Journal of Machine Engineering, Vol. 9, No. 2, 2009

machine tool, feed drive, control loop simulation,
cutting force, vibration suppression

Jiri SVEDA[1]
Michael VALASEK[1]
Zbynek SIKA[1]

SIMULATION TESTING OF THE MACHINE TOOL EQUIPPED WITH THE ACTIVE FEED DRIVE

The vibration of a machine tool is mainly caused by the dynamic acceleration of a motion axis and by the forces that act on it. All the disturbance forces are transmitted to the machine tool frame through the drive (motor) and its regulation loop and they excite its vibrations. Thus the achievable dynamics and machining quality is negatively influenced. There are several possibilities how to suppress the excited vibrations including the recently introduced "motor on motor" technique which is based on the serial connection of two linear motors. This paper presents new simulation results performed on the simulation model of a real machine tool. The maximal achievable tuning of the regulation loop parameters of the motion axis equipped with the "motor on motor" technique was confronted with the conventional feed drive setting. The "motor on motor" feed drive properties were also tested in the virtual machining operation mode where the real measured cutting force was used. The sensitivity analysis of the reaction force and the middle mass movement of the "motor on motor" feed drive solution to the predicted cutting force introduced to the feed drive control has been investigated. The middle mass is represented by the shared part of both linear motors which absorbs the high frequency part of the reaction force by its movement.

1. INTRODUCTION

The common machine tool feed drive design is equipped with the hard mounted static part of the actuator. In the case of linear motor the secondary part of the feed drive motor is directly connected with the machine frame. Such solution leads to high values of reaction forces in broad frequency spectrum generated by the control system with high parameter setting. The power strokes are transmitted directly to the machine bed during the operation and the wide spectrum of natural frequencies are excited. This is connected with the amplification of the vibrations. The oscillation of the machine bed and the motion axis consequently deteriorates the achievable machining precision and the dynamic properties

[1] Department of Mechanics, Biomechanics and Mechatronics, Faculty of Mechanical Engineering,
CTU in Prague, Karlovo nám. 13, 121 35 Praha 2, Contact e-mail: Michael.Valasek@fs.cvut.cz

of the motion axis and the whole machine tool. The new active feed drive was developed to avoid the excitation of the machine tool frame and is described in [3]. The feed drive design is based on the serial connection of two linear motors on a single motion axis where the second linear motor transforms the frequency spectrum and the amplitude of the reaction force. The principle scheme of this design is shown in Fig. 1. This conception is called “Motor on motor”.

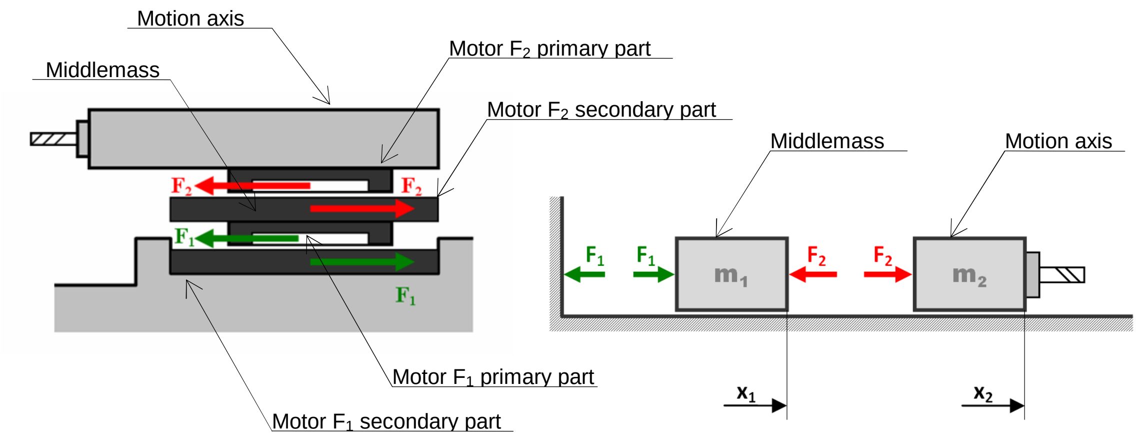

Fig. 1. Motor on motor conception

The real construction of the feed drive equipped with the “Motor on motor” design could be as shown in Fig. 2. There is the mechanical design of the motion axis with the movable middle mass for the compensation of high frequency part of the reaction forces.

