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Modelling and simulation of CNC machine tool feed drives

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Abstract

The paper presents a critical appraisal of existing methods for modelling and simulation of CNC machine tool feed drives. Their goal is the development of mathematical models which adequately replicate the dynamic behaviour of the actual machines. The advantages and disadvantages of lumped parameter models and modular approach are discussed and the suitability of mixed, hybrid, distributed-lumped modelling is emphasised. Some applications of other methods to CNC machine tool feed drives are examined. The importance of a thorough study regarding the factors influencing the machine dynamic performance and the strategies for error compensation and correction is underlined. The achieved accurate simulations for multi-axis machine tool applications will be used for automatic tuning and condition monitoring purposes.

1 Introduction

The competitive environment of modern industry is continuously requiring improvements in quality, productivity, lead times and profit. Therefore the CNC machine tools should contribute to the reduction of machining costs and lead times. This purpose can be achieved by various activities: research and development, design, prototyping using the latest technology on machine tools and their elements. Modelling, analysis and simulation of CNC machine tool feed drives play an essential role in increasing their dynamic performance.

A number of techniques have been developed in recent years and this paper is an attempt to collate and critically appraise the recent advances in modelling and simulation of CNC machine tools feed drives under non-cutting conditions.

These include lumped parameter models, modular approach, hybrid models considering distributed load, explicit damping factors and measured non-linear effects (backlash, friction). The possibilities of optimising the parameters of these models are discussed.

Also models for CNC machine tool feed drives which are based on Transmission Line Matrix (TLM) method, Finite Element Analysis (FEA) are analysed emphasising the numerical aspects of building, simulating and verifying these precise models.

The models implemented using C ++ and MATLAB / SIMULINK software packages put emphasis on the frequency-domain behaviour of the dynamic non-linear systems which are the CNC machine tools. The analysis of the validation process involving simulated resonant frequencies and those measured on the actual machines subjected to the same input signals is performed methodically in order to determine the best use of each method**.**

2 Lumped parameter models for CNC machine tool drives

The *lumped-parameter models with load inertia reflected to the motor* [1-3] have been generally used as traditional methods for modelling of CNC machine tool feed drives.

Ford [1] showed that a single-axis feed drive could be considered to be equivalent to a second order element and the resulting Bode diagrams did not contain any resonant frequencies which occurred in the machine structural elements. The interaction and behaviour of individual elements could not be examined and the models had to be altered when any system component changed. Also the effect of load components on the system response was removed because of the "lumping" technique.

Pislaru [3] plotted on the same graphs the measured and simulated Bode diagrams for the velocity loop of a CNC machine tool (Figure 1). The experimental diagrams were drawn by a Signal Analyser which generated a swept sine rate demand signal that was introduced directly into the pre-amplifier and the output taken from the rotary encoder attached to DC motor which was then differentiated to obtain a rate output. The simulated results were compared against the measured data for the same stimuli conditions at the machine. The experimental bandwidth was reduced because the lumped parameter model did not include the distributed load and structural dynamic effects, non-linearities and other aspects.

The lumped parameter model - where the load influence was represented by the load inertia referred to the motor – was a first step in the investigation of the motion control systems within CNC machine tools.

The error avoidance practices and effective design processes required the determination of transfer functions, model parameters and their effects. More research had to be carried out in order to develop accurate models which could assist the end user by allowing diagnostic and condition monitoring methods to be applied to the CNC machine tool.

Figure 1. Measured Bode diagrams and simulated ones using lumped parameter model [3]

3. Modular approach for modelling and simulation of feed drives

Pislaru et al [4] applied a *modular approach* to the modelling of CNC machine tool feed drives in order to overcome the above mentioned shortcomings. The feed drive elements were defined as modules by using the approach suggested by Fu et al [5] when building a Newton-Euler model of a robot. The kinematics motion was transmitted forward through the model and resistive force fed back. Based on this principle, the single axis feed drive model contained the reaction forces (due to friction and components inertia), which were applied as inputs to precedent modules. The analogue feed drive had a DC motor whose torque had to overcome the load element inertia, the friction forces within bearings, also friction between worktable / saddle and again between guide ways and between nut and screw.

