ANNALS of Faculty Engineering Hunedoara
– International Journal of Engineering
Tome XIII [2015] – Fascicule 1 [February]
ISSN: 1584-2665 [print]; ISSN: 1584-2673 [online]
a free-access multidisciplinary publication of the Faculty of Engineering Hunedoara

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VIRTUAL MODELING AND SIMULATION OF CNC MACHINE FEED DRIVE SYSTEM

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Abstract: This paper deals with virtual modelling and simulation of the complex CNC machine feed drive system. The first phase of our research was modelling of the very complex structure of the CNC milling machine feed drive which consists of many elements (position, velocity and current control regulators, actuators, mechanical transmission elements, etc.). All these elements have great influence on the machine tool important parameters like movement stability, positioning accuracy and dynamic stiffness. The modeling was done with Matlab-SIMULINK and Matlab-Sim Scape Toolbox software. The Matlab-Sim Scape Toolbox allowed us to use the complete CAD model of the geometry of the machine tool in modeling and automatically calculating the selected properties. The influence of changing and optimization of several feed drive parameters (position loop gain Kv, proportional gain Kp of the velocity controller, integral gain of velocity controller-Tn, electrical drive time constant Te, total moving mass m, sampling period Ts, etc.) on positioning accuracy and dynamic stiffness were simulated, tested and validated. The ready Matlab-Simulink and Sim Scape models were initially visualized in the Matlab program. They were very simplified, comparing with their later visualization in Virtual Reality EON Studio program.
Keywords: virtual modelling, simulation, CNC machine, feed drive

1. INTRODUCTION

Since the early 1990s, a paradigm shift in manufacturing from 'real' to 'virtual' production has resulted in a build-up of research interests in the field. With the aid of computers, it becomes possible to simulate some of the activities of a physical manufacturing system. The main objective is to understand and emulate the behaviour of a particular manufacturing system on a computer prior to physical production, thus reducing the amount of testing and experiments on the shop floor. By using a virtual system, less material is wasted and interruptions to the actual machine on the shop floor can be avoided [3,7].

The goal of present manufacturing technology is to produce even the first part correctly in a shortest time and most cost effective way. Since the product complexities increase and the competitive product life cycle times are reduced, the realisation and testing of physical prototypes become major bottlenecks for the successful and economically advantageous production of modern machine tools [8].

Presently, the machine tool builders can no longer afford the time-consuming and cost-intensive manufacturing and testing of physical prototypes to detect weak spots and optimise the design. Instead, the design processes of modern machine tools employ "virtual prototyping" technology to reduce the cost and time of hardware testing and iterative improvements of the physical prototype. The virtual prototype of a machine tool is a computer simulation model of the physical product that can be presented, analysed and tested like a real machine. Iterative changing of a virtual model of the machine tool during the design process and exercising design variations until the performance requirements are achieved, reduce the whole product development time and cost significantly [1].

The most important parts of every machine tool are the feed drives. Feed drives for CNC machine tools are very complex electro-mechanical systems. They must demonstrate especially good control dynamics, position accuracy, load stiffness, acceleration capacity and process velocity [2, 6].

This paper deals with virtual modelling, simulation, optimization and visualisation of CNC machine feed drive system.

2. MODELLING/SIMULATION OF VIRTUAL CNC MACHINE FEED DRIVE SYSTEM WITH MATLAB/SIMULINK AS ONE MASS MODEL

The productivity and accuracy of every CNC machine tool highly depends on feed drives characteristics. The feed drive main purpose is to move the working parts of machine tool (working table, tool unit, spindle unit etc.) through machine axes. A separate feed drive is necessary for every machine axis. Although, generally, feed drives have very simple kinematics structure their optimal design is problem which consists of selection of actuators, mechanical transmission elements and applying and tuning current, velocity and position controllers. All these elements must satisfy some requirements as a system, Also they have great influence on the machine tool important parameters like movement stability, positioning accuracy and dynamic stiffness [4, 9].

Usually the feed drive consists of actuator (rotary or linear), mechanical transmission elements and cascade control of three loops (PI current control loop, PI velocity control loop, P position control loop). The mechanical transmission elements comprise all the machine parts which lie in the torque (power) transmission flow between the actuator and the tool or workpiece. In different design variants the following mechanical transmission elements are most frequently used: clutches, ball lead screw and nut units, rack and pinion units, bearings, gears, gearboxes.

First of all we created a virtual 3D CAD model of one portal CNC milling machine (figure1). We planed a direct lead screw feed drive for all 3-axes (figure2)

The technical data of the feed drive for the virtually modelled y-axis are: (maximal force Fmax=3500 N, maximal speed Vmax= 15 m/min, nominal speed Vnom=10 m/min, acceleration a=2 m/s ^{2} , total moving mass m=60 kg, diameter of lead screw dsp= 16 mm=0.016 m, pitch of the lead screw hsp=5 mm=0.005 m, Digital AC motor B&R 8LSA43.ee030ffgg-0)

The simplified one mass models of the position and velocity loops of y-axis feed drive system are presented on figure 3 and figure4.

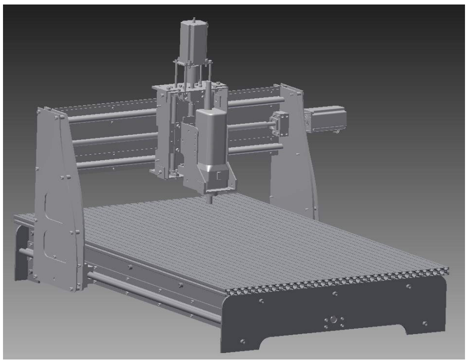


Figure 1. CAD model of the CNC machine tool

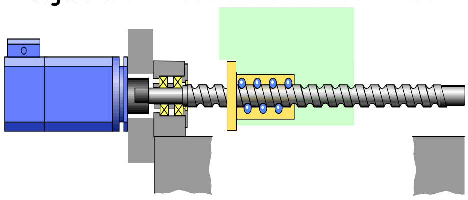


Figure 2. Direct lead screw feed drive

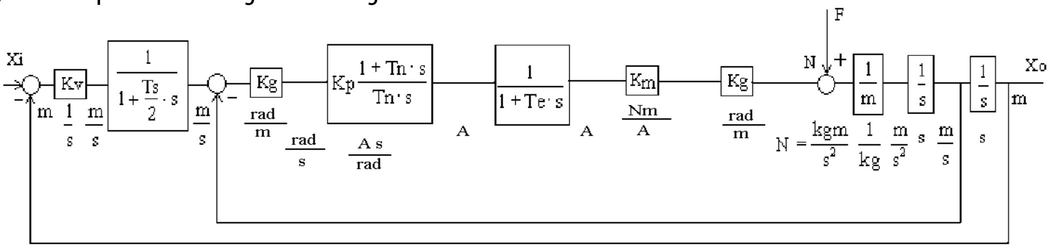


Figure 3. Simplified one mass model of the position loop for y-axis feed drive of the virtual portal CNC milling machine

