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# STUDIES REGARDING THE FEED DRIVE OF A SPECIALISED MACHINE TOOL BY MEANS OF DYNAMIC SIMULATION

**Radu BREAZ, Valentin OLEKSIK, Octavian BOLOGA**

***Abstract:*** *This paperwork presents some researches upon a proposed specialised machine tool used in the automotive industry. The machine was designed and proposed by the research team in order to offer a solution to an automotive parts manufacturer company, which had some problems in the manufacturing process of the shock absorbers. This part of the work presents some studies regarding the feed drive of the proposed machine. The processing force was estimated by means of FEM analysis and the dynamic behaviour of the motion control system was studied by means of simulation.*

***Key words:*** *automotive industry, feed drive, FEM analysis, modeling, simulation.*

## 1. INTRODUCTION

Automotive industry is one of the most demanding branches of the economy with regards off accuracy and quality of the manufactured parts. Shock absorbers are also parts which require a complex manufacturing process, in which turning operations have a great importance. In order to obtain the parts, several machining operations are performed on highly accurate CNC turning machines at an industrial automotive parts plant from Sibiu, such as:

- roughing and finishing turning operations;
- threading operations;
- drilling operations;
- operations for manufacturing a hexagonal key housing.

The last operations is also of great importance taking into account the fact that the parts (shock absorbers) will be mounted on robotic assembly lines in automobile assembling factory. Robotic arms for handling and mounting the shock absorbers into the car's body will use the hexagonal key housing, so, its manufacturing accuracy influences the handling speed and accuracy. A low accuracy of the housing could block the assembly line (and this fact happened before and could happen again if some corrective measures would not be performed in the shortest possible time).

While the first three operations (which are all plain cutting operations) are well suited to be performed on CNC turning machines with the main spindle maximum power of 11 KW and the maximum feed forces of 8 500 N, the last one (a combination between cutting and plastic deformation) may not be suited for that, by the point of view of the machine-tool loads.

Heavy machining forces and torques appear during the manufacturing of the hexagonal key housing (inbus type key housing) on the parts. They may overcome the allowable loads on the main spindle drive system and on the feed drives.

As an initial conclusion, which is sustained by the high rate of machine-tools failures and can be further sustained by calculations, the CNC turning machines are not suited for performing the above-mentioned operation.

## 2. THE PROPOSED MACHINE STRUCTURE

The research team from "Lucian Blaga" University of Sibiu proposed that the manufacturing of the hexagonal key place should take place on a special machine tool designed and build for this specific purpose.

A simplified scheme of the process and the proposed layout of the machine are presented in Fig. 1.

The most talked concept, in the field of CNC machine is the "open architecture", which involves building the machine with key hardware and software components openly available from various vendors and sources as opposed to a "closed" system in which access to these components is limited or "closed" to the end user.

Subsequently, the authors strongly believe that designing and building the proposed machine in a modular way, each module performing a specific task is the best approach in this case.

The machining process for obtaining the hexagonal key housing is quite simple, involving only two movements: a rotational motion of the workpiece and a linear motion of the tool (feed). Thus, the use of a CNC turning machine with 2½-controlled axes is not justified. Also high cost CNC equipment is not necessary for this particular manufacturing process.

However, the proposed solution meets the main requirements of the process:

- the manufacturing movements and the technological parameters will still be programmable, by means of a

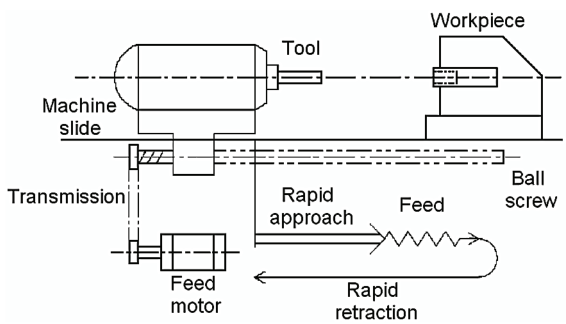


**Fig. 1.** Schematic layout of the proposed machine.

simple PLC controller, which is much cheaper than a CNC control;
- the manufacturing accuracies will be found in the same range as in the case of using an expensive CNC machine tool.

The proposed machine design involves mainly 5 modular systems:
- a one-axis motion control (positioning) system for driving the tool;
- a main spindle drive for rotating the workpiece;
- a linear displacement module with ball-screw system and rolling guideways;
- an automatic workpiece fastening system.