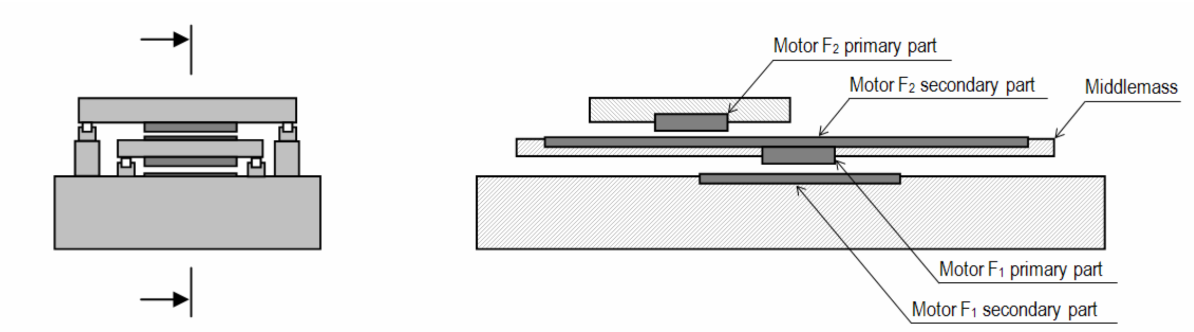

Fig. 2. Construction design of the motion axis equipped with the Motor on motor conception

The paper mainly deals with the advanced simulation results achieved on the mathematical model of the experimental milling centre LM-2. The mathematical model of the machine tool LM-2 with the “Motor on motor” design is already described in [2]. The maximal tuning of the motion axis parameters compared to the feed drive common design and the influence of the cutting force on “Motor on motor” regulation are the main topics of this paper. The real cutting forces were experimentally measured and involved in the machine tool mathematical model with the aim of better simulation results.

2. MACHINE TOOL SIMULATION

As mentioned in the previous section the paper deals with simulation of the mathematical model of the experimental milling centre LM-2 (Fig. 3) equipped with “Motor on motor” feed drive design in the Z axis [2].

Fig. 3. Experimental milling centre LM-2

The dynamic behavior of the machine tool with “Motor on motor” feed drive is based on the FEM analysis and is described by the equation (1) in the state-space form [1].

$$\begin{aligned} \dot{x} &= \begin{bmatrix} \ddot{z} \\ \dot{z} \end{bmatrix} = \begin{bmatrix} -2\xi\Omega & -\Omega^2 \\ 1 & 0 \end{bmatrix} \begin{bmatrix} \dot{z} \\ z \end{bmatrix} + \begin{bmatrix} \Phi^T \\ 0 \end{bmatrix} f = Ax + Bf \\ y &= \begin{bmatrix} \Phi & -0 \\ 0 & \Phi \end{bmatrix} \begin{bmatrix} \dot{z} \\ z \end{bmatrix} = Cx \end{aligned} \tag{1}$$

In the equation (1) z is the vector of modal coordinates, x is the state vector, y is the output velocity and displacement vector, Φ is the modal matrix, Ω is the diagonal eigenfrequency matrix, ξ is the diagonal matrix of modal damping ratio coefficients and f is the vector of loading forces.

The regulation scheme of the machine tool Z-axis is shown in the Fig. 4. It consists of three parts where the first one represents a common cascade regulation loop of the main motion axis. The other two parts deal with the control of the pre-computed reaction force and with the absolutization. The control of the pre-computed reaction force transforms the reaction force using the proposed motion of the middle mass. The algorithm for obtaining the pre-computed reaction force, which is based on the knowledge of NC code and the mathematical model of the machine tool, is described in [4]. The absolutization is a control of the suitable position of the middle mass in the vicinity of its zero position. This paper deals with the maximal possible tuning of the motion axis in comparison with the common feed drive design. The used tuning parameters are the velocity loop gain K_{pv} and the position loop gain K_v in Fig. 4.

