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A new approach to the modelling and simulation of a CNC machine tool axis drive

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Abstract

The paper presents a new approach to the modelling and simulation of a CNC machine tool axis drive. Modules have been created for different parts of the CNC machine tool. This allows greater flexibility in the construction of the model and an investigation of the interaction between model components. In this way all the shortcomings of the traditional methods are overcome.

MATLAB / SIMULINK package has been used to simulate this new model for a CNC machine tool. Simulation results are very good, in accordance with CNC machine tool theory.

The described approach allows the easy construction of detailed machine tool drive models. It represents the basis for future incorporation of geometric, non-rigid and thermal models of machine tool behaviour.

1 Introduction

Traditional methods for modelling and simulation of CNC machine tools have used lumped parameter models [1]. This approach has significant shortcomings:

- the lumping of any system removes the effect of model components with a corresponding reduction in simulation accuracy;
- changes in any system component requires the alteration of the entire lumped model ;
- it is not possible to examine the behaviour of individual components and how they interact.

Instead of creating a low order, lumped parameter model, with respect to the drive or actuator, a modularized (distributed) model of the machine tool has been created. This is an alternative approach suggested by Leonhard [2], instead of that traditionally used [3].

This modular approach permits the easy exchange of components without the need to alter the whole model. For example, the coupling between motor and load can be either direct, with belts or gears etc. and yet the rest of modules remain the same.

In addition, the modular approach allows for calculation of the forces which occur between model components. The lumped-parameter model does not offer this opportunity which is very necessary for error avoidance. Knowing the values of different forces will be useful in determining the modalities for error avoidance.

The alternative approach for the modelling and simulation of a machine tool axis drive is similar to the Newton-Euler model [4] of a robot where kinematic motion is transmitted forward through the model and resistive force flows back through the model.

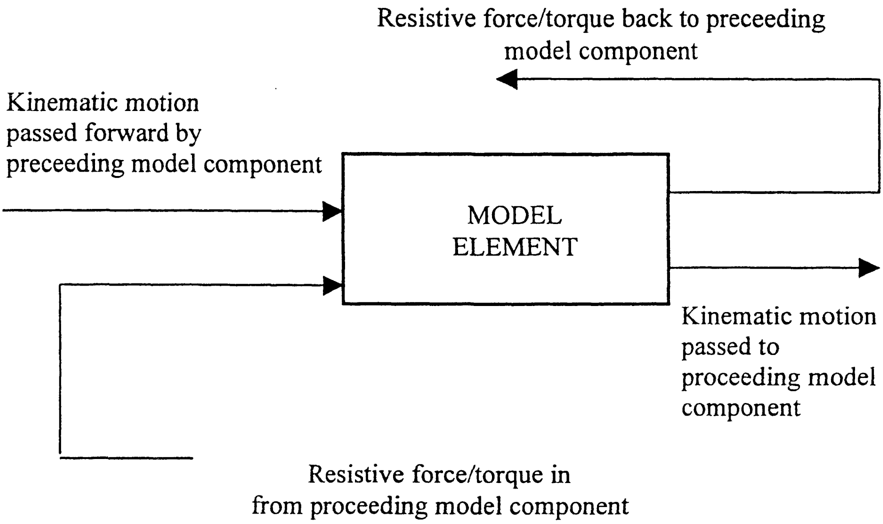

Figure 1. Forces for one component of the model

Following this pattern, the reaction forces due to friction and components of inertia are transmitted as inputs to precedent modules. In this way the technique allows the inclusion of the combined resonant states of the individual elements when it is difficult to obtain exact constituent damping factors.

2 Modelling of a Machine Tool Axis Drive

Electrical machines and actuators realise the basic function of converting electrical energy into mechanical energy. Motion systems do however

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also realise additional high level functions such as the conversion of an input reference signal, both in digital or analogue form, into precise force, torque, speed or position.

The implementation of such higher-level functions require additional elements such as sensors, encoders, power amplifiers, control electronics and communication links.

