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machine tool, testing bed,
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EXPERIMENTAL TESTING OF ACTIVE FEED DRIVE

The main disturbances of the machine tool frame are caused by operation of motion axes. Movement of high dynamic motion axes is connected with powerful force strokes that excite machine tool frame vibration and deteriorate machining surface quality and productivity. There are several possibilities how to suppress this vibration. This paper deals with the simulation and experimental testing of new advanced conception where the main motor is connected with the frame by an active element that is controlled by intelligent control technique.

1. INTRODUCTION

Contemporary machine tool feed drive construction is based on typical conception that rigidly connects static part of actuator and machine tool body. In case of the linear motor the secondary part is directly connected to the frame. It causes high value and wide frequency spectrum of reaction force that is generated by the control system with high parameter setting. The power strokes are directly transmitted to the machine bed during the operation and wide spectrum of the frequencies are excited. This is connected with amplification of vibration. Oscillation of the machine bed and motion axis then deteriorates precise machining and dynamic properties of motion axis as well as the whole machine tool.

The paper deals with the advanced technique which transforms the frequency spectrum and amplitude of the reaction force and is focused on simulation and experimental testing. The principle is based on serial connection of two linear motors in each motion axis with advanced control technique. This control technique is based on reaction force precomputation and it allows to suppress the machine tool vibrations and thereby to improve dynamic properties of the motion axis.

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2. FEED DRIVE OVERVIEW

2.1. FIXED-MOUNTED FEED DRIVE

Fixed-mounted feed drive construction is commonly used in the machine tool branch. As shown in Fig. 1, the linear motor is rigidly inbuilt to the machine bed and presents a source of the motion force which reacts equally to the machine frame and motion axis. The primary part is rigidly connected with the motion axis, in this case with the spindle of the machine tool and the secondary part is fixed-mounted to the machine tool bed.

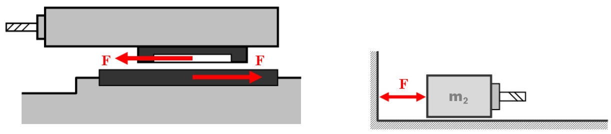

Fig. 1. Fixed-mounted feed drive design

2.2. SUSPENDED FEED DRIVE

The suspended feed drive construction [1,2] is a more sophisticated method. The configuration is shown in Fig. 2 and it consists of similar parts as in the previous conception. The primary part of the linear motor is also directly connected with the spindle. However, the secondary part is connected with the machine bed in a different way compared to the previous case. There are spring and damper used for axial fixation to the bed. This configuration allows a short movement of the linear motor secondary part and thus the frequency spectrum of the reaction force is friendlier to the machine bed vibration.

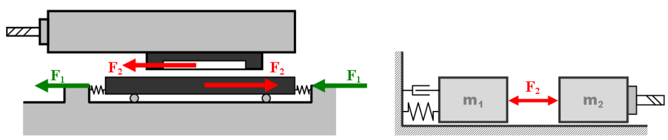

Fig. 2. Suspended feed drive design

2.3. ACTIVE FEED DRIVE – “MOTOR ON MOTOR”

“Motor on motor” is a new feed drive design. As shown in Fig. 3, this concept consists of two independent linear motors. One of them (F2) represents common feed drive which causes displacement of motion axis. The second one deals with the reaction force transformation (F1). The main advantage of this solution is a possibility to fully control the force which reacts to the machine tool body. Thus we can transform the reaction force in an effort to suppress vibrations of the body structure. This conception is similar to the conception [3] used for splitting the construction of the whole machine tools.

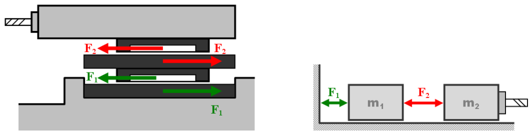

Fig. 3. Motor on motor design

3. CONTROL TECHNIQUE

3.1. IMPULSE DECOUPLING PRINCIPLE

High efficiency machining is characterized by a high dynamic movement. In such operation the actuator force shape is extremely sharp and it can look like a force step. Unfortunately this impulse frequency spectrum is very wide and many frequencies of the mechanical structure are excited. It is closely connected with excitation of vibrations.

In the new feed drive design the motor (F2) can be controlled by common cascade controller because the force of linear motor is not significantly dependent on the actual velocity of the secondary part of linear motor [2]. The main idea of the advanced control technique is to transform reaction force by means of secondary linear motor (F1) and to prepare the best condition for the axis displacement by means of additional middle mass movement. It is achieved by the additional force (F1) that transmits only low frequency part of reaction force and starts to operate earlier than the control system demands change of the position. Thereby the reaction force influence on machine tool is reduced. The NC code corresponding to the actuator (F2) has to be known because of the efficient control of the actuator (F1). Thus we can prepare better initial condition for the motion of the main axis and profit from the small movement of the additional motor middle mass (m1).

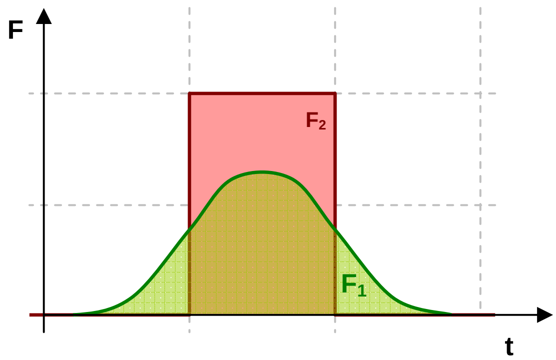

Fig. 4. Force time behavior

The time behavior of the mentioned forces can look like in Fig. 4. As shown in Fig. 4, force which acts on the bed (F1) has smoother time behavior and starts to operate earlier than the force (F2) which reacts to the spindle. This impulse decoupling system divides the sharp reaction force into high and low frequency part. The high frequency part is removed by means of middle mass displacement and the low frequency part is transmitted harmlessly into the frame by actuator (F1). It decreases force amplitudes which reacts to the bed and reduces number of excited frequencies.