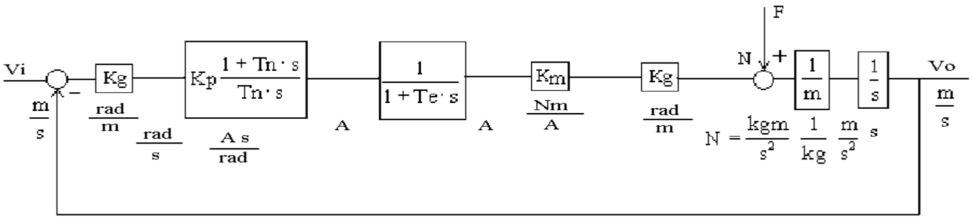


Figure 4. Simplified one mass model of the velocity loop for y-axis feed drive of the virtual portal CNC milling machine

The parameters in the models given on figure3 and figure 4 are: Kv-position loop gain [1/s], Ts-sampling period [s], s-Laplace operator, Kp-proportional gain of the velocity controller [As/rad], Tn-integral time of the velocity controller [s], Te-time constant of the current loop [s], F-disturbance force [N], m-mass of the moving elements [kg], Xi-input position [m], Xo-output position [m], Km-torque constant of the rotary motor [Nm/A], Kg-constant for transformation of linear in rotary movement [rad/m].

$Kg=\frac{2\pi\cdot i}{hsp}$, where i is reduction ratio, and hsp is pitch of the lead screw [m]. In our case i=1 for direct screw drive.

We have implemented for the CNC machine y-axis feed drive a dual loop controller with PI controller for the speed loop and P controller for the position loop. In fact the speed signal is derived from the position measurement by digital derivation.

The transfer function of position loop for the CNC machine feed drive y-axis is given with equation (1):

$$\frac{Xo(s)}{Xi(s)}=\frac{b_1s+b_0}{a_5s^5+a_4s^4+a_3s^3+a_2s^2+a_1s+a_0} \qquad (1)$$

Coefficients in the equation (1) are:

$$b_1=Tn,\; b_0=1,\; a_5=\frac{Ts\cdot Tn\cdot Te\cdot m}{2\cdot Kp\cdot Kv\cdot Km\cdot Kg^2},\; a_4=\frac{Tn\cdot m}{Kp\cdot Kv\cdot Km\cdot Kg^2}\cdot\left(Te+\frac{Ts}{2}\right),\; a_3=\frac{Tn}{Kv}\cdot\left(\frac{m}{Kp\cdot Km\cdot Kg^2}+\frac{Ts}{2}\right),\; a_2=\frac{1}{Kv}\cdot\left(Tn+\frac{Ts}{2}\right),\; a_1=\frac{1}{Kv}+Tn,\; a_0=1$$

The transfer function of velocity loop for the CNC machine feed drive y-axis is given with equation (2):

$$\frac{Vo(s)}{Vi(s)}=\frac{b_1\cdot s+b_0}{a_3\cdot s^3+a_2\cdot s^2+a_1\cdot s+a_0} \quad (2)$$

Coefficients in the equation (2) are: $b_1=Tn,\ \ b_0=1,\ \ a_3=\frac{Tn\cdot Te\cdot m}{Kp\cdot Km\cdot Kg^2},\ \ a_2=\frac{Tn\cdot m}{Kp\cdot Km\cdot Kg^2},\ \ a_1=Tn,\ \ a_0=1$

Transfer function of the compliance for the CNC machine feed drive y-axis of the virtual portal milling machine is given with equation (3)

$$\frac{Xo(s)}{F(s)}=\frac{b_3s^3+b_2s^2+b_1s+b_0}{a_5s^5+a_4s^4+a_3s^3+a_2s^2+a_1s+a_0} \quad (3)$$

Coefficients in the equation (3) are:

$$b3=Te\cdot\frac{Ts}{2},\ b2=Te+\frac{Ts}{2},\ b1=1,\ b0=0,\ a5=m\cdot Te\cdot\frac{Ts}{2},\ a4=m\cdot\left(Te+\frac{Ts}{2}\right),\ a3=m+\frac{Kp\cdot Km\cdot Kg^2\cdot Ts}{2},$$

$$a2=\frac{Kp\cdot Km\cdot Kg^2\cdot}{Tn}\cdot\left(Tn+\frac{Ts}{2}\right),\ a1=\frac{Kp\cdot Km\cdot Kg^2\cdot}{Tn}\cdot(1+Kv\cdot Tn)\ \text{and}\ a0=\frac{Kp\cdot Km\cdot Kg^2\cdot}{Tn}\cdot Kv.$$

Using the models given on figure3 and figure4 we created MATLAB/SIMULINK one mass model given on figure 5.

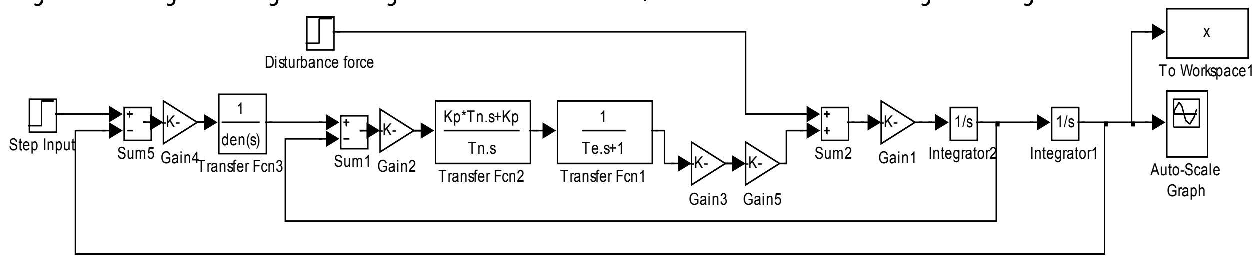


Figure 5. Simulink one mass model for y-axis feed drive

With the aid of the bode diagrams of the position (figure 6) and velocity loop (fig 7) of the y-axis feed drive obtained with SIMULINK one mass model shown on figure5, we calculated the bandwidth of the position and velocity loop.