A machine tool axis drive consists of three major blocks:

- *CNC controller block* – calculates the motion of the various axes necessary to execute the required cutting path. It has a corresponding control algorithm for monitoring the motion and the communication interface for data exchange between the system and the external world.
- *axis actuator* – realises the basic electromechanical energy conversion. It is generally an electrical motor (typically a DC drive for Beaver VC35 or an AC drive for Takisawa MAC-V2). Electric drive will include rotary encoder, DC drive (preamplifier, current control loop, power amplifier) and transducer.
- *mechanical system* – is the mechanical linkage which transmits the motive force generated by the drive to be converted into relative motion between the tool and the work piece. Typically it contains the following: coupling between the drive and ballscrew, ballscrew and nut unit, slide and slideway and associated bearings.

All these blocks are presented in the block diagram of a CNC machine tool axis drive.

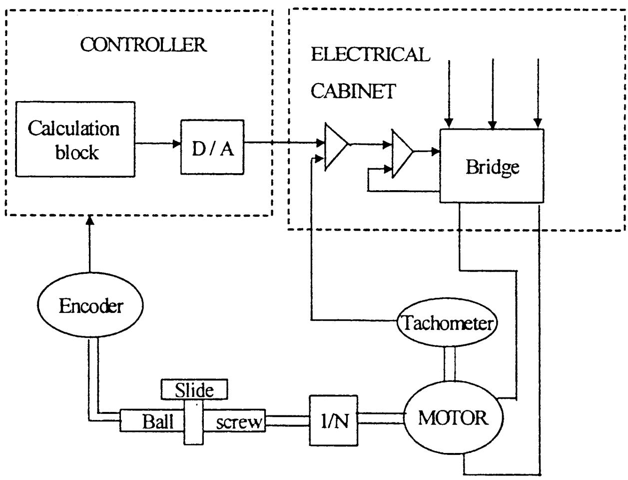

Figure 2. Block diagram of CNC machine tool axis drive[5]

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2.1 Computer integration

To model such a system as a CNC machine tool, it is necessary to analyse both linear and non-linear elements.

SIMULINK is a dynamic system simulation software package which provides a comprehensive graphical user interface that allows complex control system models to be developed and simulated in a short period of time. It has a large library of predefined blocks for use within system models. The only obvious disadvantage arises when the users model contains elements that are not defined in the libraries. Certain non-linear functions are not defined in SIMULINK libraries[6] (such as variable friction). They have to be designed as a look-up table in the native MATLAB[7] programming language. The developed SIMULINK implementation of variable friction model will contain more than one block (Coulombic friction) to obtain results as near as possible to real ones.

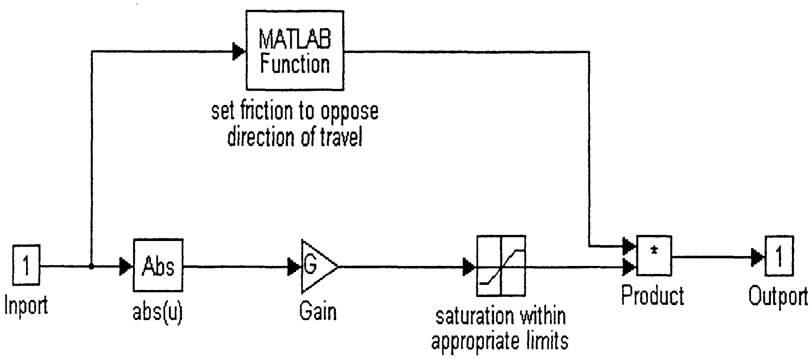

Figure 3. SIMULINK implementation of variable friction model

The SIMULINK model for the CNC ma • ine tool axis drive, presented in Figure 4, has two major parts:

1. *drive model* - containing controller, pre-amplifier, amplifier, motor, tachometer and encoder models.
2. *load model* - containing torques due to driven pulley, ballscrew inertia, ballscrew drag, bearings and slideway friction.