3.2. FORCE IMPULSE OPTIMIZATION

Because the reaction force (F1) is now fully controlled there is used a mathematical method to find its best shape [4,5]. The mathematical method is based on exploitation of genetic algorithm to find an absolute extreme of the target function (1)

$$tf = c_1 \cdot \sum_{i=1}^{n} F_i^2 + c_2 \cdot \sum_{i=1}^{n-1} \left(F_{i+1} - F_i\right)^2 + c_3 \cdot \sum_{i=1}^{n} x_{1i}{}^2 + c_4 \cdot \left(x_{1(n)} - x_{1(n-1)}\right)^2 \tag{1}$$

The genetic algorithm intelligently computes value of the target function for a large number of force shapes. The results shown in Fig. 5 represent solution of target function in relation to the reaction force smoothness and middle mass displacement and final velocity on a two mass model of mechanical system. From our point of view the solutions located on the red surface are interesting, these solutions are called “pareto-set”. Here are all three observed criterions minimal, that means efficiency of the method is maximal. Solutions outside the red line are unnecessary and extend computation time.

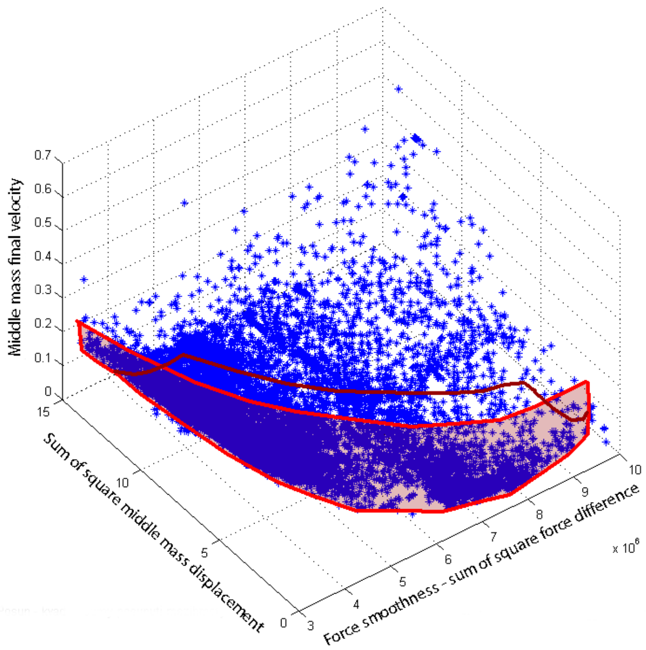

Fig. 5. Genetic algorithm optimization results

Time behavior of the optimized force is shown in the Fig. 6, where the shown characteristics is relevant to the selected equivalent point from the pareto-set. There is also shown comparison of the reaction force between the fix, spring and active feed drive design. The suspended feed drive transforms the reaction force shape but the force amplitude has very high value and is connected with powerful oscillation. The active feed drive reduces the force shape sharpness with low force amplitude and small middle mass displacement (shown in the Fig. 7). It is connected with soft behavior of reaction force which suppresses vibration.

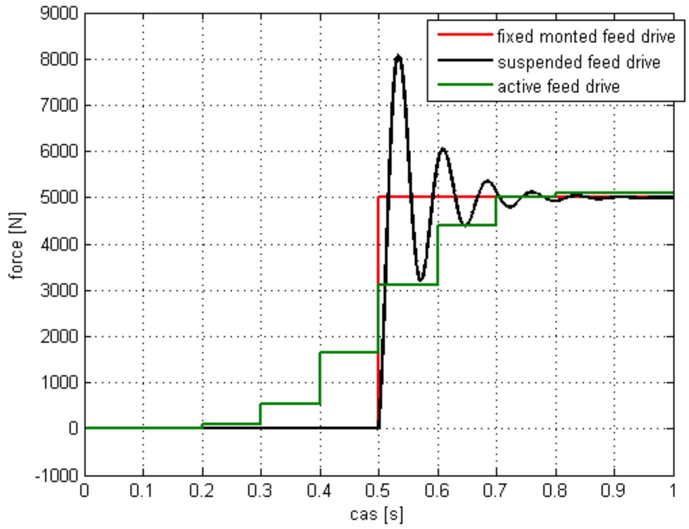

Fig. 6. Optimized force time behavior

There is used force discretization for simpler optimization of demanded force shape. The final force shape should be interpolated by a cubic spline in each time interval.

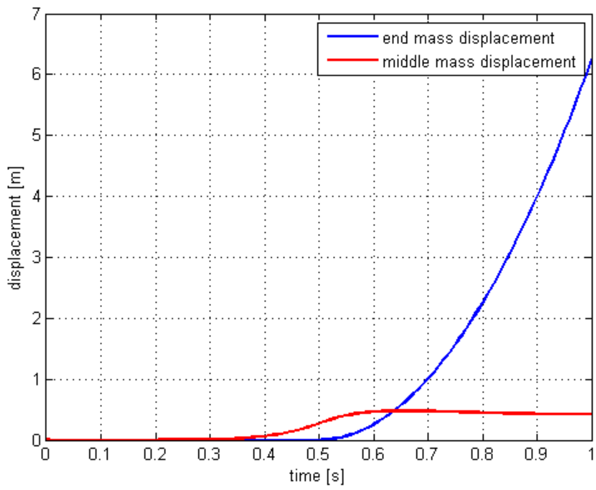

Fig. 7. Active feed drive displacement (end mass100kg, middle mass 70 kg)

Optimized reaction force shape looks like a low-pass non-causal filtration of the actuating force. Comparison of the optimized reaction force and reaction force obtained by the non-causal filtration is shown in the Fig. 8. From this result follows that the non-causal filtration tracks the optimization results very closely and could be used as a pre-computing algorithm for the demanded reaction force.