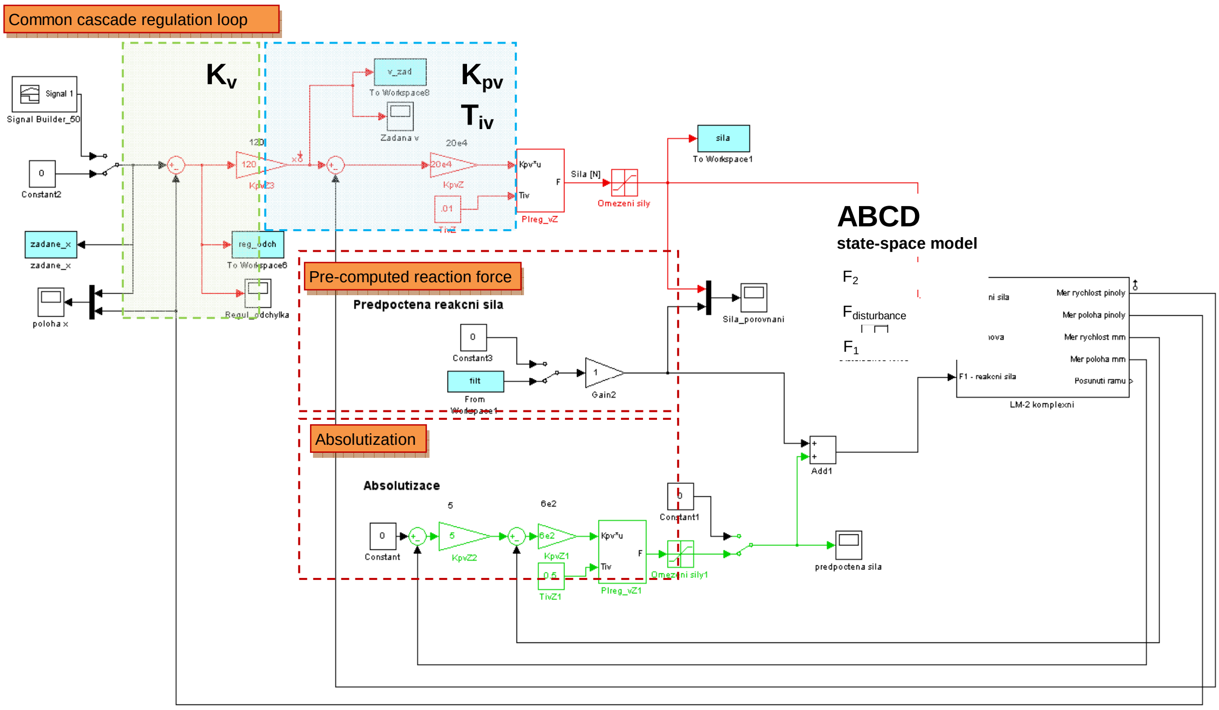

Fig. 4. LM-2 machine tool Z-axis regulation loop

The velocity loop tuning was performed as the first step. The sensitivity analysis of the velocity loop frequency pass-band to the velocity loop gain K_{pv} was done with the aim of obtaining the maximal K_{pv} setting. The Bode diagram of the velocity loop for the various K_{pv} settings is shown in the Fig. 5. The velocity loop frequency pass-band with the common feed drive design is restricted due to the excited structural shapes around the frequency 200 Hz and achieves the value 40 Hz. The corresponding gain of the velocity loop K_{pv} is 60 000 Ns/m. This value of the K_{pv} is also set on the real machine tool. If the active feed drive with the “Motor on motor” design is activated, the structural shapes around frequency 200 Hz are not excited anymore and the K_{pv} and the velocity loop pass-band can be improved. The relevant value of the K_{pv} is 200 000 Ns/m in this case, because the velocity loop frequency pass-band does not rise more than 90 Hz for the higher K_{pv}. Conversely the higher value of the K_{pv} amplifies a noise in the regulation loop.

The tuning of the position loop gain is based on the monitoring of the regulation deviation at the demanded position ramp. The value of the position loop gain K_v can be raised thanks to the previous velocity loop tuning which is allowed by the “Motor on motor” design. The common feed drive position loop gain K_v can be set up to 50 1/s. The position loop gain K_v of the feed drive with the “Motor on motor” design can be increased up to 140

1/s, it means more than two times higher than in the common design. The comparison of the regulation deviation is shown in the Fig. 6. The increase of the K_v leads to the decrease of the regulation loop deviation which is connected with the better response of the motion axis to the demanded trajectory. The regulation deviation of the position loop can be decreased nearly three times.