The input of the model can be arranged to be trapezoidal or sine wave. A comparison is made with the feedback pulse train. The difference is introduced into the controller whose transfer function is:

$$H_{controller} = \frac{G_2 \ G_3 \ A}{s} \tag{1}$$

where G_2, G_3 - D/ A conversion scaling

A - a scaling term to simulate the potentiometer setting to control preamplifier input demand

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From the controller output is subtracted the tachometer output. The voltage error is introduced into the preamplifier.

$$H_{preamplif} = K \frac{1 + sT_1}{s^2 + sT_2 + T_3} \tag{2}$$

where T_1, T_2, T_3 - time constants
K - the preamplifier gain

The difference between preamplifier output and current loop represents an input for amplifier.

$$H_{amplif} = K_{br}\ K_{ia} \tag{3}$$

where K_{br} - the bridge voltage
K_{ia} - the current loop scaling

The DC motor transfer function is:

$$H_{motor} = \frac{1}{s L_a + R} \tag{4}$$

where L_a - the armature inductance
R - the armature resistance

The slide axis is modelled by lumping the DC servo motor together with its associated drive shaft and pulley. The remainder of the machine slide has been modelled as a series of mechanical components. Their effect upon the drive system is considered as an external and independent perturbing load torque:

$$T_{reaction} = T_{p2} + T_{BSd} + T_{BSi} + T_{SF} + T_{friction} \tag{5}$$

where T_{p2} - torque due to driven pulley inertia

$$T_{p2} = J_{p2} \frac{d\omega_2}{dt} \tag{6}$$

J_{p2} - the driven pulley inertia
ω_2 - the angular velocity of driven pulley

T_{BSd} - torque due to ballscrew drag

$$T_{BSd} = J_{BS} \frac{d\omega_2}{dt} \tag{7}$$

J_{BS} - ballscrew inertia

T_{BSi} - torque due to ballscrew inertia

$$T_{BSi} = s J_{BS} \tag{8}$$

T_{SF} - torque due to slideway friction

$$T_{SF} = \frac{1}{\eta}\left(\mu W + s M\right) \tag{9}$$

η - the ballscrew efficiency
μ - the slideway friction coefficient
M - the load mass
W - the slide weight

$T_{friction}$ - torque due to friction in bearings (given by Eschmann [8])

$$T_{friction} = M_0 + M_1 = f_0\, 10^{-7}\, (\upsilon n)^{2/3}\, T^3 + \mu_1 f_1 F(T/2) \tag{10}$$

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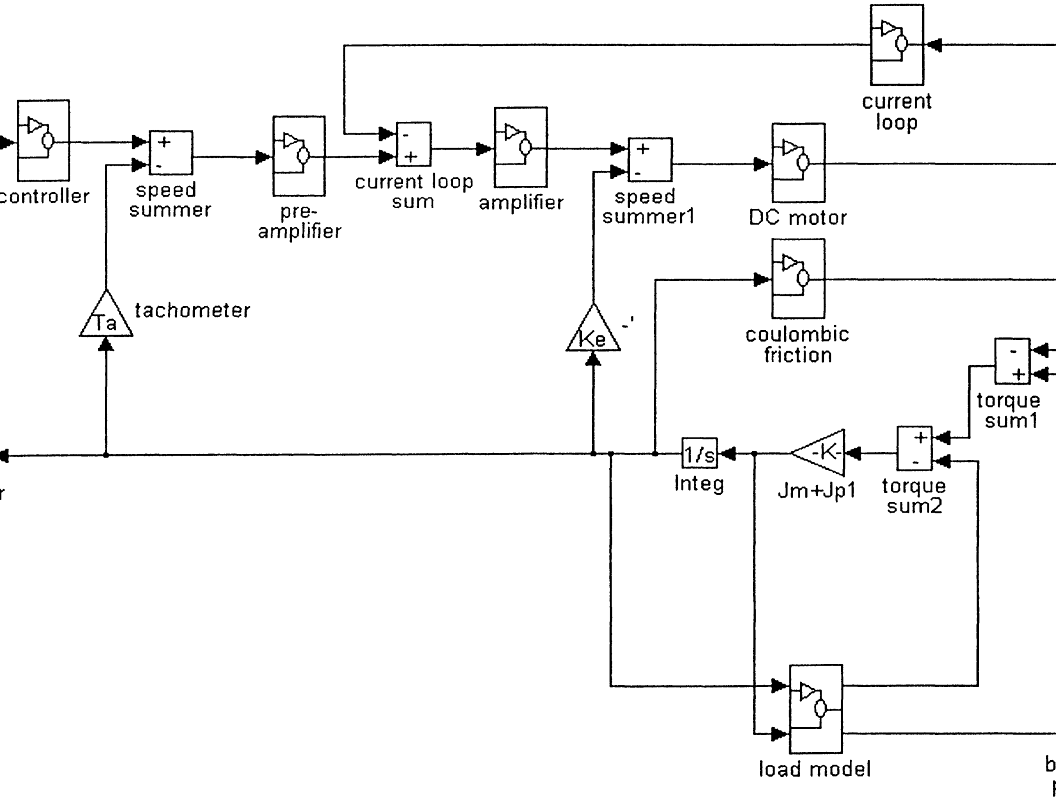

