Improving CNC machine tools performance by using modular approach

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Abstract

The paper presents a comparison of single axis simulation results for various stimuli conditions against measurements for the same stimuli conditions on the machine. The results compare well and further comparison can be demonstrated against previously derived lumped parameter models for the same machine.

Sinusoidal and co-sinusoidal inputs are introduced into a complex 2D model including geometric error components measured directly from the machine by laser interferometer. The simulated circular position error traces could then be directly compared with machine measured error traces obtained from using ball bar plots.

Measured Bode plots based on the swept sine measurement technique show how the machine is operating across a broad frequency range and provide further information than a step response. A Signal Analyser injects waveforms into the open position loop axis drive and generates Bode diagrams by comparing inputs with outputs. The measured Bode plots compare well with the same diagrams generated from simulated model and in this way the proposed model is validated.

1 Introduction

Machine monitoring and control, especially in the manufacturing process, requires reliability and deterministic on-time performance. The increasing requirements of industrial applications for higher performance, better reliability and lower cost have imposed the necessity to produce realistic models of the motion control systems.
CNC machine tool control systems have errors due to geometric, non-rigid, thermal and dynamic effects. Previously work has largely concentrated on simulation methods based on "lumped parameter" methods and the assumption of linearity. The real system has non-linear control elements and the need is to move from the "lumped parameter" methods to a consideration of distributive elements if the structural dynamic effects are to be more deeply understood.

A modular approach has been applied previously for modelling and simulation of a CNC machine tool axis drive, but only theoretical results were presented. However, it was necessary to validate that model on the basis of practical results and this is one of the aims of this paper.

The causes of inaccuracy and potential methods of accuracy improvement are studied because a permanent need for improved machine tool accuracy is present in the industrial processes. The 2D model of the machine tool is adapted to incorporate machine tool rigid body errors, the ball bar plot is simulated and the results of simulations compare well with the measurements done with a ball bar.

2 Modelling of a CNC Machine Tool Axis Drive

Lumped parameter models [1, 2] have been used as traditional methods for modelling and simulation of CNC machine tools. A modularized (distributed) model of a machine tool axis drive [3] was developed to overcome the significant shortcomings of lumped parameter models. This alternative approach suggested by Leonhard [4] permits the easy exchange of components without the need to alter the whole model. In addition, the modular approach allows for calculation of the forces which occur between model components and 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 [5] of a robot where kinematic motion is transmitted forward through the model and resistive force flows back through the model.

The analytical equations describing the components of a CNC machine tool axis drive are obtained by a combination of theoretical analysis and experimental testing. A pictorial and a quantitative representation of the cause-and-effect relationship between the variables of the system is provided by the combination of a block diagram and the mathematical expressions relating the input and output of each block. Because the system is complex, simplifying assumptions are made to arrive at the likely form of the equations. In this way is developed a parametric model of the system.

The "classical" approach to control theory, based on the transfer function and associated techniques of analysis are applied for the analysis of the dynamic behaviour of the drive.

The model resulting from the modular approach described in [3] is implemented in SIMULINK 2.0. Simulation tools are always measured by their effectiveness, complexity, cost and their contribution to the understanding of the problem. Version 2.0 of SIMULINK has been chosen because of its advantages:
- reduced simulation time;
- high fidelity simulation (intrinsic zero crossing detection);
- ODE (Ordinary Differential Equation) solvers;
- improved algebraic loop solver;
- signal labels - attach labels to signals and propagate signal labels etc.

The mathematical model of the drive, resulting from the modular approach, produces data that can be analysed to predict the performance, accuracy, stability and safety of the drive system. By using SIMULINK, it was possible to analyse the signals present in the system.

The model for a non-linear function such as Coulomb friction contains more than one block to obtain results as near as possible to real ones and is developed by Pislaru et al. in [3].

In Figure 1 is presented the block diagram of the CNC machine tool drive in SIMULINK 2.0, for one axis when the input is a velocity signal and the feedback signal is produced by a rotary encoder attached to the DC motor.

![Block diagram of CNC machine tool axis drive in SIMULINK 2.0.](image)

Figure 1: Block diagram of CNC machine tool axis drive in SIMULINK 2.0.

When you simulate a system, it is not only one equation of motion you need. There are necessary many equations to analyse a system and to be able to link the model into a control system. Following this principle, the subsystem "Load model" has been built on the basis of Equations 4 - 10 from [3] and its constituent elements are shown in the Figure 2.