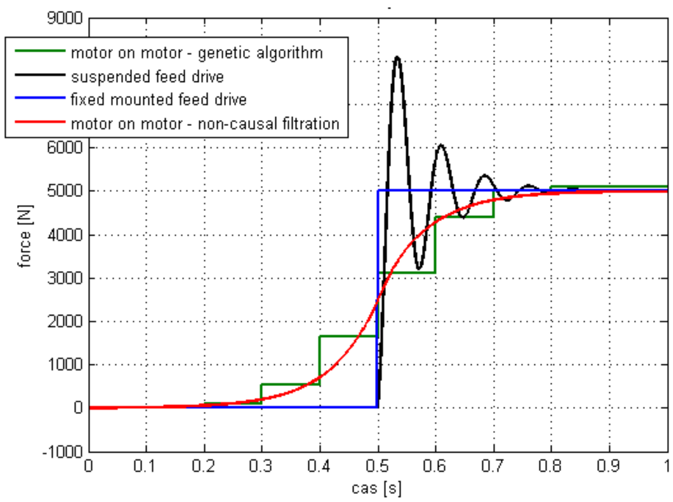

Fig. 8. Time behavior of the reaction force obtained from non-causal filtration

The important issue which gives us information about the method quality is the power spectral density of the reaction force. As shown in Fig. 9 many frequencies are excited by the application of fixed-mounted principle. It is caused by the sharp profile of the reaction force. Better situation is by the application of the suspended feed drive. The time behavior of the reaction force is not so sharp and lower number of frequencies is excited. Finally the best solution is based on the “motor on motor” conception. As shown in Fig. 9 number of excited frequencies is minimal and their amplitudes are lower than by the other conceptions.

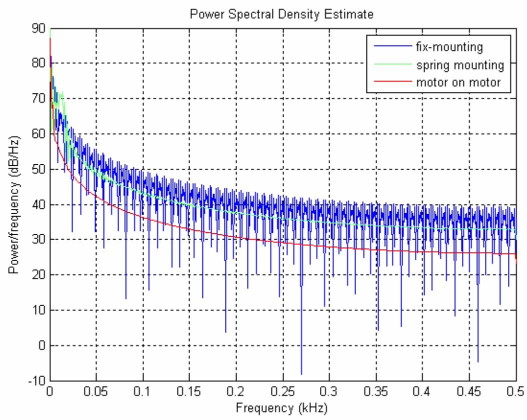

Fig. 9. Power spectral density comparison

3.3. REGULATION SCHEME

Regulation scheme in Fig. 10 is generally splitted into two parts. The first one is common regulation of the motion axis. It can be based on common cascade regulation with position and velocity loop. The second part of the regulation is focused on reaction force transformation through middle mass movement proposed in the previous chapter. It is also divided into two parts where the first one deals with pre-computation of the reaction force by the non-causal filtration and the second one with absolutization.

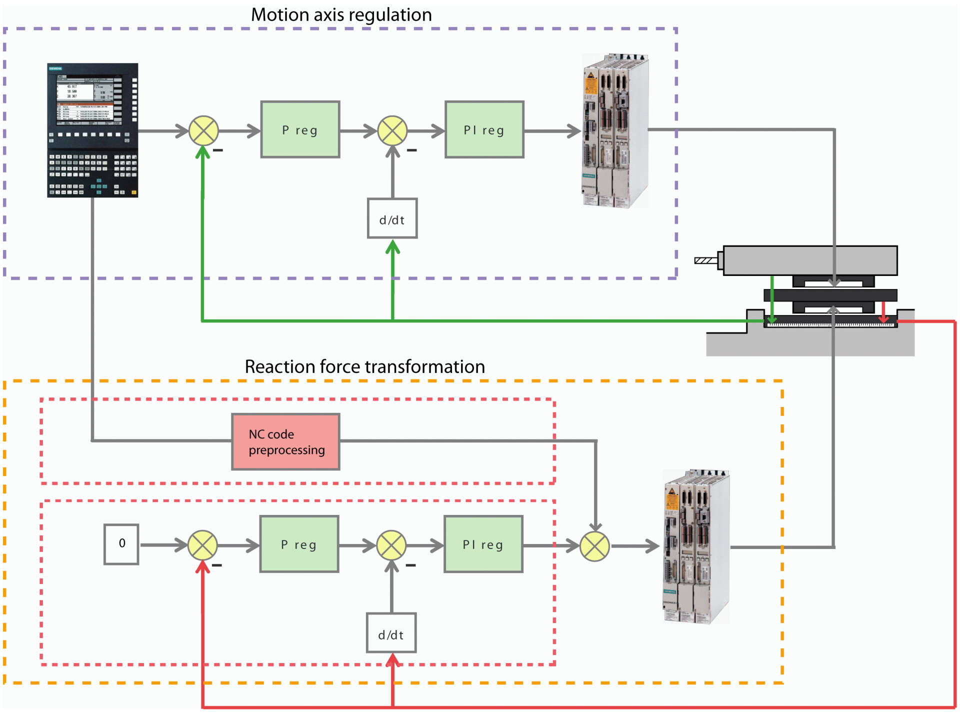

Fig. 10. Regulation scheme

The non-causal filtration regulation part is based on NC code preprocessing designed in the previous chapter. Based on the simulation model, the NC code (demanded position) is earliest transformed with the aim of preparing the best initial condition of the feed drive. The absolutization part is then an independent regulation loop with lowered dynamic parameters. Its main purpose is to hold the middle mass position in restricted range in case of disturbance force and mathematical model inaccuracy.

4. SIMULATION TESTING

Z axis of experimental milling center LM-2 placed in RCMT (Research Center of Manufacturing Technology, CTU in Prague) laboratories was chosen for simulation testing of the method and the machine tool is shown in Fig. 11. This machine has 3-highly dynamical axes equipped with linear motors with possibility to involve suspended feed drive in each axis. A complete FEM and simulation model of LM-2 was created, so it is possible to make simulation tests of the method involved in Z-axis and check its influence on the vibration suppression.