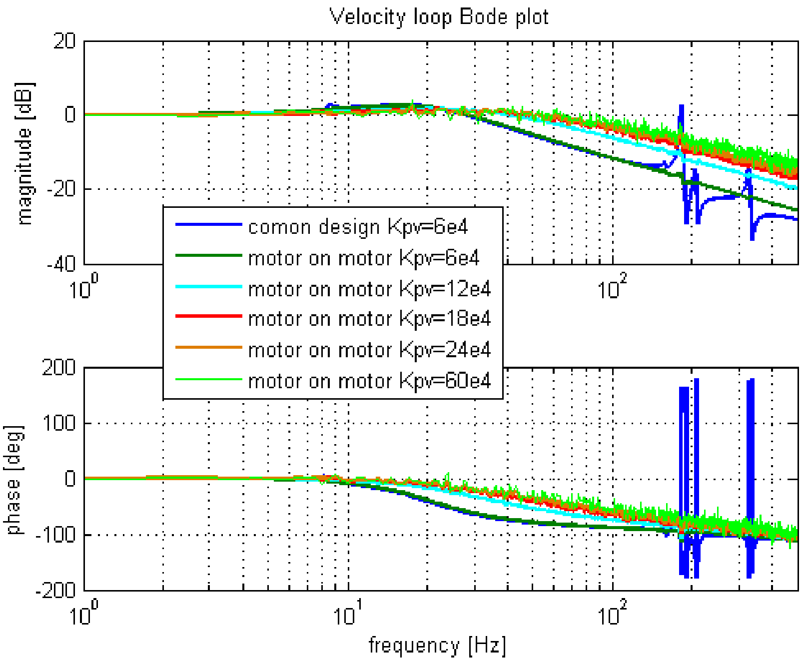

Fig. 5. Velocity loop Bode plot for various K_{pv}

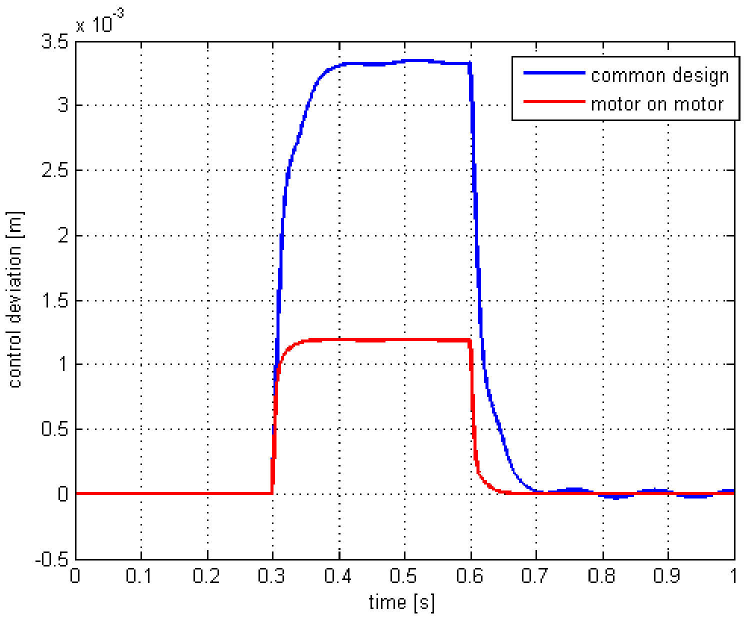

Fig. 6. Regulation deviation by the velocity step 10 m/min

Another aspect of the position loop tuning is the increase of the dynamical stiffness. The dynamical stiffness is the resistivity of the feed drive to the disturbance force. The position displacement of the motion axis by the disturbance force 1000 N is shown in Fig. 7. The displacement of the common feed drive is 110 μm and the displacement of the "Motor on motor" design is only 20 μm. It means that the dynamical stiffness of the feed drive is increased from 9 N/μm to 50 N/μm, i.e. more than five times.

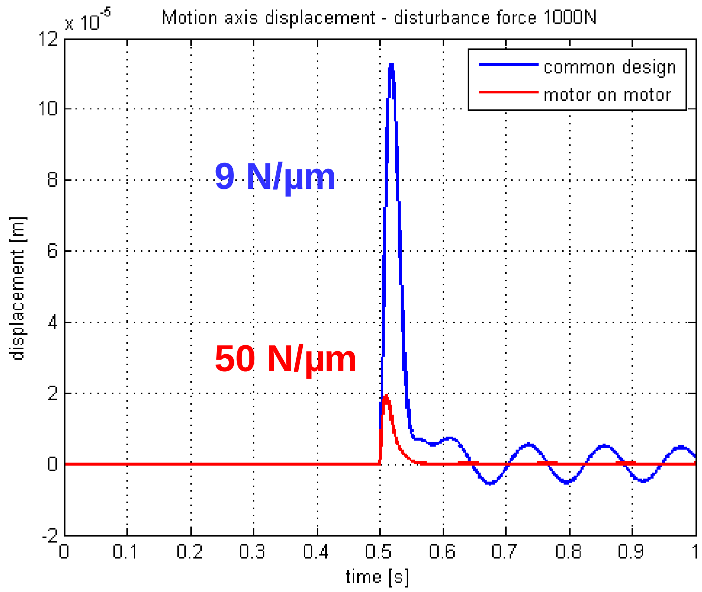

Fig. 7. Motion axis displacement by the disturbance force step with amplitude 1000 N

3. CUTTING FORCE ANALYSIS

The analysis of the influence of the cutting force to the feed drive regulation is described in this section. It is done by the simulation. The real measured cutting force on the LM-2 machine tool is employed in the simulation. Because the prediction of the cutting force can improve the regulation of the "Motor on motor" feed drive, the predicted cutting force is exploited in the regulation. This paper does not use the proper prediction of the cutting force but as the predicted cutting force the exact measured force with a disturbance is used instead. The result is a sensitivity analysis of the regulation behaviour to the prediction quality of the cutting force. The proper prediction of the cutting force can be used e.g. from [5].

The experimental scheme of the cutting force measurement is shown in the Fig. 8. The test machining was in the X direction of the machine tool coordinate system with the constant position of Y and Z axes. The tool was 20A3R032B20C-SAP11D with a cutting inserts APKX 1103PDER-M, 8040 with a TiN surface layer and a tool holder Diebold HSK 63-F ∅20. The work piece was made from steel CSN 12050.9 with hardness 190 HB. It was the climb milling without cooling. The parameters of the milling are presented in the Tab. 1.