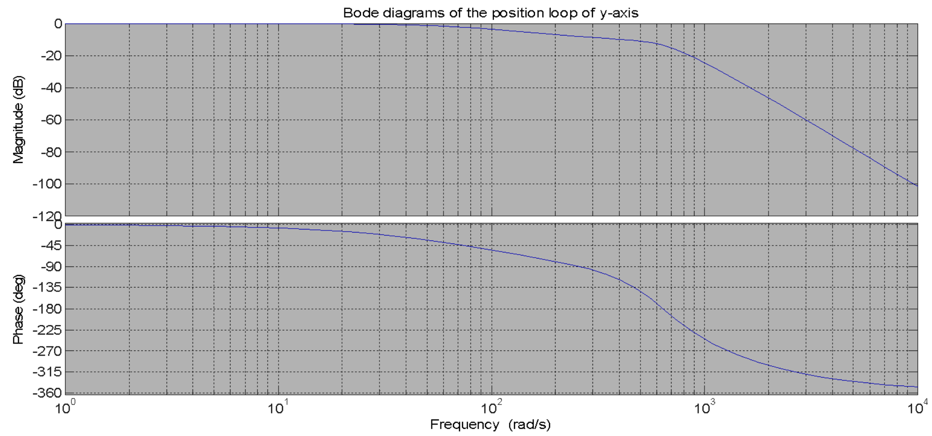


Figure 6. Bode diagrams of the position loop of the y-axis of the virtual portal milling machine

Bandwidth of the position loop of the y-axis of the virtual portal milling machine is approximately 14.5 Hz

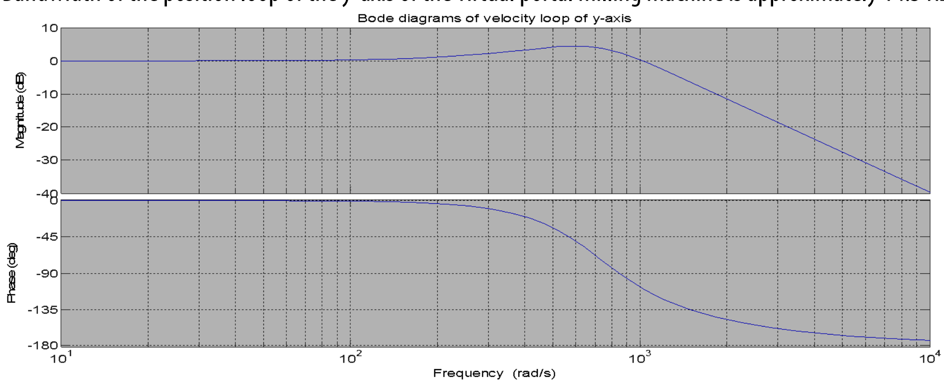


Figure 7. Bode diagrams of the velocity loop of the y-axis of the virtual portal milling machine

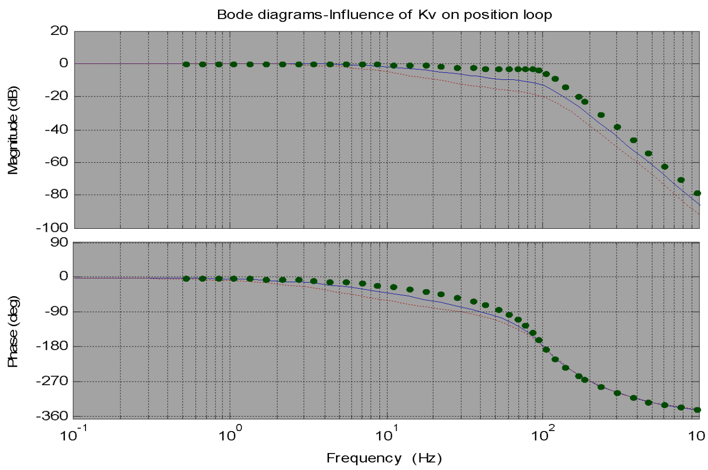
Bandwidth of the velocity loop of the y-axis of the virtual portal milling machine is approximately 196 Hz.

Amplitude in bode diagrams can be calculated with the equation (4)

$$|F(j\omega)|\ dB = 20 \log |F(j\omega)| \qquad |F(j\omega)| = 10^{\frac{|F(j\omega)|dB}{20}} \tag{4}$$

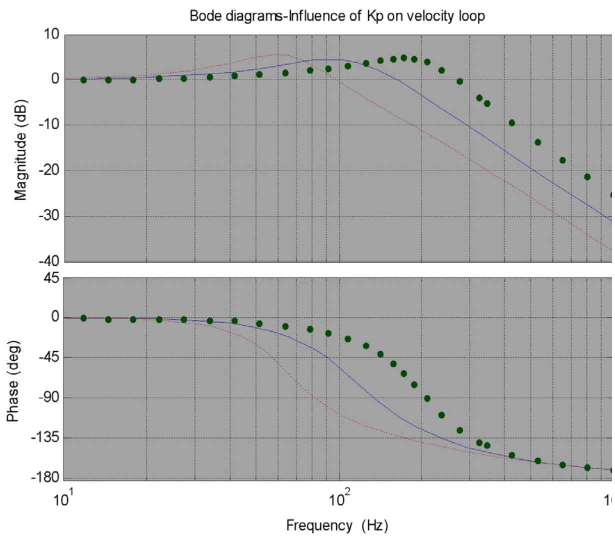
Cut-off angular frequency ωg is a point at which the amplitude response has dropped by -3 dB. A conversion of above equation results in $|F(j\omega)| = 10^{\frac{-3}{20}}$ =0.7079. The frequency range from 0 to ωg is called bandwidth.

Using the SIMULINK one mass model for CNC machine y-axis feed drive shown on figure 5 we simulated the influence of changing of the Kv, Kp, Tn, m, Te and Ts on the bandwidth of the position loop and velocity loop (examples are given on figure 8 and figure 9) and compliance of feed drive of y-axis of the virtual portal milling machine in frequency domain (examples are given on figure10 and figure11).



Kp=0.017 [As/rad], Tn=0.0028 [s], Ts=0.002 [s], Te=0.0007 [s], m=60 [kg]

Figure 8. Influence of different values of the position loop gain Kv on the bandwidth on position loop of y-axis feed drive



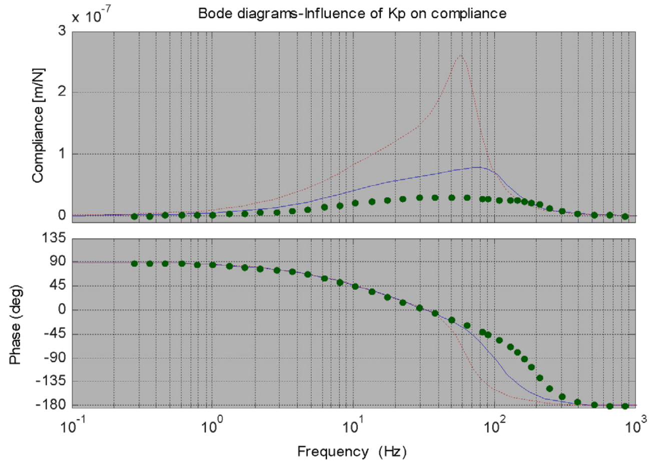
(------)Kp=0.017 [As/rad]; (- - -) Kp=0.0085 [As/rad]; (. . . .) Kp=0.034 [As/rad] Tn=0.0028 [s], Te=0.0007 [s], m=60 [kg]

Figure 9. Influence of different values of the proportional gain of the velocity controller Kp on the bandwidth on velocity loop of y-axis feed drive

Nominal values of the parameters of the y-axis feed drive of the virtual milling machine are given below: (Kv=80 -position loop gain [1/s], Ts=0.002 -sampling period [s], Kp=0.017 -proportional gain of the velocity controller [As/rad], Tn=0.0028 -integral time of the velocity controller [s], Te=0.0007 -time constant of the current loop [s], m=60-mass of the moving elements [kg], Km= 1.63 -torque constant of the rotary motor [Nm/A], Kg= 1256 -constant for transformation of linear in rotary movement [rad/m].