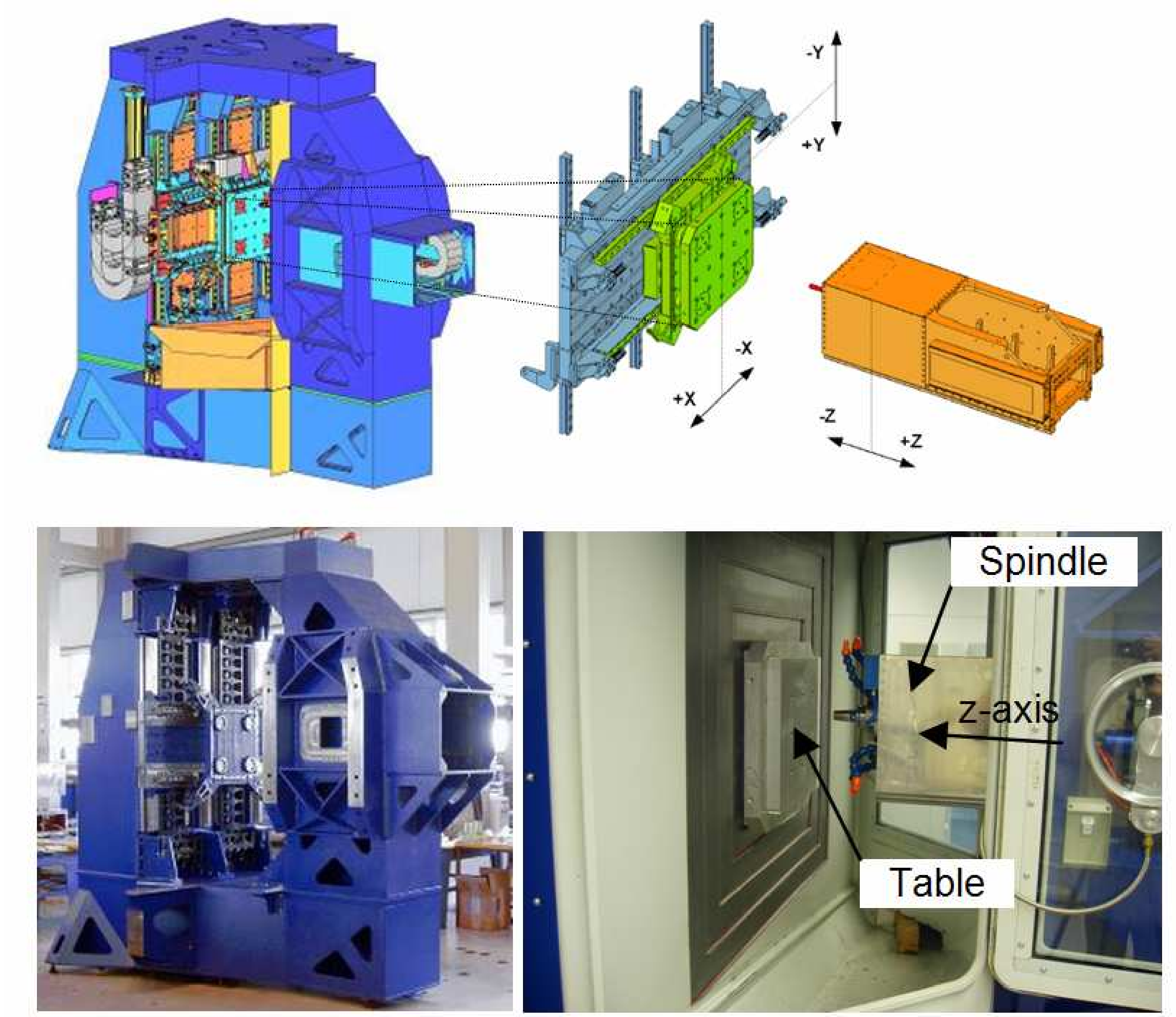

Fig. 11. LM-2 machine tool – CAD model and photo

4.1. MACHINE TOOL MODEL

The machine tool FEM model is created by shell elements and it contains all important parts of the machine tool. In Fig. 12 is shown FEM model with highlighted Z-axis which is mathematically equipped with motor on motor conception.

The detailed motor on motor construction in the FEM model is shown in Fig. 13. Movement of the spindle and middle mass (shared secondary part of the linear motors) is allowed by means of extremely low springs stiffness in Z-axis.

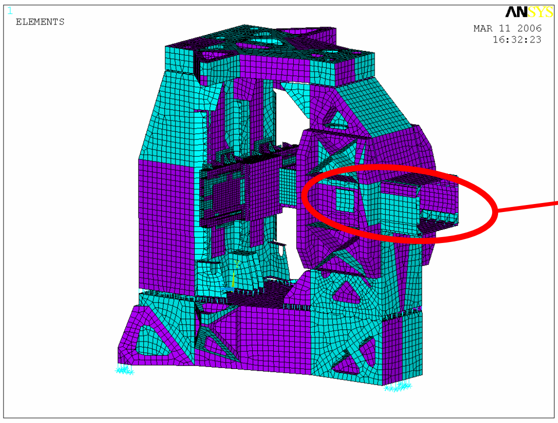

Fig. 12. FEM model of LM-2 machine tool

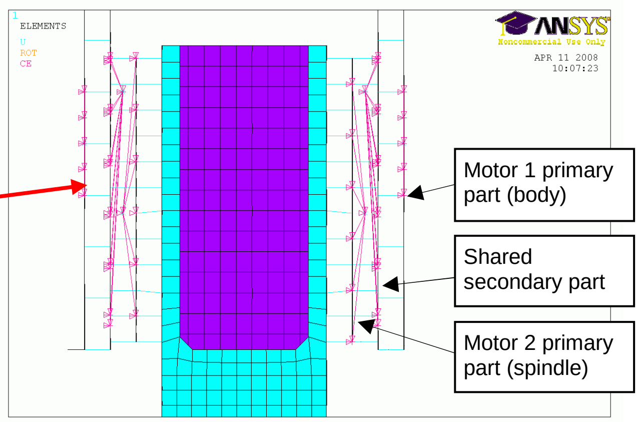

Fig. 13. Motor on motor FEM implementation

Modal analysis of the described FEM model is performed and modal matrix Φ with eigen frequency vector ω are stored. Because we have modal analysis results and the common dynamic equation that solves machine tool dynamics looks like equation

$$M\ddot{x}_d + C\dot{x}_d + Kx_d = f \tag{5}$$

it is necessary to involve by the substitution [6,7]

$$x_d = \Phi z \tag{6}$$

where Φ is the modal matrix and z is the vector of modal coordinates. We obtain modified equation (7) by connection of equations (5) and (6).

$$M\Phi\ddot{z} + C\Phi\dot{z} + K\Phi z = f \tag{7}$$

The modal matrix is normed by the mass matrix and assuming symmetry matrices M and K we can write

$$\Phi^T M\Phi = E \tag{8}$$

$$\Phi^T K\Phi = diag\left(\omega_i^2\right) \tag{9}$$

By multiplying equation (7) with matrix Φ^T from the left side and using relations (8) a (9) we obtain

$$\ddot{z} + \Phi^T C\Phi\dot{z} + diag\left(\omega_i^2\right)z = \Phi^T f \tag{10}$$