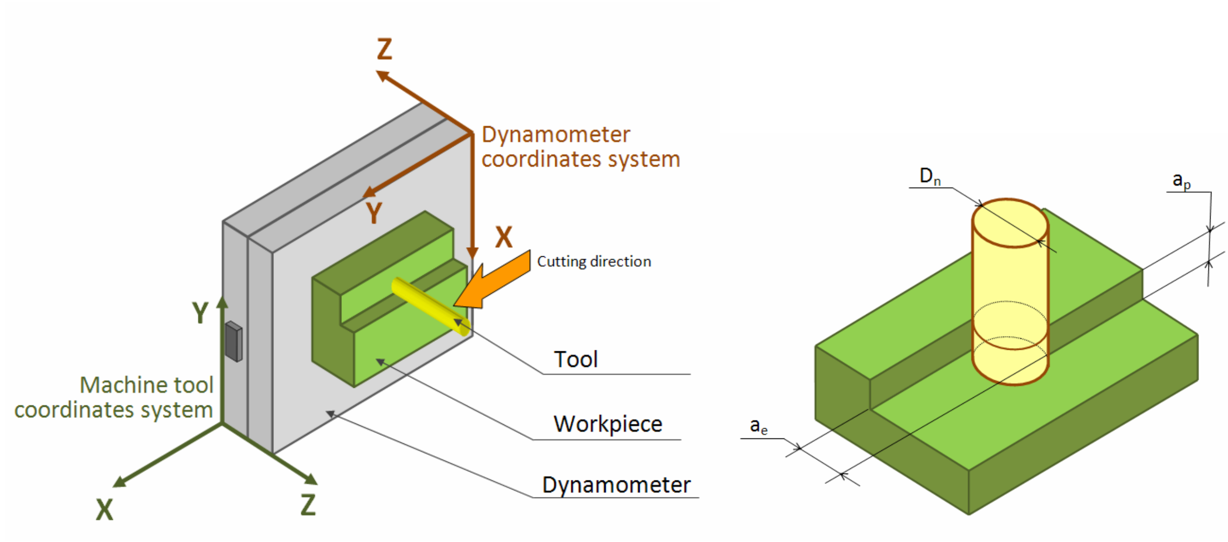

Fig. 8. Scheme of the experiment with the cutting force measurement on the LM-2 machine tool

Tab. 1. Work condition of the test milling

Parameter	Mark	Unit	Value
Cutting speed	v_c	[m.min^{-1}]	210
Cutting depth	a_p	[mm]	2
Cutting width	a_e	[mm]	16
Feed per tooth	f_z	[mm]	0.15
Number of teeth	z_i	[-]	3
Diameter of milling cutter	D_n	[mm]	20
Rate of feed	v_f	[mm.min^{-1}]	1504
Spindle rpm	n	[ot.min^{-1}]	3342

The measured cutting force by a dynamometer is shown in the Fig. 9. The biggest force is in the X and Y axes, the force in the Z axis has a lower amplitude but it is also important. The simulation model of the “Motor on motor” feed drive in the Z axis is used.

The simulation test was performed in the Z axis at first. The motion axis was in the position loop with the zero demanded translation. The measured cutting force acting on the ram at the point of the tooltip in the simulation model and the influence to the reaction force and to the middle mass displacement was monitored. Because of the middle mass displacement minimization the pre-computed cutting force was added to the pre-computed reaction force that is described in [4]. The final reaction force is now computed not only from the acceleration force based on NC code analysis and the absolutization action but also from the predicted cutting force. A part of the regulation scheme with the pre-computed cutting force application is shown in Fig. 10.