In the simulations one parameter has been changed, and the others were kept constant.

The parameter was changed ± 100%.



(------)Kp=0.017 [As/rad]; (- - -) Kp=0.0085 [As/rad]; (. . . .) Kp=0.034 [As/rad] Kv=80[1/s], Tn=0.0028 [s], Ts=0.002 [s], Te=0.0007 [s], m=60 [kg]

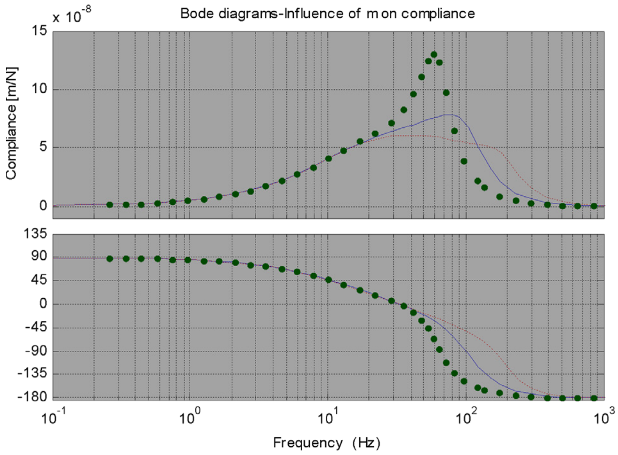
Figure 10. Influence of different values of the proportional gain of the velocity controller Kp on compliance of y-axis feed drive

One of the most important requirements with regard to feed drive system concerns its sensitivity to load disturbances. The qualitative measure of this sensitivity is the feed drive stiffness.

The dynamic feed drive system stiffness can be defined as a measure of influence of disturbance force F (torque T) on the output position Xo (angular position Θo) deviation in the transient period [5]

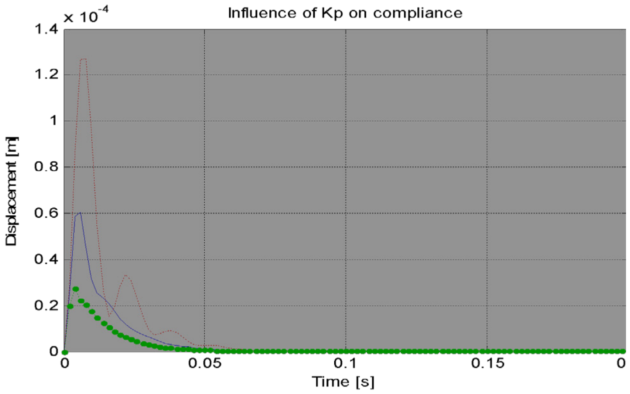
$$Sd(s) = \frac{F(s)}{Xo(s)} = \frac{T(s)}{\Theta o(s)} \tag{5}$$

From the simplified model of the position loop of y-axis of the portal milling machine dynamic stiffness for feed drive system becomes



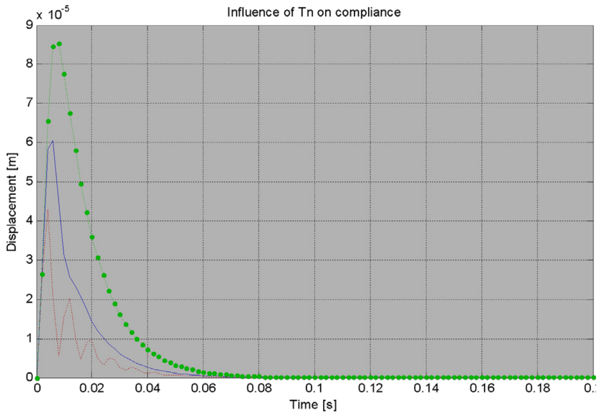
(------) m=60 [kg]; (- - -) m=30 [kg]; (. . . .) m=120 [kg]
Kv=80[1/s], Kp=0.017 [As/rad], Tn=0.0028 [s], Ts=0.002 [s], Te=0.0007 [s]

Figure 11. Influence of different values of the mass of the moving elements m on compliance of y-axis feed drive



(------) Kp=0.017 [As/rad] Sd= 16.52 [N/μm];
(- - -) Kp=0.0085 [As/rad] Sd=7.87 [N/μm] (. . . .) Kp=0.034 [As/rad] Sd= 36.7 [N/μm] Kv=80[1/s], Tn=0.0028 [s], Ts=0.002 [s], Te=0.0007 [s], m=60 [kg] , F=1000 [N]

Figure 12. Influence of different values of the proportional gain of the velocity controller Kp on the compliance of y-axis feed drive



(------) Tn=0.0028 [s] Sd=16.52 [N/μm]; (- - -) Tn=0.0014 [s] Sd=23.2 [N/μm] (. . . .) Tn=0.0056 [s] Sd= 11.73 [N/μm]
Kv=80[1/s], Kp=0.017 [As/rad], Ts=0.002 [s], Te=0.0007 [s], m=60 [kg], F=1000 [N]

Figure 13. Influence of different values of the integral time of the velocity controller Tn on the compliance of y-axis feed drive

$$Sd(s)=\frac{F(s)}{Xo(s)}=\frac{a_5s^5+a_4s^4+a_3s^3+a_2s^2+a_1s+a_0}{b_3s^3+b_2s^2+b_1s+b_0} \quad (6)$$

Coefficients in the equation are:

$$b3=Te\cdot\frac{Ts}{2},\ b2=Te+\frac{Ts}{2},\ b1=1,\ b0=0,\ a5=m\cdot Te\cdot\frac{Ts}{2},\ a4=m\cdot\left(Te+\frac{Ts}{2}\right),\ a3=m+\frac{Kp\cdot Km\cdot Kg^2\cdot Ts}{2},$$

$$a2=\frac{Kp\cdot Km\cdot Kg^2\cdot}{Tn}\cdot\left(Tn+\frac{Ts}{2}\right),\ a1=\frac{Kp\cdot Km\cdot Kg^2\cdot}{Tn}\cdot(1+Kv\cdot Tn)\ \text{and}\ a0=\frac{Kp\cdot Km\cdot Kg^2\cdot}{Tn}\cdot Kv.$$

Compliance is in fact inverse value of dynamic stiffness.