## 3. THE FEED DRIVE

One of the most important components of the proposed machine, which have the greatest influence upon the accuracy of the manufactured hexagonal key housing is the feed drive.

### 3.1. Structure

Although machine tools designs, both for cutting and sheet metal industry vary immensely, the electro-mechanical configuration of their feed drives is largely standardized. In almost all cases the re-circulating ball screw has established itself as the solution for converting the rotary motion of the servomotor into linear slide motion. The ball screw bearing takes up all axial forces of the slide. The servomotor and ball screw drive are usually directly coupled. Toothed belt drives are also widely used to achieve a compact design and better adapt the speed. For position measurement of feed axes on CNC machine tools it is possible to use either linear encoders or re-circulating ball screws in conjunction with rotary encoders [3–5].

Because of the trend toward digital axes in drive technology, a large share of new servomotors feature rotary encoders, which in principle can serve together with the feed screw for position control. With such a drive configuration the decision must be made as to whether to ad a linear encoder or simply to use a ball screw working in combination with the already existing motor encoder [6].

The feed drive (the kinematic chain for feed movements will be realised as one-axis motion control system for driving the tool on a linear trajectory.

This system will consist of:
- programmable logic controller with motion control unit for generating the reference inputs (position reference, velocity reference and acceleration reference – trapezoidal and parabolic velocity profile will be used as velocity reference;
- servo drive for controlling the motor;
- permanent magnet AC synchronous servomotor;
- feedback devices for closing the position and velocity loops (incremental encoder).

### 3.2. Processing force

In order to design the component modules of the machine, the maximum technological resistant force had to be estimated. A theoretical analysis and simulation based upon FEA method in the plastic domain was performed used the SUPERFORM software.

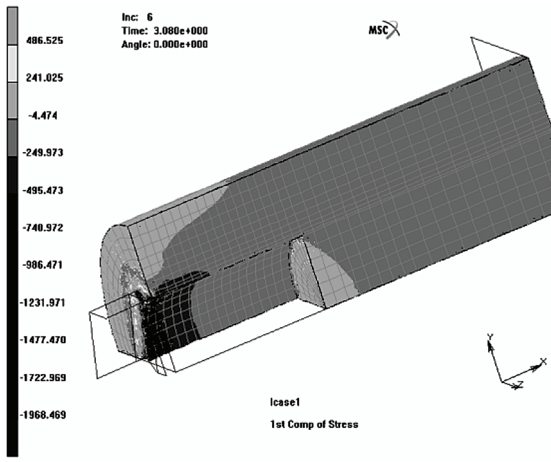


**Fig. 2.** The main stress $\sigma_1$.

The main stress $\sigma_1$ is presented in Fig. 2, for the beginning of the operation, at the moment of the first chip removal. It was found by analysis that the forces are quite constant during the process. Another conclusion based upon non-linear analysis in the plastic domain was the fact that the displacements of the materials are in the imposed field of tolerances, so the cutting process wont influence upon the geometry of the piece. The maximum technological resistant force was found to be 4 080 N, which was taken as basis for the designing process.

### 3.2. Modelling and simulation

In order to obtain an optimum dynamic behaviour of the system a model based upon transfer functions was developed in MATLAB & Simulink.

The simulation diagram, presented in Fig. 3, is based upon the model of permanent magnet synchronous motor fed by PWM inverter with closed speed control, presented in [7], modified by the authors to be used in the CNC machine tools feed drives [1, 2].

The main modifications of the model presented in [7] involved the introduction of the positioning loop, and the introduction of the effects of the mechanical part of the system (transmission system, friction, cutting forces).

The electrical system is characterised by the following relations (in a *d-q* rotor oriented axes system)

$$\begin{aligned}
\frac{\mathrm{d}}{\mathrm{d}t} i_d &= \frac{1}{L_d} u_d - \frac{R}{L_d} i_d + \frac{L_q}{L_d} p\omega_r i_q, \\
\frac{\mathrm{d}}{\mathrm{d}t} i_q &= \frac{1}{L_q} u_q - \frac{R}{L_q} i_q - \frac{L_d}{L_q} p\omega_r i_d - \frac{\lambda p\omega_r}{L_q}, \\
T_e &= 1.5 p[\lambda i_q + (L_d - L_q) i_d i_q],
\end{aligned} \tag{1}$$

where:
$L_q$, $L_d$ – inductances correspond to the *q*, *d* axes [H],
$R$ – stator resistance [Ω],
$i_q$, $i_d$ – currents correspond to *q*, *d* axis [A],
$u_q$, $u_d$ – voltages correspond to the *q*, *d* axes [V],
$\omega_r$ – rotor angular speed [rad/s],

