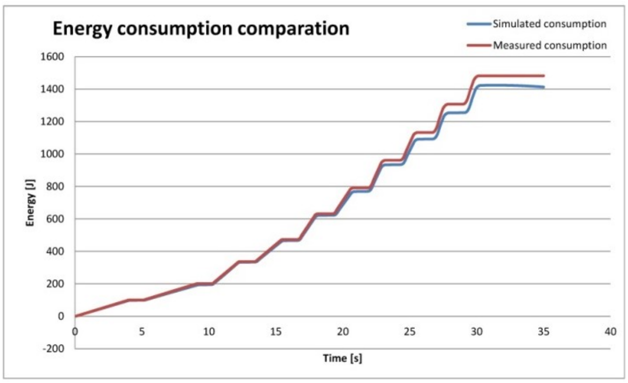


Figure 7. Time course of comparison of consumpted energy while zero load

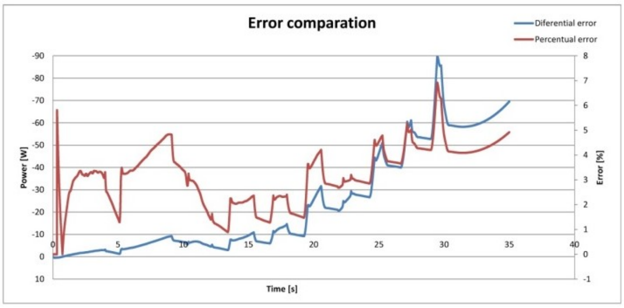


Figure 8. A time course of diferential and percentual error while zero load

The next step was measuring and a simulation under load 17,336 kg.As in the previous measurement are more noticeable (Fig. 9, Fig. 10, Fig. 11) deviation of power peaks which are difficult to predict, but the comparison of a simulation and the measurement deviation is up to 10%.

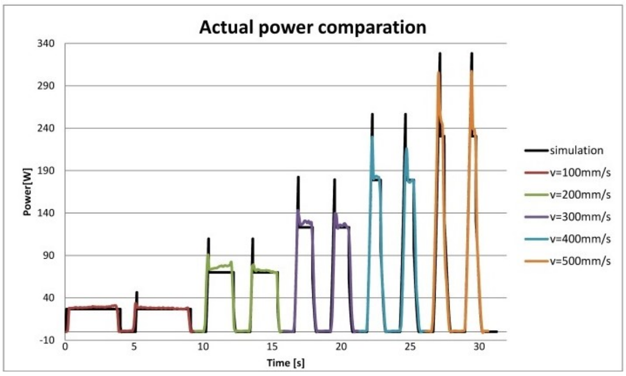


Figure 9. Comparison of actual power course while 17,336 Kg load

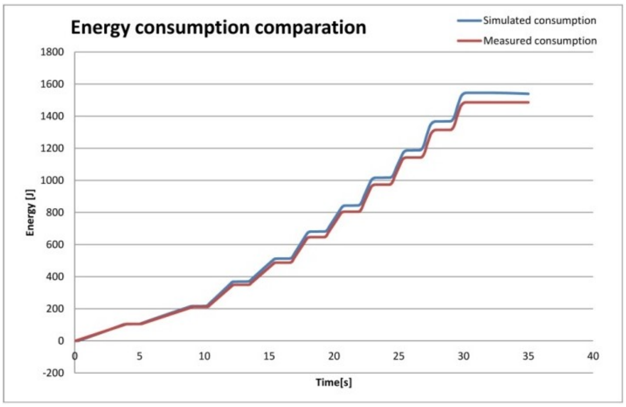


Figure 10. Time course of comparison of consumpted energywhile 17,336 Kg load

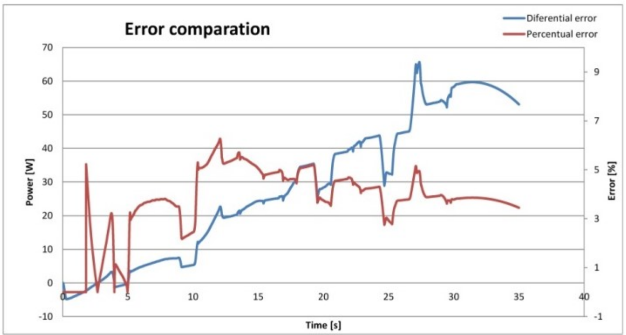


Figure 11. A time course of differential and percentual errorwhile 17,336 Kg load