All other reaction forces which occur during machine functioning have been considered. For the simulation their value is provisionally set to zero, but the place where they apply has been determined. In future simulations, their calculated values will be introduced into the load model.
3 Simulation Results

The description of a system in the frequency domain is given in terms of the response to a sinusoidal input signal after all initial transients have died out. The steady output is a sinusoid of the same frequency as the input, but with a shift of phase and a change of amplitude, provided the system is linear.

The presence of non-linearities in the system is suggested by any distortion of the output waveform. The output then contains the basic forcing frequency plus certain of its harmonics because any non-linearity that is present in the system introduces signal components at higher frequencies.

The experimental set-up with an "open" position loop is simulated to obtain Bode diagrams with valid results above 50 Hz. The controller is taken out from the loop, the swept sine signal was introduced directly into the pre-amplifier and the output is considered the linear encoder signal showing the position of the worktable. In the subsystem "Load model" is introduced the resonant frequency of 94 Hz of the belt drive transfer function measured experimentally and the corresponding value of 0.16 for the damping factor calculated theoretically by Holroyd et al. [6].

SIMULINK 2. 0. uses an LTI (Linear Time-Invariant) Viewer which linearizes the analysis model in order to plot the Bode diagrams. In this case, the effect of the non-linear elements is not visible on the Bode diagrams.
Figure 3: Simulated results for the open position loop using SIMULINK 2.0.

4 Comparison between simulated results and measured data

Experiments are important in the process of developing relevant knowledge, experience and skills. These experiments have to demonstrate and develop connections between theory and practice transparently.

The PC/ Spectrum network analyzer HP 3566A is utilized for measurements in the frequency-domain. It uses an FFT (Fast Fourier Transform) algorithm to convert an analog input (time-domain) signal to a digital signal displayed in the frequency domain. The resulting spectrum measurement shows the energy of each frequency component at each point along the frequency spectrum.

Most measurements made with spectrum analyzers use a logarithmic amplitude scale (based on decibels) because it is nearly impossible to view any harmonic with small amplitudes on the same display as the fundamental frequency.

Swept sine analysis is a very common measurement technique involving a swept sine wave source and a time-domain integration process that emulates a tracking bandpass filter. The primary objective is to measure the gain and phase shift of a device by measuring only the fundamental component of the stimulus signal and only the fundamental component of the device's response signal (assuming the frequencies of the fundamentals are the same).
To achieve the narrow filter bandwidths required to measure low-frequency systems, the HP3566A utilizes a Discrete Fourier Transform (DFT) to evaluate the energy within a narrow frequency span. The transform is evaluated at several points during a sweep with the centre frequency of the analysis corresponding to the frequency of the swept sine source.

4.1 Measurement Technique

The initial idea for determining the Bode diagrams of one axis was to introduce sinusoidal inputs into the controller and to measure the controller output. However, due to the fact that the wiring diagrams for the electrical drive of the controller were not available, the alternative was to introduce a sinusoidal signal (generated by PC Spectrum Analyzer HP3566A) as a disturbance into the pre-amplifier. The amplitude of the signal was limited to 250 mV due to the fact that the mechanical transmission has to have a maximum acceleration of \(0.5 \times g = 0.5 \times 9.81 \text{ m/s}^2\). The maximum value of the frequency which could be measured in this way is 50 Hz due to Shannon's law and the sampling time of the existing controller (10 ms).

To measure frequencies above 50 Hz, it was necessary to "open" the position loop (the controller is not controlling the position loop anymore). In this way it was possible to introduce an input signal with a greater amplitude (1V) able to generate enough energy which makes the output signal greater than the noise level and moves the worktable for distances bigger than 1 \(\mu\text{m}\).

![Diagram of Experimental setup for measurements in open - loop position control and closed-loop velocity control](image)

The pulses generated by the linear encoder are counted by the digital scalar card to determine the position of the slide. The input voltage is proportional to the
velocity so the values measured by the linear encoder are differentiated in order
to compare alike input and output signals. The differentiation is performed by a
general data logging software developed at University of Huddersfield and the
resulting digital signal is transformed into a voltage by a D / A card. Then the
analogue signal is introduced into the PC Spectrum Analyzer HP 3566 A.
Simon [7] has introduced the equations needed for prescribing a circle in a given co-ordinate system when considering circular interpolation:

\[ x = x_0 + R \cos \varphi = x_0 + R \cos (\omega \cdot t) = x_0 + R \cos \left(\frac{\varphi}{R} \cdot t\right) \]  
\[ y = y_0 + R \sin \varphi = x_0 + R \sin (\omega \cdot t) = x_0 + R \sin \left(\frac{\varphi}{R} \cdot t\right) \]  

(1)  

(2)  

where \( \varphi \) - angle at centre [ rad]  
\( \omega \) - angular velocity [ rad / sec]  
The equations are extracted from analytical geometry and are implemented into the internal interpolator of the CNC machine tool.