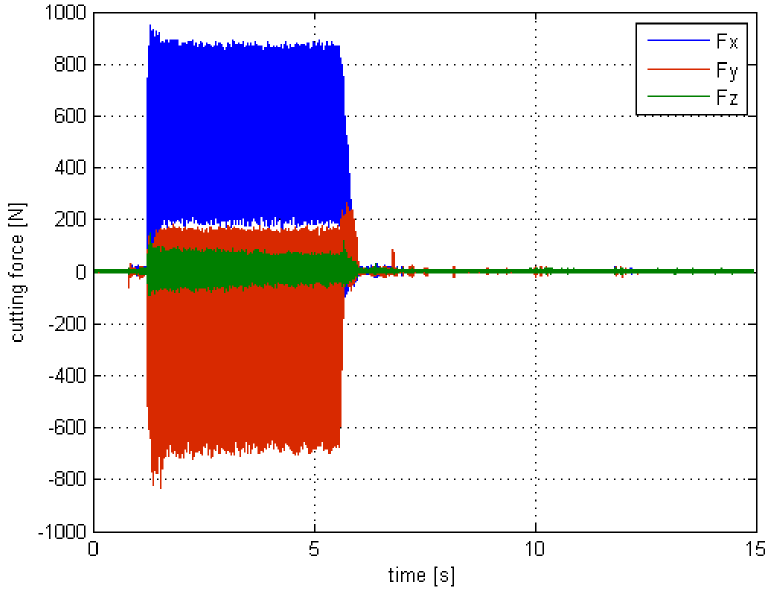

Fig. 9. Measured cutting force on the milling centre LM-2

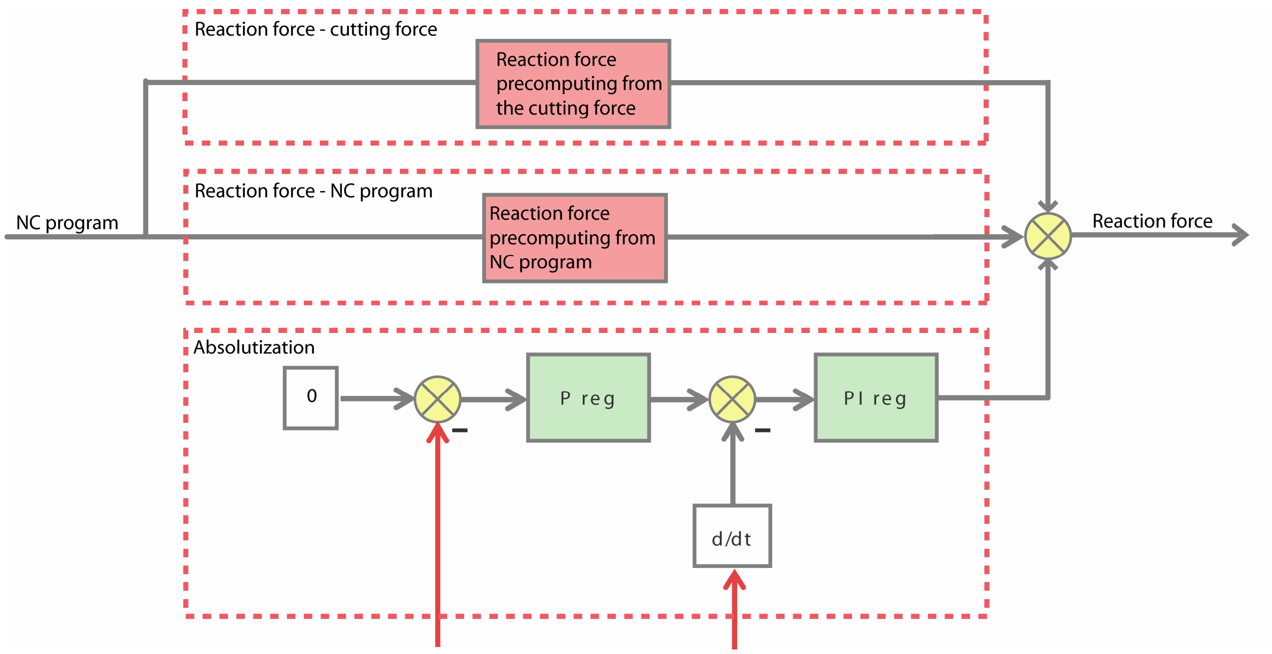

Fig. 10. Reaction force computation block diagram

The predicted cutting force was filtered, as well as the pre-computed action force from the NC code, before the sum with the other parts of the reaction force is carried out because of the reason of removing high frequencies. It was used 1st order non-causal low-pass filter with cut-off frequency 2 Hz. The high frequency part of the cutting force is compensated by the middle mass movement.

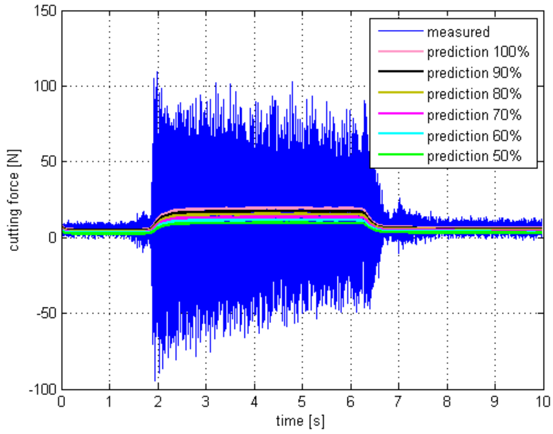

Fig. 11. Measured cutting force in the Z-axis and its filtration with disturbance error

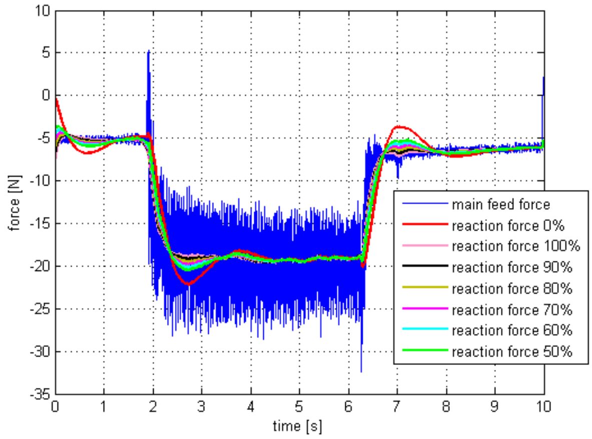

Fig. 12. Action force and reaction force by cutting force prediction with disturbance

The measured cutting force in the Z-axis and its filtration with the disturbance error is shown in the Fig. 11. The disturbance error is a simple reduction of the force amplitude where “prediction 100%” means that its knowledge is ideal. The result of the action and reaction force simulation during the milling process is shown in the Fig. 12. The main acting force, that holds the motion axis in the constant position, is depicted by the blue line. The reaction force without the cutting force prediction is depicted by the red line. The other colors show reaction force with cutting force prediction in the different accuracy.