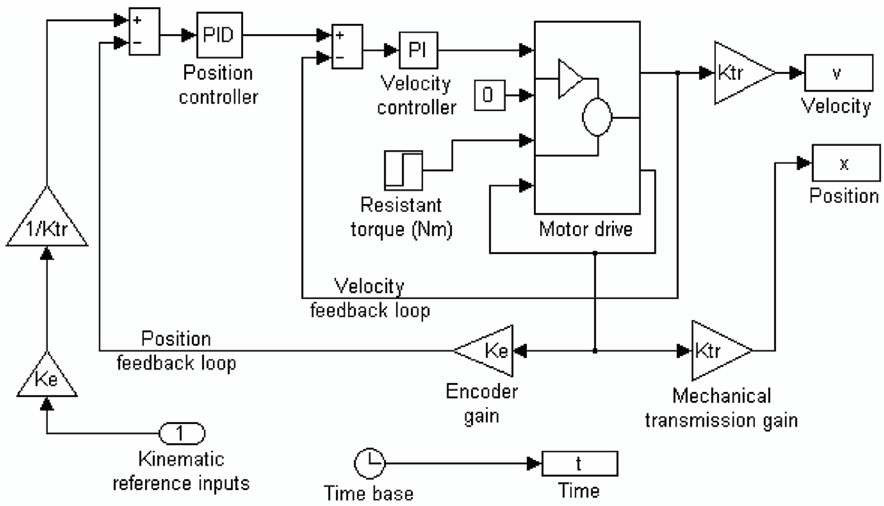


**Fig. 3.** The simulation diagram.

λ – flux induced by the permanent magnets in the stator windings [Wb],
$p$ – poles pairs,
$T_e$ – electromagnetic torque of the motor [N·m].

The following relations characterize the mechanical system:

$$\frac{\mathrm{d}}{\mathrm{d}t}\omega_r = \frac{1}{J}(T_e - F\omega_r - T_m), \qquad (2)$$
$$\frac{\mathrm{d}}{\mathrm{d}t}\theta = \omega_r,$$

where:
$J$ – equivalent moment of inertia of the motor and load [kg·m$^2$],
$F$ – equivalent viscous friction of the motor and load [N·m·s/rad],
θ – angular position of the rotor [rad],
$T_m$ – mechanical resistant torque at the motor's spindle [N·m].

In order to drive the machine slide, reference inputs for the motion control system have to be generated. For a single axis movement, a typical set of cinematic inputs involves the use of the trapezoidal velocity profile. Other profiles to be used are, for example, the parabolic profile, or even profiles defined by spline-curves, for highly sophisticated applications.

The trapezoidal velocity profile has some drawbacks, such as the apparition of the "jerk" phenomenon, due to the shape of the acceleration (rectangular profile), but it is widely used because of the ease of implementation.

Furthermore, the "jerk" phenomenon is to be taken into consideration only when large loads have to be moved. Also, the lags, which normally appear in the control loops, lead to smother output acceleration profiles, different from the rectangular one and consequently, the possibility of apparition of the "jerk" are significantly reduced.

Because of the numerical character of the system, the reference inputs had to be also generated in a discrete way. A sampling time for generating these inputs was chosen equal to 0.001 seconds, which is ten times larger as the sampling time of the control loops.

Fig. 4 shows a typical set of simulated reference inputs used for simulating the system behavior in no load-conditions and Fig. 5 shows a similar set of inputs for load conditions.

Based upon the above mentioned simulation diagram, a set of dynamic simulations were performed, following both a theoretical strategy and a trial and error process, in order to find the optimal values for tuning the system's controllers.