For example, the influence of Kp and m on compliance in frequency domain for y-axis feed drive is shown on figure10 and figure11.

Also we made simulation of the dynamic stiffness of the feed drive of y-axis of the portal milling machine and influence of changing of the Kv, Kp, Tn, m, Te and Ts on dynamic stiffness in time domain, using the SIMULINK model given on figure 5.

$$Xo(t)=L^{-1}\left[\frac{Xo(s)}{F(s)}\cdot\frac{F}{s}\right][m] \quad (7)$$

To estimate the dynamic stiffness we will use the following equation

$$Sd=\frac{F}{\max Xo(t)}\ [N/m] \quad (8)$$

$$Sd=\frac{F}{\max Xo(t)\cdot 10^6}\ [N/\mu m] \quad (9)$$

where F is the disturbance force and maxXo(t) is the maximal position deviation (displacement) caused by the disturbance force. The disturbance force used in simulation F is 1000 [N].

The dynamic stiffness is in fact reciprocal value of compliance.

The influence on compliance of different values for Kp and Tn are shown on figure12 and figure13.

Table 1

changing range	Kv =40-160 [1/s]	Kp=0.0085-0.034 [As/rad]	Tn=0.0014-0.0056 [s]
increasing in %	400	400	400
changing Sd [N/μm]	15.89-17.71	7.87-36.7	23.2-11.73
changing Sd in %	+11.45	+466.33	-49.44
changing range	m=30-120 [kg]	Te=0.00035-0.0014 [s]	Ts=0.001-0.004 [s]
increasing in %	400	400	400
changing Sd [N/μm]	19.59-14.71	18.94-12.9	17.14-15.8
changing Sd in %	-24.91	-31.47	-7.82

Simulations have shown that increasing position loop gain Kv and proportional gain of the velocity controller Kp increase dynamic stiffness. Also increasing integral time of the velocity controller Tn, mass of the moving elements m, time constant of the current loop Te and sampling period Ts, decrease the dynamic stiffness (Table 1).

3. MULTI BODY MODELLING AND SIMULATION OF VIRTUAL CNC MACHINE FEED DRIVE SYSTEM WITH MATLAB SIM SCAPE TOOLBOX

The MATLAB Sim Scape Toolbox allowe us to use the complete CAD model of the geometry of the machine tool (figure1) in multi body modeling (figure 14 and figure 15) and automatically calculation of selected properties of the feed drives.

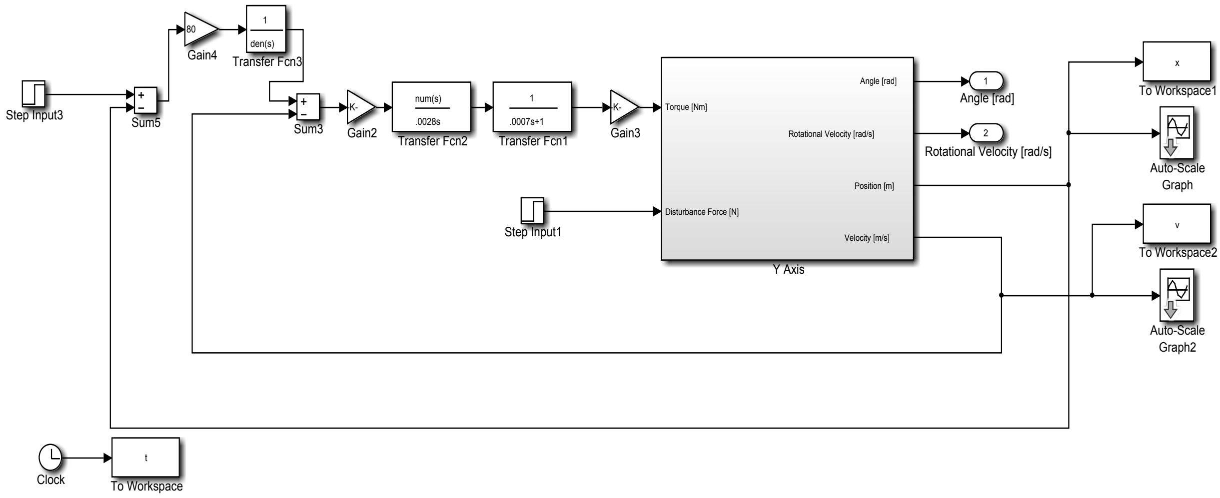


Figure 14. Multi body Sim Scape model of y-axis feed drive of virtual portal CNC milling machine