By substitution equation (11)

$$\Phi^T C\Phi = diag\left(2\xi_i\omega_i\right) \tag{11}$$

in the equation (10) we obtain

$$\ddot{z} + 2\xi\Omega\dot{z} + \Omega^2 z = \Phi^T f \tag{12}$$

where

$$\xi = diag(\xi_i) \text{ and } \Omega = diag(\omega_i) \tag{13}$$

Equation (12) describes machine tool dynamics with exploitation of modal matrix and eigen frequency vector. It can be easily transformed into state space approach (14) which is suitable for Matlab/Simulink simulations [6].

$$\dot{x} = \begin{bmatrix} \ddot{z} \\ \dot{z} \end{bmatrix} = \begin{bmatrix} -2\xi\Omega & -\Omega^2 \\ 1 & 0 \end{bmatrix} \begin{bmatrix} \dot{z} \\ z \end{bmatrix} + \begin{bmatrix} \Phi^T \\ 0 \end{bmatrix} f = Ax + Bf, \qquad y = \begin{bmatrix} \Phi & -0 \\ 0 & \Phi \end{bmatrix} \begin{bmatrix} \dot{z} \\ z \end{bmatrix} = Cx \tag{14}$$

Described state space model connected with control algorithm designed in chapter 3.3 presents virtual model of machine tool LM-2 with motor on motor conception. Simulation tests were performed on it and the results are described in the following chapter.

4.2. SIMULATION RESULTS

Position ramp of the Z-axis with spindle was performed as a first testing set. Before the testing simulation demanded position was transformed into a force impulse by means of non-causal filtration mentioned in chapter 3. The final shape of the force impulse in comparison with the full reaction force is shown in Fig. 14 and the simulated position ramp in Fig. 15. Machine tool body reaction force with an active absolutization control loop is shown in Fig. 16. We can see that the new reaction force has extremely low amplitude and smooth shape. Thanks to it machine tool structural shapes are not excited and position loop gain Kv can be tuned.

Important information about the method quality is also middle mass displacement. This displacement has to be minimal however long enough. The middle mass displacement associated with the position ramp is shown in Fig. 17. From the figure flows, that we can achieve extremely high dynamical parameters by small control displacement of the middle