When comparing measured and simulated data was achieved deviation up to 10%.Increased deviation is also caused by imperfect time synchronization of measured and simulated recording.Differential and percentual error are then calculated from actual power data, affected by the bug more than when compared to the record of energy consumption, which would have the shape of deviation as gradually rising curve due to cumulative error manifested in this case. Final measurement and simulation was under load 22,711 Kg, results are shown in Fig. 12, Fig. 13 and Fig. 14.

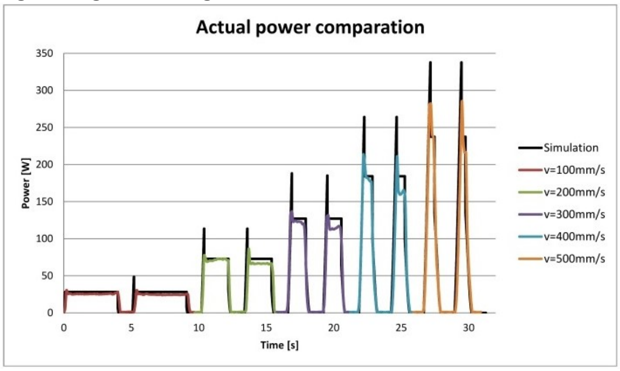


Figure 12. Comparison of actual power course while 22,711Kg load

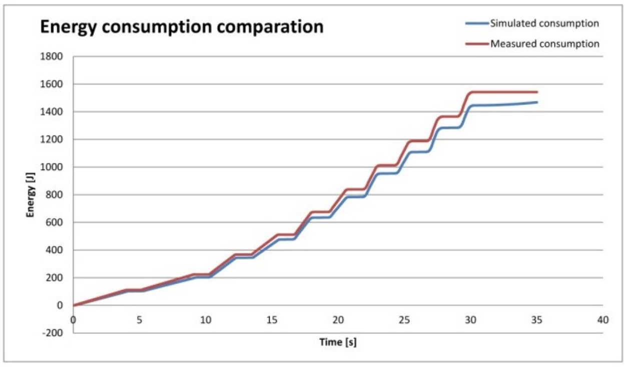


Figure 13. Time course of comparison of consumpted energy while 22,711Kg load

Figure 14. A time course of differential and percentual error while 22,711Kg load

Variable	Clamping table load [Kg]		
	0	17.336	22.711
Average diferential error [W]	23.8979	28.4603	46.1149
Average percentual error [%]	3.1951	3.7308	7.4343
Maximum diferential error [W]	89.5604	65.6364	108.593
Maximum percentual error [W]	6.9205	6.2675	13.0441

Table 1. Summarization of measurement results

4 CONCLUSION

Within the framework of the realized experiment was carried out a series of measurements, which led to the verification of the method for the evaluation of energy demands of mechanisms used for machine tools construction.In the case of this realized experiment it is about the feed mechanisms that are involved in the cutting process.This is a model case where the series of measurements are performed on measuring stand simulating linear feed axis.This linear axis is only loaded with a load which demonstrates the load from the workpiece and the cutting process itself is not included in the simulation.In the simulation and realized experiment is great emphasis on quantifying the resistance forces acting against the direction of movement, which is caused by less than one hundred percent efficiency of transfer mechanisms for linear reciprocating movement.It creates a nonzero torque of the ball screw in steady motion.The results and a summary of the method are carried out in graphs and a table (Table 1) summarizing the accuracy of this method.In the case of lower loads the results are quite positive, for the maximum load are the maximum error is over the 10% threshold, which is probably due to the imperfect time synchronization of simulated and measured data.

Another possible development of this method is suitable for application for multi-axis machine tools, which greatly expands the possibility of use.An essential element that should be addressed in the context of achieving the complexity of this method is the influence of the cutting process for immediate the heel actual power of the machine tool and the inclusion of peripheral devices to the simulation.

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