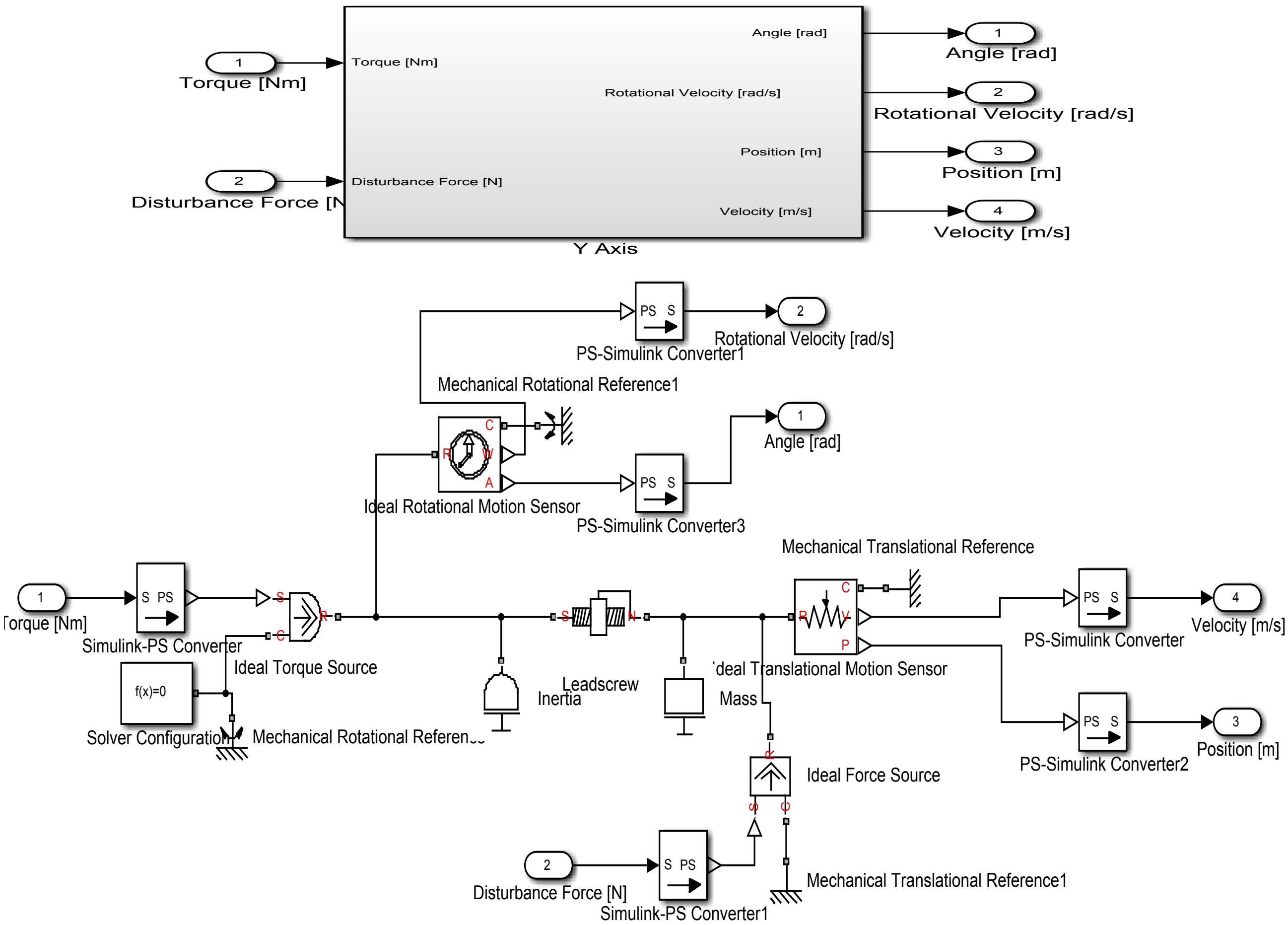
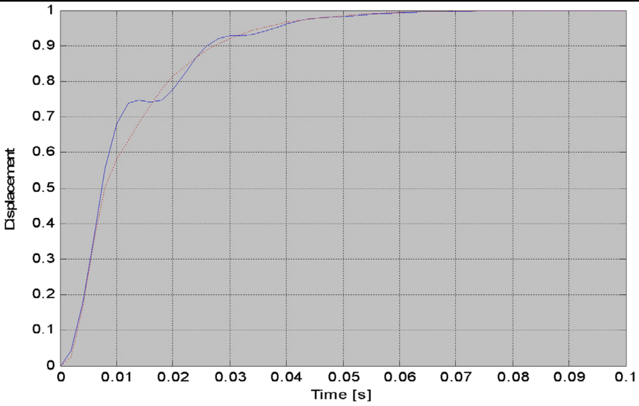


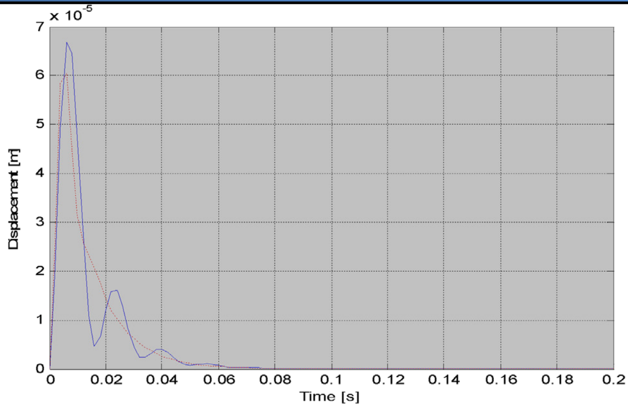
Figure 15. Sim Scape model of mechanical elements of y-axis feed drive of virtual portal CNC machine tool

On figure 16 and figure17 are given comparisons between Sim Scape model (multi body model) and Simulink model (one mass model) on the position output on step input, and elasticity (displacement) output on step disturbance force as input.



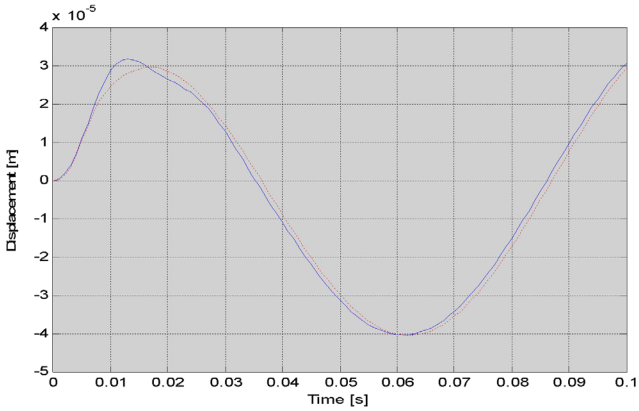
(------) Sim Scape model (multi body model) (- - -) Simulink model (one mass model)

Figure 16. Comparison of the position outputs from Sim Scape model (multi body model) and Simulink model (one mass model) for y-axis feed drive of CNC portal milling machine on the step function for position as input



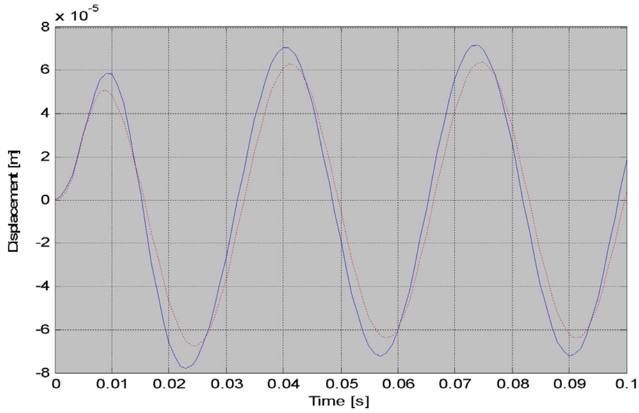
(---) Sim Scape model (multi body model) Sd=14.98 [N/μm]; (- - -) Simulink model (one mass model) Sd=16.52[N/μm]

Figure 17. Comparison of the elasticity (displacement) outputs from Sim Scape model (multi body model) and Simulink model (one mass model) for y-axis feed drive of CNC portal milling machine on the step disturbance force of 1000 [N] as input



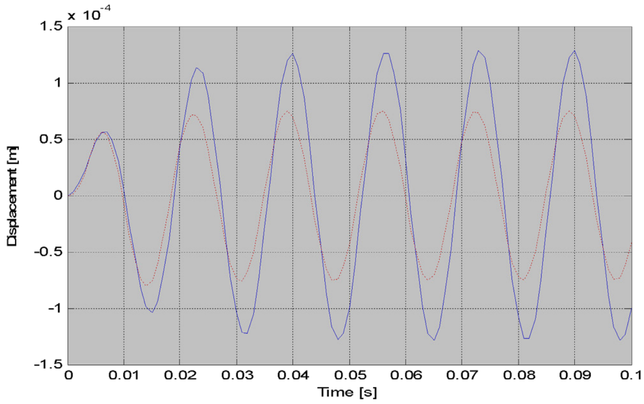
(------) Sim Scape model (multi body model); (- - -) Simulink model (one mass model)