Pislaru also developed two-axis models [6, 7] and three-axis models [8] using the same modular approach. The machine geometric errors (measured by laser interferometer) were inserted into the two-axis model and a mathematical procedure for the calculation of the ball bar predicted values was established. The modular approach offered greater flexibility in model construction (various components could be included /removed without altering the whole system model) and the requirements for the control part (controller, pre-amplifier, power-amplifier, motor) could be evaluated by reaction force computation. The single axis simulation results for a trapezoidal rate demand [9] compared well with the measured data. Simulated Bode diagrams were produced using Linear Time Invariant (LTI) viewer from MATLAB and the models for the timing belt and ball-screw, including for non-linear behaviour [10], were built. The authors supposed that it was possible to simulate the effect of resonant states of feed drive components without including the measured values of damping factors into the models. The simulation results were similar to measured Bode diagrams and ball bar plots, but the simulated dynamic performance had to be improved because the effect of system resonant states was not present in the simulation results.

Holroyd et al [11] investigated the dynamic characteristics of a CNC machine tool feed drive and modelled its elements as point inertias connected by springs and dampers. An eigenvalue approach was used for determining undamped natural frequencies of the drive. It was evident that more research should be done regarding modelling non-linearities such as belt tension, friction between belt and pulley, etc.

4. Hybrid models with distributed load, explicit damping factors and measured non-linear effects (backlash, friction)

Pislaru [3] performed a comparison between lumped parameter models and modular approach and developed a *hybrid model* of CNC machine tool feed drive with distributed load, explicit damping coefficients, backlash and friction. The model was a combination of distributed and lumped elements described by partial differential equations and ordinary differential equations as suggested by Bartlett and Whalley [12]. The ball-screw was modelled with distributed parameters (seven SIMULINK modules were produced), while other components (bearings, belt and pulleys, motor, etc.) had lumped parameter models.

The non-linearities and modal parameters (resonant frequencies, damping factors) were measured by specialised equipment (laser interferometer, accelerometers, signal analyser). Novel measurement practices for decoding signals generated by encoders (rotary encoders situated on DC motor, ball-screw end and linear encoders) were defined. The influence of time constants and gains of closed loops for velocity and position control was considered. Also a novel application of Continuous Wavelet Transform (CWT) for modal parameter identification of machine tool feed drives was elaborated.

The non-linearities included into the hybrid model described in [13] were defined by ordinary differential equations (friction) and partial differential equations (backlash). Although the hybrid model had several disadvantages (worktable positioned at half of travel length and swept sine / random white noise was applied to the pre-amplifier), the simulation results when the nut oscillated at the middle of the screw shaft were similar to the machine responses (Figure 2).

Figure 2. Measured Bode diagrams and simulated ones using hybrid model with distributed load, explicit damping factors and measured non-linear effects [13]

The values of simulated resonant states however were still slightly different than the experimental ones therefore more research had to be done in order to optimise the hybrid model.

Holroyd et al [14] developed a generalised eigenvalue method to estimate the undamped and viscous damped natural frequencies, damping coefficients and mode shapes of an analogue feed drive. A study on the influence of stiffness and damping coefficients within hybrid model on the resonant states was performed. The results could be useful in optimising the hybrid model parameters so the simulation results are in accordance with the real data.

The lumped parameter models, modular approach and the hybrid models assumed that the machine load was static or oscillating around a point situated at half of travel length. Modern CNC machine tools are used in high speed machining applications therefore the emphasis of modelling techniques should be on dynamic performance characterisation and enhancement. The performance factors limiting the accuracy of trajectories can be categorised as system non-linearities (friction, backlash, quantisation, saturation, etc.), system uncertainties (modelling error, parameter variation, external load, etc.) and system dynamic constrains (axes dynamic mismatch, system bandwidth, mechanical response). Several authors concentrated on these aspects and used various methods (classical mechanical theory, TLM method, FEA) which improved the speed and accuracy of simulation process.

5. Other methods for modelling and simulation of feed drives

The dynamic behaviour of a ball-screw with moving nut was modelled by Holroyd et al [15] in C language using a finite element approach. The ball-screw was divided into a large number of elements and contact and boundary conditions for each element and adjacent ones were studied.

An important conclusion was that the natural frequencies of the ball-screw system vary in time due to two causes:

- The lateral restraint produced by the nut when the screw transversally vibrated
- The relation between screw torsion and axial motion and worktable/saddle tilting.