Figure 4. Block diagram of CNC machine tool axis drive in SIMULINK

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where M_0 - load - free component of the total frictional torque
M_1 - load - dependent component of the total frictional torque
f_0 - coefficient taking into account the bearing design and lubrication method
ν - operational viscosity of oil or grease base oil
n - speed of bearings
T - pitch circle diameter of bearings
μ_1 - friction coefficient dependent on load and bearing design
f_1 - coefficient taking into account direction of load application
F - resulting bearings load

In the load model (shown in Figure 5) have been considered all the reaction forces which occur during machine functioning.
For the simulation their value is zero, but the place where they apply has been determined. In the future simulations, their calculated values will be introduced into the load model.

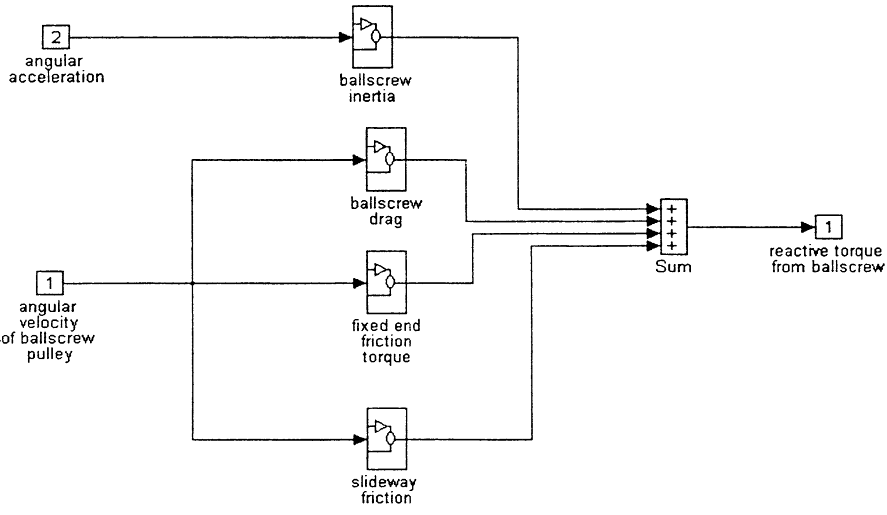

Figure 5. SIMULINK model for load of a CNC machine tool axis drive

3 Simulation Results

A trapezoidal form is used as an input stimulus to check out the performance of the CNC machine tool during acceleration, deceleration and functioning at constant rate (the maximum required value for velocity is considered to validate the proposed model). In the case of a particular CNC machine tool, the fast traverse rate 5000 mm / min = 0.0833 m /s.

The model response to this stimulus is shown in Figure 6. It could be observed the rapid response in less than 0.1 s with no overshoot. Therefore this system is critically damped as required.

In most servo systems, the open loop transfer function includes complex poles. As long as these poles are far enough from the imaginary axis, they do not pose a special problem. However, it becomes more and more difficult to compensate the system for complex poles as they come closer to the imaginary axis. A typical source for those poles is the effect of torsional resonance of the load-motor-tachometer combination and it is highly desirable to reduce the effect of those poles.

Since it is impossible to eliminate the effect of resonance completely, it is desirable to be able to measure or express quantitatively the effect of resonance, or the sensitivity of the system to sinusoidal inputs at the resonance frequency.

A simple way to describe the resonance effect is by observing the system response to sinusoidal input signals at various frequencies. The ratio of the response amplitude to the amplitude of the input signal indicates the closed-loop gain (or sensitivity of the system at various frequencies).
In Figure 7 is presented the response of the model when a sine wave is introduced as an input stimulus. Again the magnitude is equal with the maximum required value for velocity.