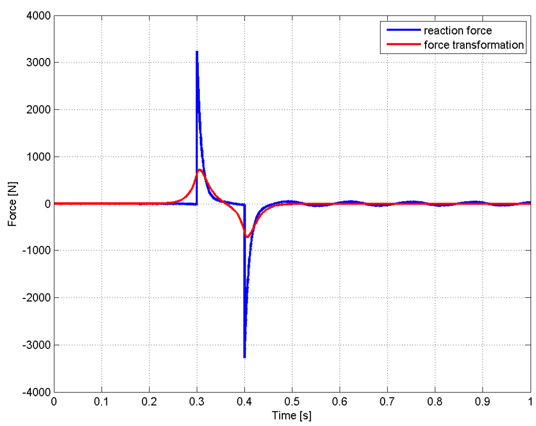

Fig. 14. Force impulse and reaction comparison

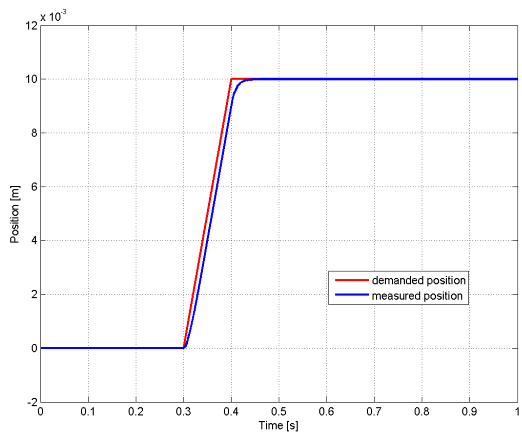

Fig. 15. Position ramp

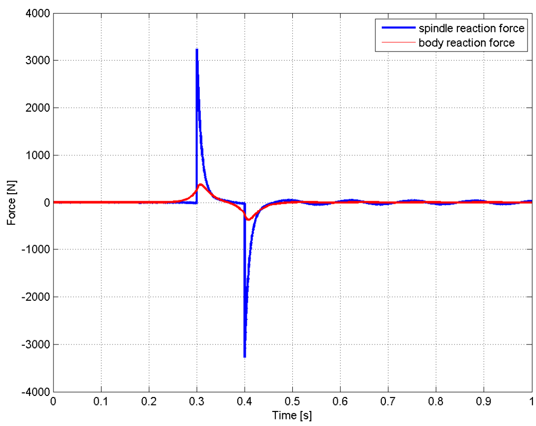

Fig. 16. Reaction force with active absolutization

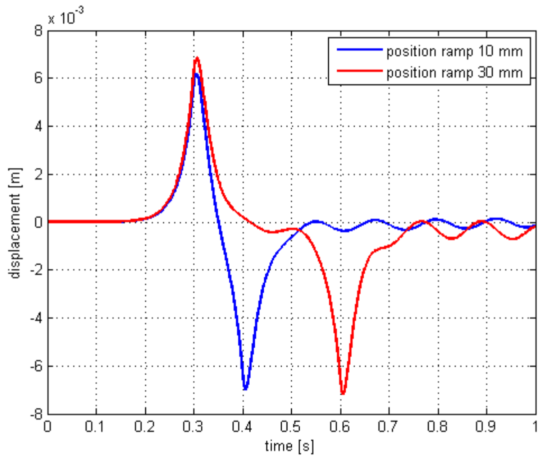

Fig. 17. Middle mass displacement

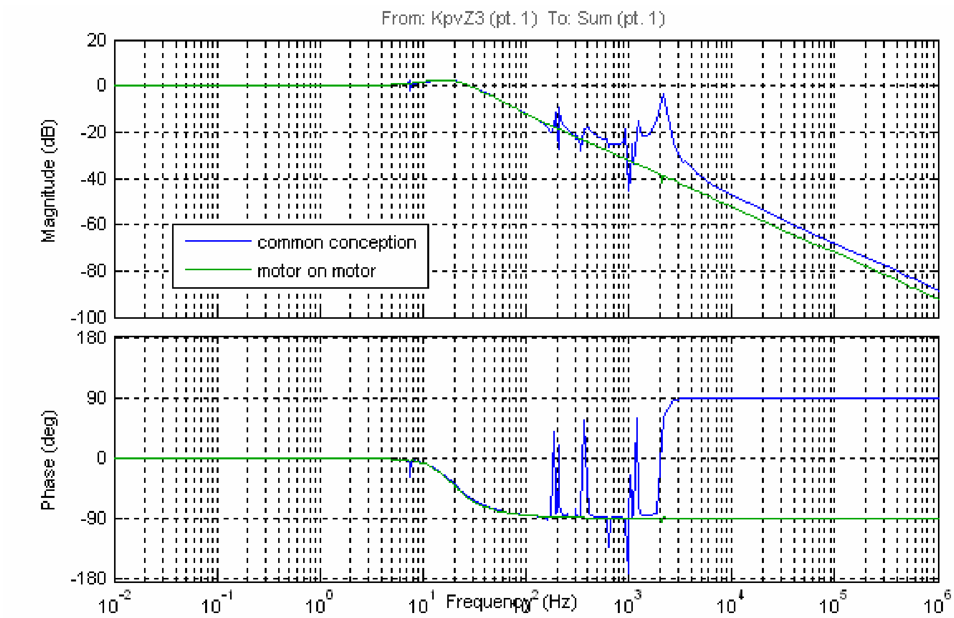

Fig. 18. Velocity loop Bode plot

mass. The same result is also visible from the velocity loop Bode plot in Fig. 18. Motor on motor conception does not excite structural shapes of machine tool by high dynamic movement thus the dynamic parameters can be improved.

The last two figures represents dynamical stiffness test that give us information about disturbance force immunity. In the Fig. 19 is shown parasite displacement of the motion axis by force disturbance amplitude 500 N. In the Fig. 20 is then shown middle mass movement connected with this disturbance force. The motor on motor conception that is characterized by series connection of two linear motors improves motion axis dynamical stiffness by means of position loop gain Kv improvement. Nevertheless it is connected with bigger displacement of the middle mass caused by “lazy” absolutization.

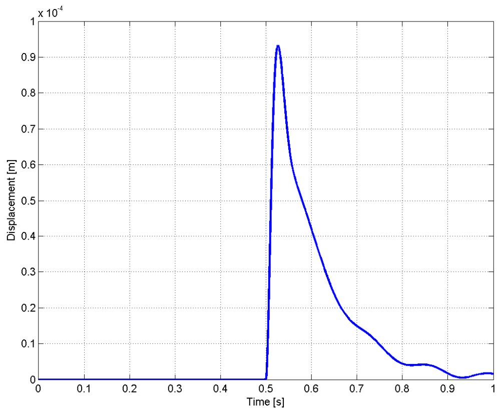

Fig. 19. Dynamical stiffness – spindle displacement

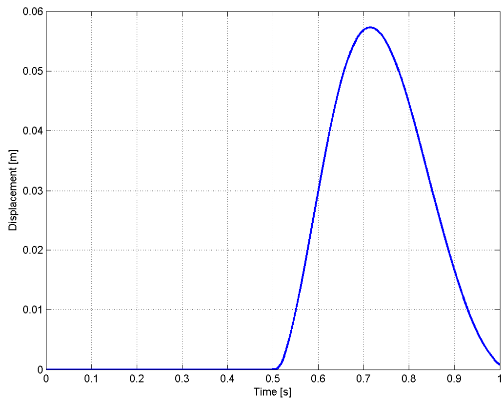

Fig. 20. Dynamical stiffness – middle mass displacement

5. EXPERIMENTAL TESTING

Because the real implementation of the described method on the LM-2 machine tool is extremely expensive, first experimental testing was performed in frame of cooperation with RCMT on finished experimental testing bed STD-1 that is placed in RCMT laboratory and is shown in Fig. 21. It is suitable for "motor on motor" method application only by a small modification. Schematic structure of the experiment including imaginary spindle and work piece is shown in the Fig. 22.

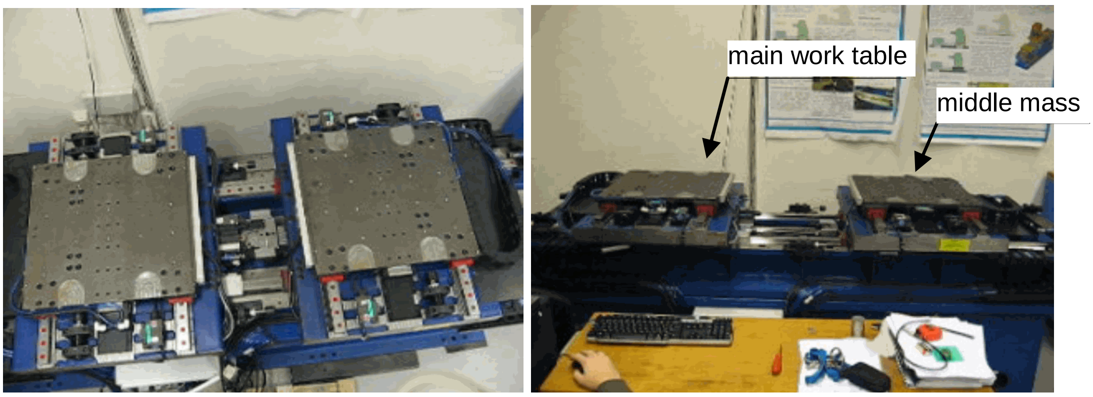

Fig. 21. Experimental testing bed STD-1

As shown in the Fig. 23, the experimental bed STD-1 is equipped with two independent tables between them is included linear motor. This linear motor represents the main working actuator (F2) and with the measurement x_{2a} ensures precision positioning of the main motion axis. The table which represents middle mass is connected with the machine frame by the help of reaction and absolutization motor (F1) and transforms the reaction force.