To provide a model that conforms more closely to an actual machine, it is necessary to model the geometric error components (linear positioning, horizontal and vertical straightness, yaw, pitch, roll and squareness) for each axis and incorporate them into the simulation.

Postlethwaite [8] defined a method of predicting the volumetric geometric error of 3-axis machines for all types and configurations. Blake [9] confirmed the geometric error equations for the Beaver type VC 35 configuration and also included terms for non-rigid errors. The following equations are for a Beaver type configuration where the X- axis worktable travels on top of the Y- axis worktable:

\[ E_x = e_x (x) + e_y (y) + e_z (z) + \theta_{xy} (x,y) \cdot Y + \phi _z (y) \cdot Y \]  
\[ E_y = e_y (y) + e_x (x) + e_z (z) - \phi _z (x) \cdot X \]  

(3)  

(4)  

where \( X, Y \) - position co-ordinates of the axes;  
\( e_x (x), e_y (y) \) - X- axis, respectively Y-axis linear positioning error  
\( e_y (x), e_y (y) \) - X, Y straightness errors in the XY plane;  
\( e_z (z), e_y (z) \) - Y, Z straightness errors in the YZ plane;  
\( \theta_{xy}, \phi _z \) - X,Y axis pitch errors;  
\( \theta _{xy} \) - squareness errors in the XY plane;  
\( E_x, E_y \) - actual error movement of \( X, Y \) axes.

These equations have been implemented in SIMULINK 2.0 into the subsystems "X-axis error calculation" and "Y-axis error calculation".

A set of geometric error data was collected from the two-axis table of a vertical machining centre Beaver VC 35 using laser interferometer. The data is stored in the form of a number of look-up tables and some constants (such as Z straightness) for use by the geometric model. The constant values were measured previously by Ford et al. [10] on CNC machine tool Beaver VC 35 existent at University of Huddersfield.

The X and Y ball-screw positions, produced by the simulation of the two-axis model, are used as inputs to the geometric model. The errors are then added to
the X and Y ball-screw positions. In this way are taken into account both the axes drives and the geometric characteristics of the machine tool.

After the geometric errors were integrated into the simulation, the ball bar plot procedure was applied. The velocity (feedrate) was considered to be 3000 mm / min = 50 mm / sec because this is the value used for the ball bar test.

Figure 6: Ball bar plot simulation considering position demand and integration of geometric errors into simulation

The actual ball bar plot taken from the machine and the simulation plot can be seen to be of similar form.

The inertial spikes are present at each pole of the plot, due to axis characteristics (friction, inertia etc.). As a result of the axis squareness error (10 arcsec for actual machine), the plot has an oval shape. A similar oval shape would result from a servo mismatch, however the counterclockwise run would be shifted 90 degrees. These traces are imposed over each other, so the error results from the axis squareness.

Figure 7: Simulation plot

Figure 8: Ball bar plot
6 Conclusions

The paper presents a comparison of single axis simulation results for a swept sine signal introduced directly into the pre-amplifier of the CNC machine tool axis drive against measurements for the same stimuli conditions at the machine. The validation of the model for the CNC machine tool axis drive built using a modular approach is another step to a full investigation into the dynamic state where valid structural resonances (such as dynamic errors, geometric (rigid and non-rigid body) errors and thermally induced errors) will be introduced together with measured data.

The presented method contributes to knowledge of modelled and simulated motion control systems for CNC machine tools. Determination of transfer functions, parameters and their effects will increase the knowledge for the designer and can be used in error avoidance practices. Accurate models will also assist the end user by allowing diagnostic and condition monitoring methods to be applied to the CNC machine tool.

The paper contains also the comparison between the simulated results using a two-axis model and a mathematical procedure to calculate the predicted values of the ball bar and the actual data obtained from practical measurements.

For the moment, the method has been applied only to a machine with an analogue drive. In the future, the modular approach will be used in studying machine tools with linear transducers and digital drives.

References