Cutting forces and friction forces (excepting Coulombic friction) were not examined during machine functioning.

Simulation results are similar to those obtained by applying control theory and machine tool theory. This represents the first step in validating the proposed model. The next one will be the comparison with actual data taken off the CNC machine tool.

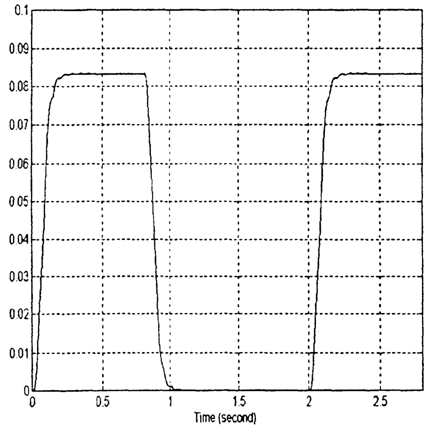

Figure 6. Model response to trapezoidal input

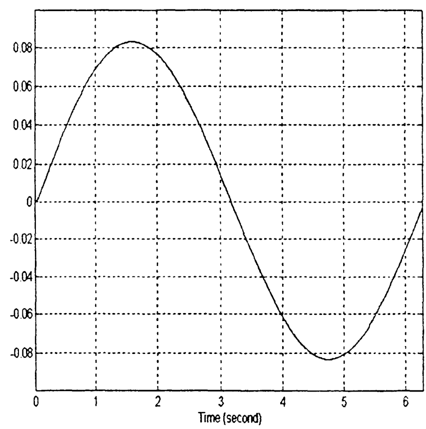

Figure 7. Model response to sinusoidal input

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4 Conclusions

The modular approach to the modelling and simulation of a CNC machine tool axis drive is an important contribution to machine tool theory.

The paper presents the first phase, the building of the model and simulator, in a larger project. There are a number of future steps to be completed such as:

- comparison with actual data from a CNC machine tool;
- demonstration of the flexibility of the modular approach in the modelling of different axis drive systems;
- development of the models for the other axes and finally, a three-dimensional model for CNC machine tool axis drives.

In comparison to lumped-parameter models, the modular approach is considered to be more appropriate for parameter identification. Further research will validate this point.

This new approach to the modelling of a machine tool axis drive will be useful in the development of diagnostic and condition monitoring systems when the errors in machine tools such as geometric, thermally induced and non-rigid effects are considered. Determining the errors produced by different modules is beneficial for error avoidance because each component imposes errors on the CNC machine tool.

Simulation results are the same as calculated using classical control theory and due consideration to machine tool elements.

Finally, the modular approach will be very useful for the identification and performance analysis of dynamic errors from CNC machine tools.

5 References

1. Ford, D. G., *General Purpose CAD / CAE Aid to Design a Machine Tool System,* Ph.D. Thesis, The University of Huddersfield, U. K., 1987.
2. Leonhard, W., *Control of Electric Drives*, Springer-Verlag, 1990.
3. Gross, H., *Electrical Feed Drives for Machine Tools*. John Wiley and Sons Ltd., 1983.
4. Fu, K., Gonzalez, R. S., Lee, C. S. G., *Robotics, Sensing, Vision and Intelligence*. McGraw-Hill International Ltd., 1988.
5. Ford D. G., Postlethwaite S. R., White A. J., Pislaru C., *Time and Spatial Error Correction in CNC Machines.* Presentation for IEE Electronics, Computing and Control Section in conjunction with the Manufacturing section meeting, University of Huddersfield, 8 December 1998.
6. *MATLAB. High Performance Numeric Computation and Vizualization Software*. The MathWorks, Inc., 1992.
7. *SIMULINK. Dynamic System Simulation Software.* The MathWorks, Inc., 1993.
8. Eschmannn, P., Hasbargen, L., Weigand, K. - Ball and Roller Bearings. Theory, Design and Application, Chapter 4, *Friction, Temperature and Lubrication*, John Wiley and Sons, pp. 201 - 247, 1985.