Figure 18. Comparison of the tracking error from Sim Scape model (multi body model) and Simulink model (one mass model) for y-axis feed drive for CNC portal milling machine on the sinus disturbance force with frequency of 10 [Hz], angular frequency 62.8 [rad/s] and amplitude 1000 [N] as input



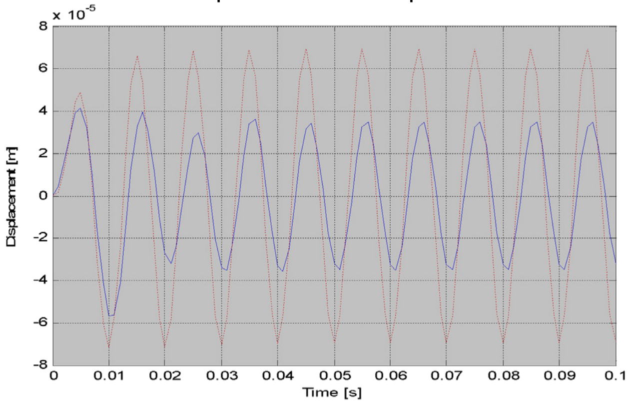
(------) Sim Scape model (multi body model); (- - -) Simulink model (one mass model)

Figure 19. Comparison of the tracking error from Sim Scape model (multi body model) and Simulink model (one mass model) for y-axis feed drive for CNC portal milling machine on the sinus disturbance force with frequency of 30 [Hz], angular frequency 188.4 [rad/s] and amplitude 1000 [N] as input



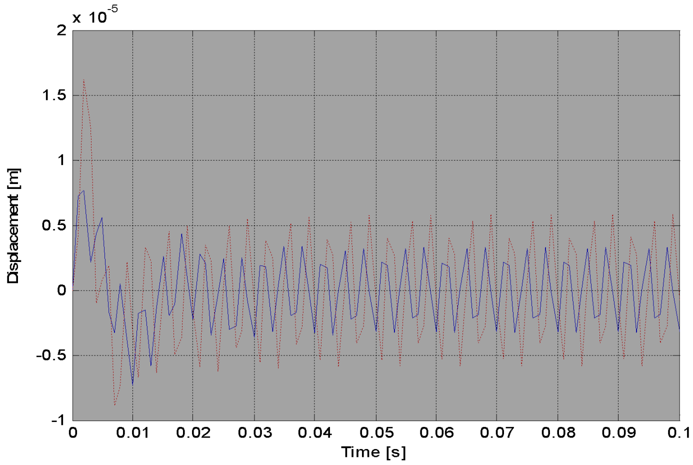
(------) Sim Scape model (multi body model); (- - -) Simulink model (one mass model)

Figure 20. Comparison of the tracking error from Sim Scape model (multi body model) and Simulink model (one mass model) for y-axis feed drive for CNC portal milling machine on the sinus disturbance force with frequency of 60 [Hz], angular frequency 376.8 [rad/s] and amplitude 1000 [N] as input



(------) Sim Scape model (multi body model); (- - -) Simulink model (one mass model)

Figure 21. Comparison of the tracking error from Sim Scape model (multi body model) and Simulink model (one mass model) for y-axis of CNC portal milling machine on the sinus disturbance force with frequency of 100 [Hz], angular frequency 628 [rad/s] and amplitude 1000 [N] as input



(------) Sim Scape model (multi body model);
(- - -) Simulink model (one mass model)

Figure 22. Comparison of the tracking error from Sim Scape model (multi body model) and Simulink model (one mass model) for y-axis of CNC portal milling machine on the sinus disturbance force with frequency of 300 [Hz], angular frequency 1884 [rad/s] and amplitude 1000 [N] as input

The difference of dynamic stiffness obtained with Sim Scape model (multi body model) Sd=14.98 [N/μm] and Simulink model (one mass model) Sd=16.52[N/μm] is 10.28% which is completely acceptable.

The simulations and comparison of tracking errors for Sim Scape model (multi body model) and Simulink model (one mass model) had shown that for lower sinus disturbance frequencies up to 60 Hz the tracking error is bigger for Sim Scape model (multi body model) (figure 18, figure 19 and figure 20), but for higher sinus disturbance frequencies than 60 Hz the tracking error is bigger for Simulink model (one mass model) (fig, 21 and figure 22).

Using the CAD model of the virtual CNC machine tool and using the Sim Scape models of every machine tool feed drive (x, y and z axis) we obtained the complete model of CNC portal machine tool feed drives (figure 23).

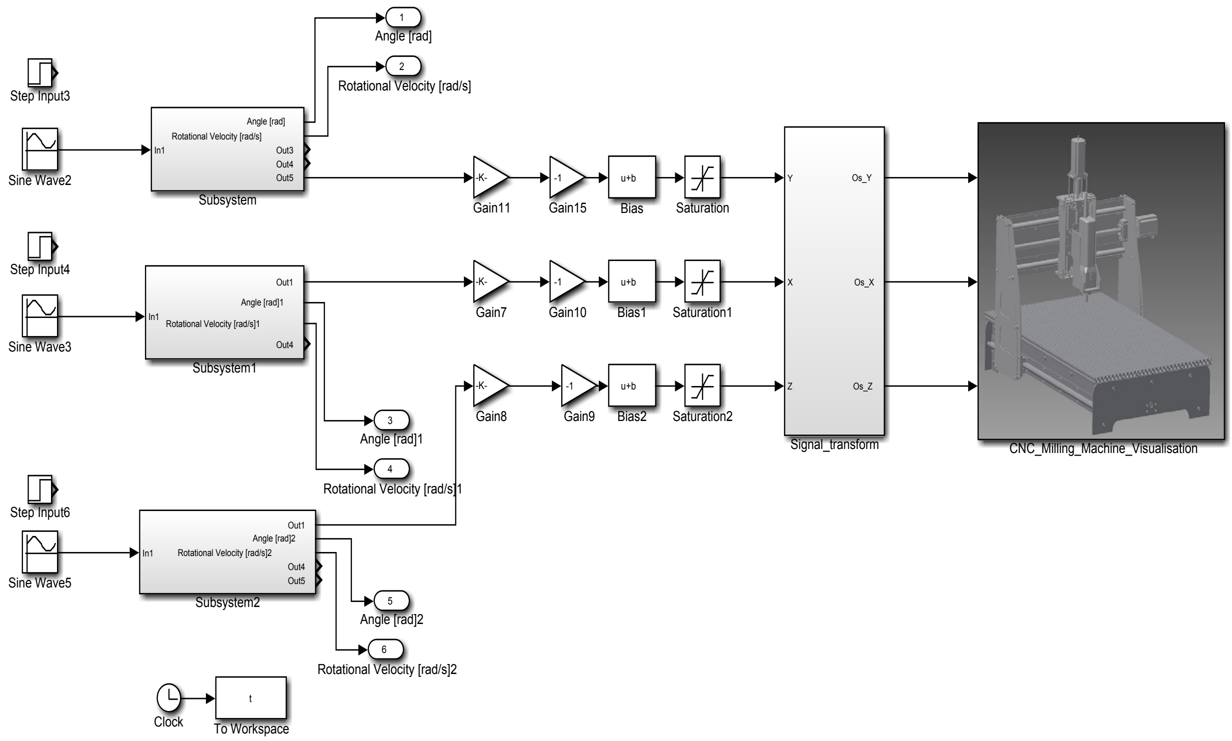


Figure 23. Complete model of CNC portal machine tool feed drives (x, y and z axis) with visualisation in SIMULINK