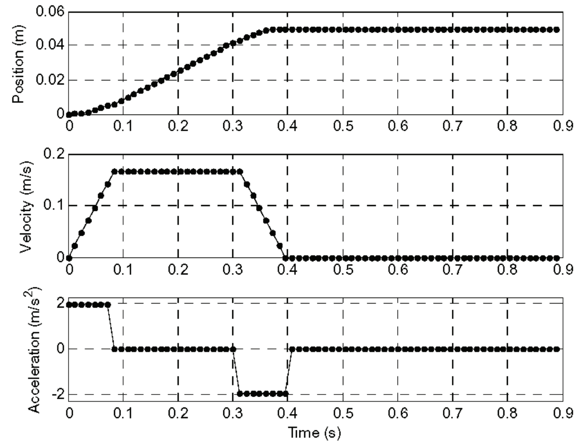


**Fig. 4.** Kinematic reference inputs for no-load conditions.

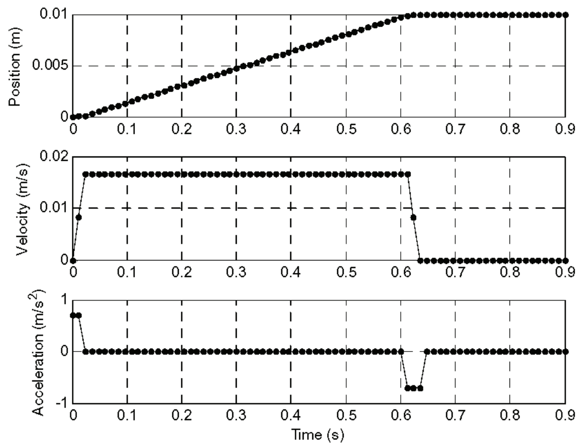


**Fig. 5.** Kinematic reference inputs for load conditions.

Some results of the simulation for the output velocity of the machine slide both in no-load and load conditions are presented in Figs. 6 and 7.

From Fig. 7 it can be seen that the systems deals well with the force disturbance, which causes some velocity overshoot and some oscillations, but quite rapidly damped.

The kinematic parameters of the movements are presented in Table 1.

The main parameters parameters of the simulated feed drive are presented in Table 2.

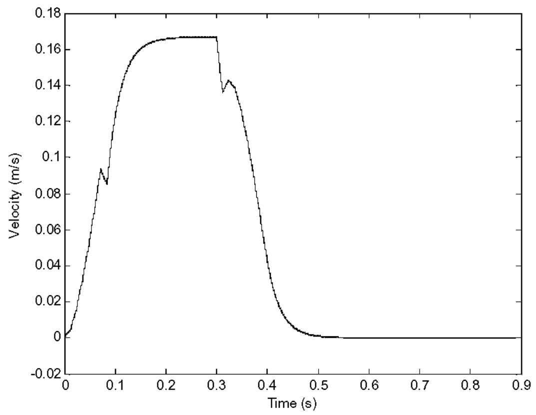


**Fig. 6.** Velocity output for no-load conditions.

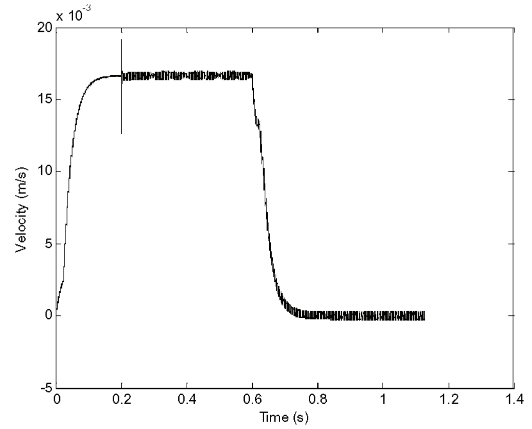


**Fig. 7.** Velocity output for load conditions.

*Table 1*

**Kinematic parameters of the movements**

| **Type of movement** | Rapid approach | Feed |
|---|---|---|
| Displacement [m] | 0.05 | 0.005 |
| Maximum velocity [m/s] | 0.2 (12 m/min) | 0.02 (1.2 m/min) |
| Maximum acceleratin [m/s$^2$] | 2 | 1 |

*Table 2*

**Parameters of the feed drive**

| **Actuation system** | **Feedback system** | **Transmission system** |
|---|---|---|
| Synchronous motor 3 KW | Encoder 1000 pulses/rev | Ball screw Step=10 mm |

## 4. CONCLUSION

Further research will be performed in order to improve behavior of the system. This goal may be accomplished either by using more comprehensive control laws such as fuzzy logic controllers or by using more sophisticated position feedback devices (absolute linear encoder instead of incremental rotational encoder). Also the parabolic velocity profile will be used instead of the trapezoidal one.

However, the simulation results show the fact that the feed drive of the proposed machine has achieved the imposed performances with regards of dynamic behavior and accuracy.

The next stage of this research program will be the implementation of the designed solution, which will be followed by comprehensive experimental tests in order to fulfill the task of accurate manufacturing of the hexagonal key housing of the shock absorbers on a specialized machine tool.

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