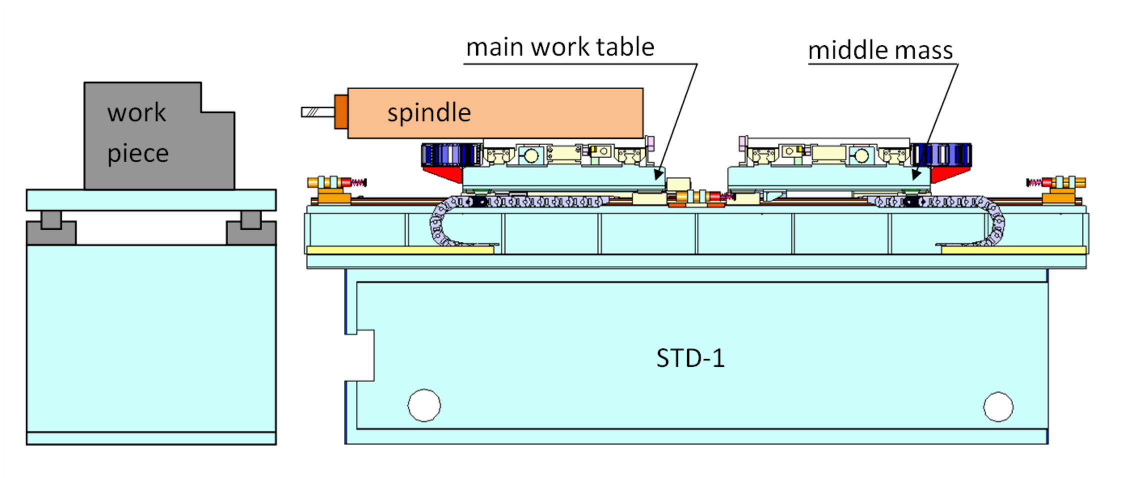

Fig. 22. Schematic drawing of experiment on STD-1

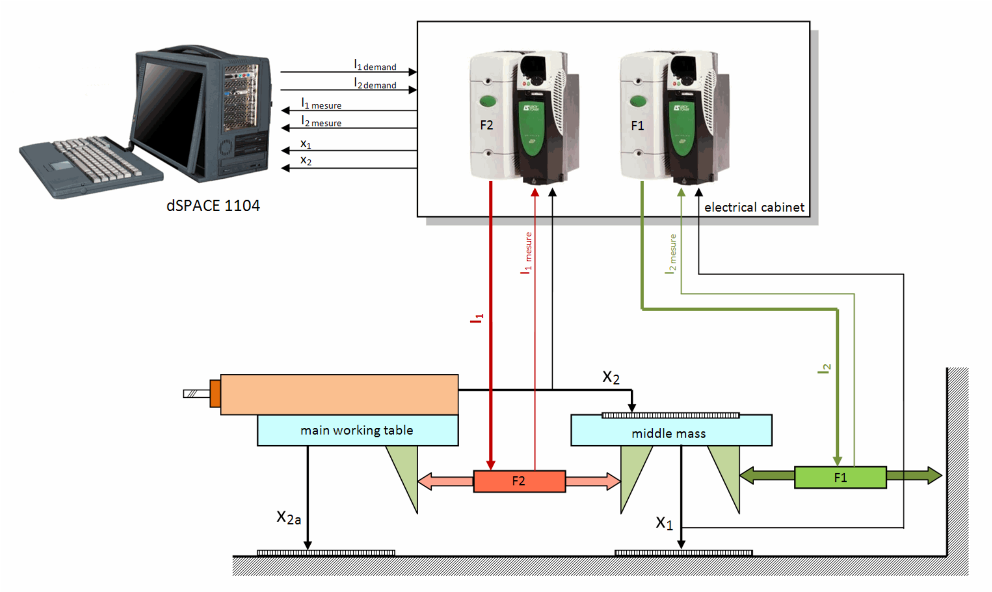

Fig. 23. Schematic drawing of coordinates of experiment on STD-1

Motor parameters:

- main working motor F_2, F_{2max}= 2 x 1320 N, k_2= 224 N/A
- reaction and absolutization motor F_1, F_{1max}= 2 x 288 N, k_2= 227 N/A

The force effect of the main working motor is software restricted to the force capacity of reaction motor because of elimination of different force effects.

The main control algorithm of each motor is performed in dSpace platform and Control Desk software equipment, which is compiled from a regulation scheme developed in Matlab/Simulink (depicted in Fig. 24). The shown regulation scheme is splitted into some parts which were described in chapter 3.3 of this paper. These are parts main motor (position regulation of the main axis), pre-computed reaction force and absolutization. The pre-computed reaction force is obtained by the transformation of measured actuating force of the main motor (F2) by blocked motion of the middle mass.