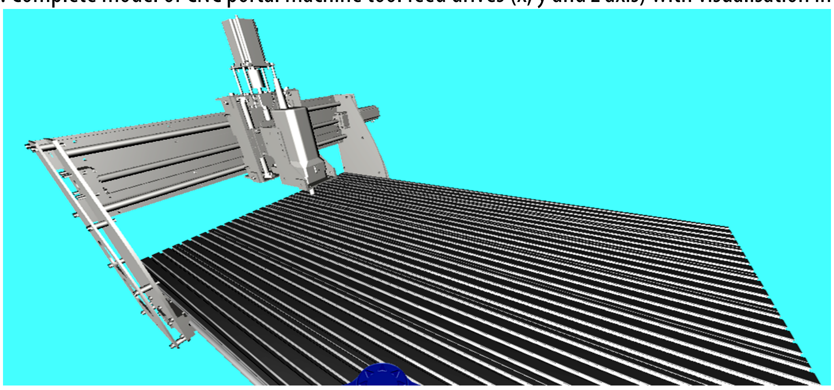


Figure 24. Simple visualisation in SIMULINK of the complete model of CNC portal machine tool

In this model as subsystems are implemented the model of control of each axis in Simulink (figure14) and a mechanical model of each axis in SimScape (figure15).

4. VISUALISATION OF THE WHOLE MACHINE TOOL WITH ALL FEED DRIVES IN VIRTUAL REALITY SYSTEM

The second phase of the research was visualization of the whole machine tool using the CAD model of machine tool (figure 1) and models of the feed drives developed in Matlab-Simulink and Sim Scape (figure14, figure15 and figure 23) in Virtual Reality system with EON Studio software. The using of EON studio software significantly improved the model and visualization quality (figure 25)

With the visualization we were able to simulate the real work of the whole CNC machine tool (contouring operations, changing tools, etc.).

In the available literature we did not find any example of visualization the machine tools and their feed drives in Virtual Reality system with using of EON Studio software

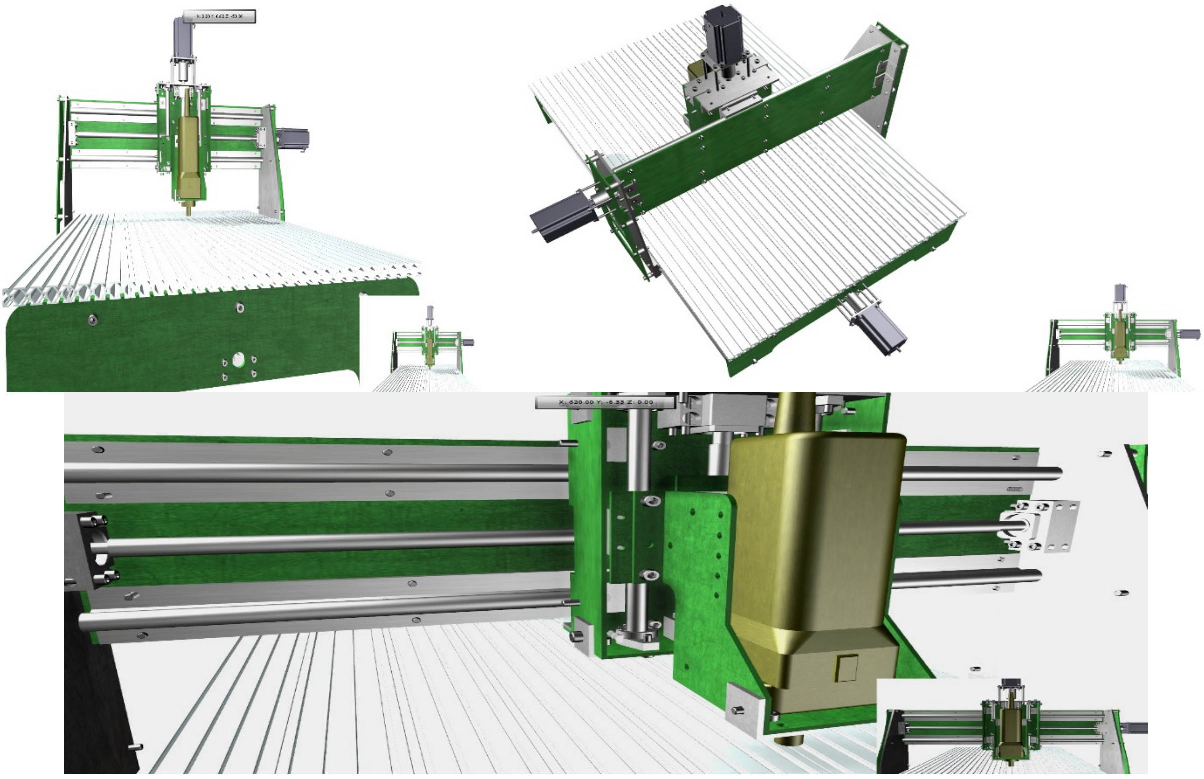


Figure 25. Visualisation of the whole CNC portal machine tool in EON studio software

5. CONCLUSION

Presented method of CNC machine tool feed drive virtual modelling and simulation enables design, performing complex analysis, testing, optimisation and using different types of control structures for feed drives in a computer simulation environment. It significantly reduces time of development and design of different construction variants for CNC machine feed drive systems and reveals real possibilities of the construction during a new machine design in the phase when possible changes are not economically critical. Also it enables effectively optimization the CNC machine tool feed design with respect to position accuracy, dynamic stiffness and control dynamics.

For a machine tool designer, product designer, or manufacturing engineer, the virtual modelling and engineering evaluation system can help in increasing the precision of the machining process and decreasing the lead-time.

This whole research could be very useful to machine tool producers, because they could change their practice of making time consuming and very expensive real prototypes of the CNC machine tools, with creating virtual prototypes of machines.

Acknowledgments

This research was funded from the European Community's Research Infrastructure Action - grant agreement VISIONAIR 262044 - under the 7th Framework Programme.

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