The displacement of the motion axis is shown in the Fig. 13 by the blue line. It should be zero. The other colors show displacement of the middle mass with cutting force prediction with the different accuracy. The value of the reaction force is very little dependent on the accuracy of the cutting force prediction. On the contrary to the reaction force the middle mass movement of the “Motor on motor” feed drive is strongly dependent on cutting force prediction accuracy.

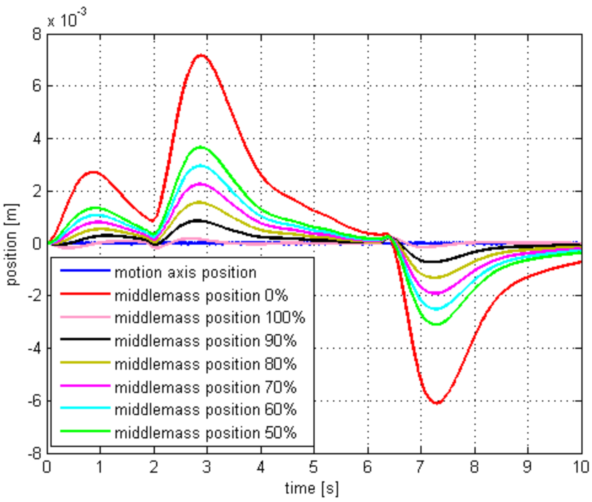

Fig. 13. Motion axis and middle mass displacement by cutting force prediction with disturbance

Another simulation testing with the bigger milling load was performed for the better analysis of the cutting force prediction. There is a simplification in the model, where the all milling parameters of the X axis were applied to the Z axis including the cutting force amplitude. The Z axis simulation model is equipped with the “Motor on motor” feed drive design. Such an experimental scheme with demanded position ramp is shown in the Fig. 14.

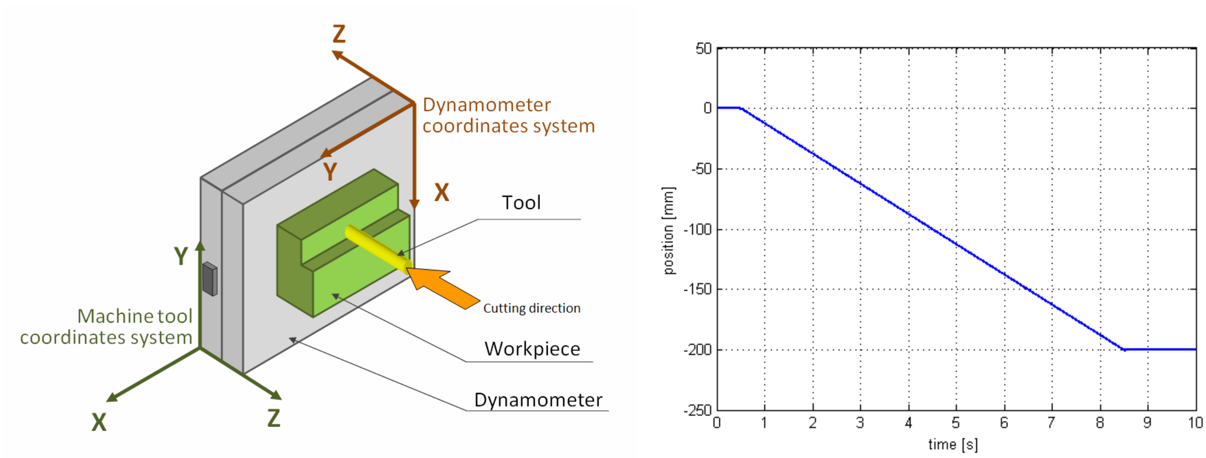

Fig. 14. Idea experiment scheme with higher load in Z axis and its position ramp

The comparison between the real and the predicted filtered cutting force is shown in the Fig. 15. The filtration is the same type like in the previous simulation tests. The result of the action and reaction force simulation by the milling process with the higher load is shown in the Fig. 16. The main acting force, which moves the motion axis along the demanded position ramp, is depicted by the blue line. The other colors show the reaction force with the cutting force prediction with the different accuracy. The behavior is similar to the previous simulation test but has higher amplitude caused by the higher load. Moreover

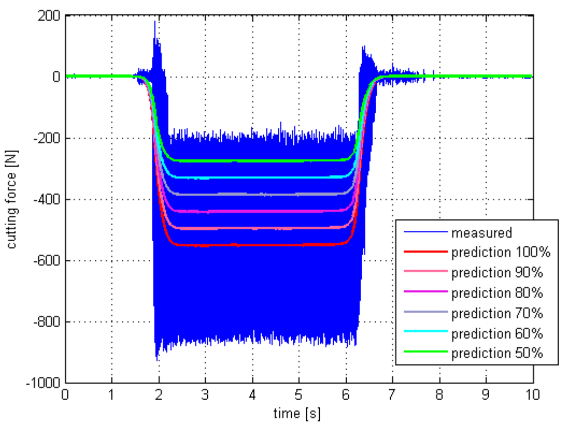

Fig. 15. Measured cutting force in the Z-axis and its filtration with disturbance error