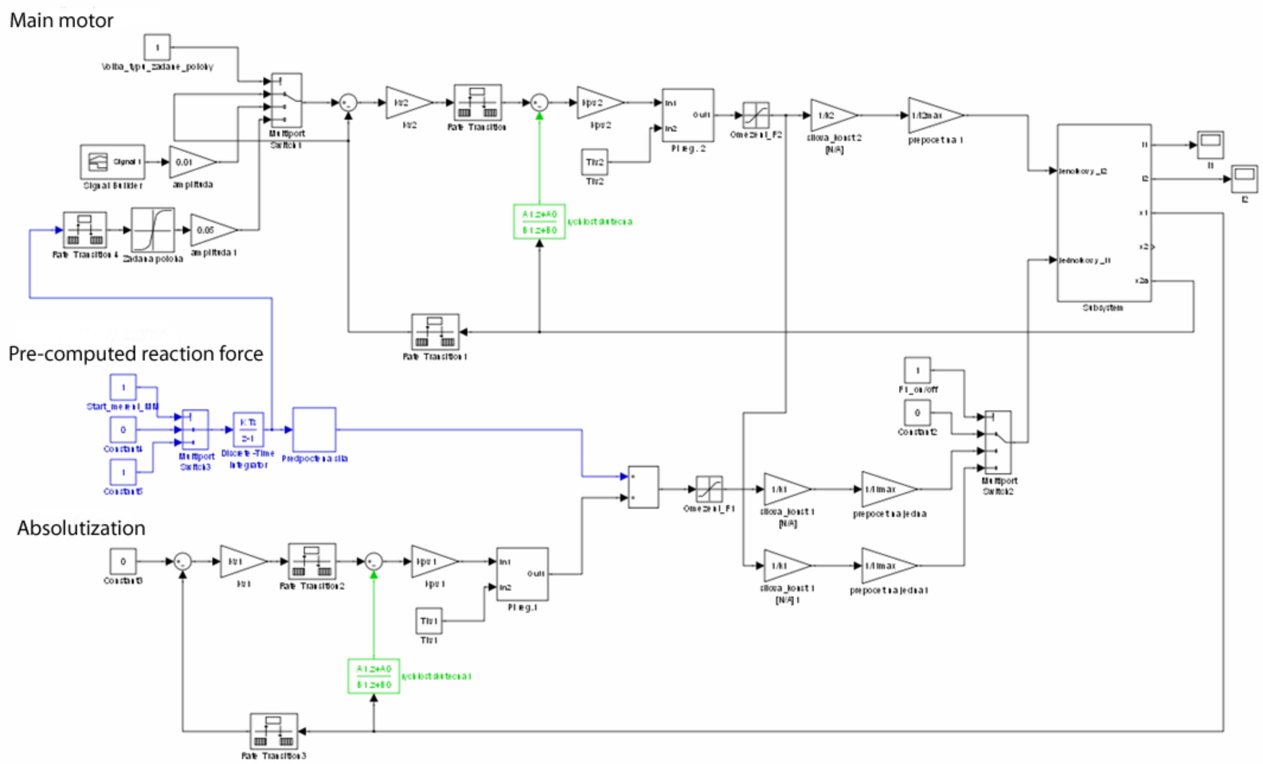

Fig. 24. Control block diagram

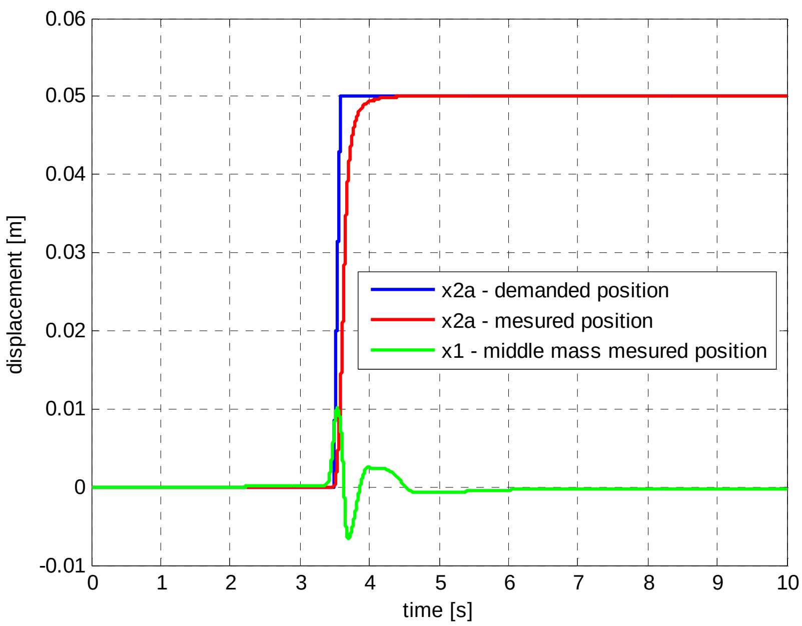

Fig. 25. Measured displacement

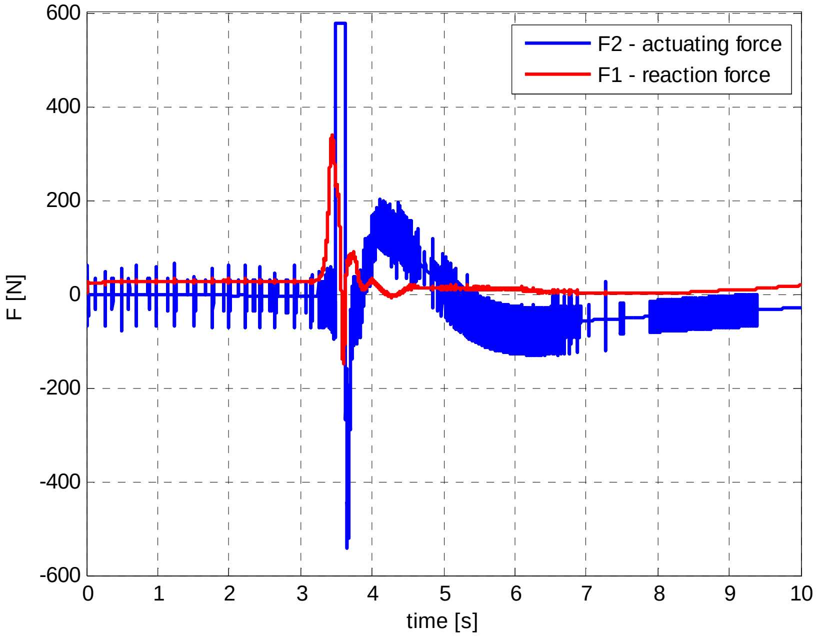

Fig. 26. Measured actuating and reaction force

Measured displacement and force behavior are shown in Fig. 25 and Fig. 26. In the first figure it is shown the time behavior of the demanded and measured position of the motion axis by displacement ramp with amplitude 50 mm. The green line in the figure shows middle mass displacement which is significantly smaller than displacement of the main motion axis. In the second figure it is shown the time behavior of measured actuating and reaction force.

From the measured characteristics it follows that the “motor on motor” method lowers reaction force amplitude by keeping the actuating force and also makes the reaction force smoother. It is connected with elimination of structural oscillation of the machine tool. In addition, it is achieved only with a small middle mass displacement in order of millimeters, within the range significantly smaller than displacement of the main motion axis.

6. CONCLUSION

The designed technology for the impulse decoupling brings new level of the motion dynamics to the machine tool branch. We can achieve reduction of the reaction forces and excited frequencies by exploitation the new decoupling principle. The machine tool equipped with the “motor on motor” conception will be protected from the vibrations and allows high dynamics and precise machining.

The technology is based on the possibility to fully control the reaction force. It is possible thanks to the additional active actuator with relative small stroke which is in series with the main motion motor.

The main target of the paper is to short introduce the method and bring information about the simulation and experimental testing. The method was simulation tested on experimental milling center LM-2 and the experimental tests were performed on testing bed STD-1.

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