The models previously developed were implemented in SIMULINK (hybrid models) and C language (dynamic model of a ball-screw). Simulation times were of the order of hours due to the great number of model elements therefore further research was carried out in order to reduce the simulation times.

Christopolous [16] showed the analogy between electrical circuits and physical systems based on the transmission line modelling (TLM) method. The elements of various systems could be represented by capacitors, inductors and resistances considering the wave propagation through a variety of mediums. Bartlett and Whalley [17] validated this method of approach by developing the admittance and impedance modules for two hybrid systems - ventilation systems used in long tunnels and rotor shells. TLM has been successfully applied especially for power electronic, electromagnetic, acoustics and several mechanical applications (not much emphasis on digital controllers implemented on CNC machine tools).

Moreno-Castaneda et al. [18] have built a TLM model for a digital drive where the controller commanded the movement of worktable linked to a motor through a ball-screw. The dynamic behaviour of the elements has been described by differential equations and corresponding TLM models have been derived. The high processing speed and relatively uncomplicated procedures for modelling both continuous and discrete elements were the main advantages of using TLM to model the feed drive system behaviour. The developed model assumed that the digital drive contained only linear elements even though the real feed drive system presents non-linearities.

Pislaru et al [19] improved this model by including TLM models for non-linearities (Coulomb and viscous friction, backlash), axial and torsional forces applied on the ball-screw nut during its linear movement and structural stiffness of various elements. The friction for worktable-slides and screw-nut contacts was modelled based upon Karnopp approach [20] and a hysteresis loop represented the machine backlash. The direct responses from the actual digital axis-controller and simulated results compared well when a trapezoidal velocity signal was applied to the digital drive and its TLM model. More research should be done in order to minimise or eliminate the errors between these results by including accurate TLM models for performance factors such as stiffness, pre-sliding friction, system uncertainties, dynamic constraints etc.

The Finite Element Analysis (FEA) was used by Myers et al. [21] to model the dynamic behaviour of a CNC machine tool. The authors emphasised the necessity for high static and dynamic machine stiffness to ensure accurate machining processes. Static, dynamic and modal analyses were performed using Pro/Engineer software package and the frequency response curves were plotted. The results were similar with the measured values from an actual CNC machine tool operating under non-cutting conditions although only one damping factor was used for the entire machine structure.

The methods for modelling and simulation of CNC machine tool feed drives have been continuously improving because machine tools of increasing accuracy are needed when higher tolerances and smoother surfaces are required. The machine performance depends on geometric, thermal and load errors and various compensation algorithms and measurement strategies for the automatic acquisition and analysis of errors have been developed [22-25].

The research findings regarding the factors influencing the performance of CNC machine tools should be used when object oriented modelling methods using hybrid, distributed-lumped parameter representations are developed and implemented. In this way the simulated dynamic behaviour of CNC machine tool feed drives under non–cutting and cutting conditions would comprise the effect of the spatial dimensions, mass shifts, non-linearities etc.

6 Conclusions

The paper presents a review of the existing methods for the modelling and simulation of CNC machine tool feed drives. The simulated results obtained by using conventional lumped parameter models are compared against the measured Bode diagrams and the necessity of employing other accurate methods is underlined. The modular approach allows the analysis of various forces between drive elements, but the effect of resonant states is not visible. The hybrid, distributed-lumped modelling techniques are the most appropriate to represent the interaction between the position loop controller, servo system and the worktable mechanism. The integrity, flexibility and applicability of these models for CNC machine tool feed drives design and analysis are commented upon.

Computationally fast and efficient algorithms are required to compute, predict and eliminate the instantaneous errors of modern high-speed machines. The TLM method is successfully applied for accurate modelling of non-linear and dynamic behaviour of CNC machine tools feed drives.

The behaviour of the ball-screw with moving nut could be represented by using TLM method and classical mechanical theory. The TLM method is faster and mathematically attractive avoiding the need to be come to involved in the boundary value problems associated with partial differential equations.

The FEA could be used for a full investigation into the dynamic state where valid structural resonances (dynamic errors, rigid and non-rigid body errors and thermally induced errors) are introduced into the machine model.

Future research should concentrate in using hybrid modelling, TLM, FEA and other modern numerical methods for developing accurate feed drives models which could become parts of automatic tuning and condition-monitoring methods. They should contain the influence of performance factors on the surface finish produced by modern high-speed CNC machine tools.

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