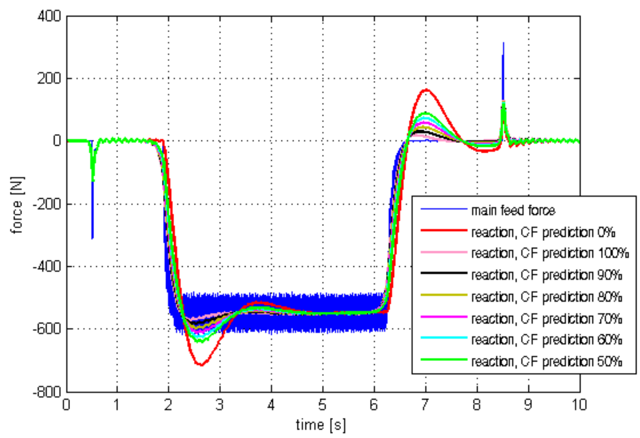

Fig. 16. Action force and reaction force by cutting force prediction with disturbance

there are force peaks at the beginning and the end of the simulation. They are caused by the acceleration and deceleration of the motion axis corresponding to the demanded position ramp. Nevertheless the reaction force shape is smoother than the main feed drive force in all cases thereby danger of the excitation of the natural frequencies is reduced. The accuracy of the cutting force prediction has not essential influence to the reaction force smoothness of the “Motor on motor”.

As in the case with the lower cutting load, the movement of the middle mass is strongly dependent on the correct cutting force prediction. The displacement of the motion axis and the middle mass with the cutting force prediction by the different accuracy is shown in the Fig. 17.

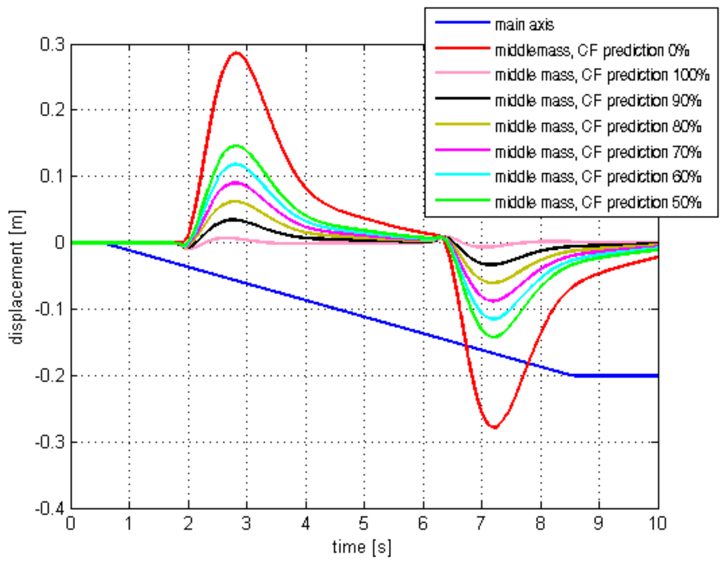

Fig. 17. Motion axis and middle mass displacement by cutting force prediction with disturbance

4. CONCLUSION

Based on the results described in this paper, the new active feed drive with “Motor on motor” design is able to improve the motion axis dynamics. The simulation experiments were performed on the mathematical model of the experimental milling centre LM-2. The gain of the velocity loop K_{pv} was increased more than 3x and the gain of the position loop K_v was increased more than 2x. It is also connected with the lower position regulation loop and the better dynamical stiffness (5x).

The influence of the cutting force to the “Motor on motor” regulation was also investigated in this paper. The prediction of the cutting force can improve the regulation quality in terms of the lower middle mass displacement. But the reaction force smoothness, which is important for the resistivity to the natural shapes excitation, is not so strongly dependent to the correct cutting force prediction.

ACKNOWLEDGEMENTS

The authors appreciate the support by the project “Algorithms for computer simulation and application in engineering” MSM 6840770003.

REFERENCES

[1] PREUMONT A., 1997, *Vibration Control of Active Structures - An Introduction*, Solid Mechanics and Its Applications,Vol. 50, Kluwer Academic Publisher, Dordrecht.

[2] SVEDA J., SIKA Z., VALASEK M., 2008, *Machine tool with undisturbed frame*, Matar Praha 2008, Part 1: Drives & Control, Design, Models & Simulation. Prague, 71-76, ISBN 978-80-903421-9-4.

[3] SVEDA J., SIKA Z., VALASEK M., 2008, *New active mounting of machine tool feed drive*, XXII International Congress of Theoretical and Applied Mechanics, Adelaide, Australia, University of Adelaide, ISBN 978-0-9805142-0-9.

[4] SVEDA J., VALASEK M., SIKA Z., 2009, *Experimental Testing of Active Feed Drive*, Journal of Machine Engineering - High Performance Manufacturing, 8/4, XX CIRP Conference, Karpacz, Poland, ISSN 1895-7595.

[5] TLUSTY J., 1985, *Machine Dynamics*, Handbook of High Speed Machining Technology, Edited by King, R.I., Chapman and Hall, New York.