International Journal of Mechanical Engineering (IJME)
ISSN(P): 2319-2240; ISSN(E): 2319-2259
Vol. 2, Issue 5, Nov 2013, 39-44

International Academy of Science, Engineering and Technology
Connecting Researchers; Nurturing Innovations

A REVIEW ON REAL-TIME SIMULATION OF CNC MACHINE TOOL DYNAMICS

C. PISLARU

Senior Lecturer, University of Huddersfield, EPSRC Centre for Innovative Manufacture in Advanced Metrology, Huddersfield, England, United Kingdom

ABSTRACT

This paper is an endeavour to critically appraise the existing methods used for real-time simulation of machine tool dynamics with the emphasis on modelling and simulation of the dynamic behaviour of CNC machine tool feed drives and mechatronic systems for machine tools. The actual approaches for linking the feed drive models with structural models for CNC machine tools are examined. Also the feasibility of using the multidisciplinary approach employing the concepts of virtual machine tools and virtual machining into the design and control processes related to manufacturing process is analysed.

KEYWORDS: Computer Numerical Control (CNC), Feed Drive System, Hardware in the Loop, Machine Tool, Mechatronic, Motion Control, Simulation

INTRODUCTION

Manufacturing makes a major contribution to world economies and the hardware, software and methodologies used by modern CNC machines have all matured into state of the art software packages and multi-axis machining centres. Along with enhanced quality requirements throughout industry, manufacturing requirements are becoming increasingly stringent for high-quality products in terms of precise dimension, form and geometry, improved surface finish and integrity. Machine tools are an integral part of the manufacturing processes and the major contributor to the accuracy of components. *ARC Advisory Group (2010)* point out the actual challenges faced by machine tool builders: “highly competitive market and customer demands driven by tight capital equipment budgets and significantly shortened delivery times. Customers also demand smarter machines, longer lifecycles, easy maintenance and reliability”.

To compute, predict and eliminate the instantaneous error in a precision engineering process requires computationally fast and efficient algorithms. This can be achieved by using a mathematical model of the system, which adequately replicates the dynamic behaviour of the process. In particular the prediction of transient, induced stress levels, noise, vibration and wear manifest all in the final implementation which, in general would at best, be less than optimum in terms of dynamic performance and accuracy. These problems become acute in precision engineering and error corrections in metal cutting.

Machine tool systems employ a variety of relatively “long” distributed elements such as drive shafts and concentrated assemblies such as gears, bearings, couplings and load platforms that can be described by analogous sets of equations. Consequently, a wide range of machine systems can be modelled as hybrid, distributed-lumped parameter realisations. This paper compares various methods for modelling and simulation of the dynamic behaviour and recommends the most appropriate ones for real-time applications.

Machine tools of increasing accuracy are needed if higher tolerances and smoother surfaces are required because the ability to produce accurate components has many advantages: reduced tolerances; shorter build times; greater interchangeability; reduced costs incurred by re-manufacturing; reduced set-up time. There are diverse software packages used to model the electrical parts (controller, motor, etc.) and mechanical elements (ball-screw system, transmission, guideways, worktable, slideways, column, etc) and this paper analyses the advantages and shortcomings of the existing approaches for linking the feed drive models with structural models for CNC machine tools.

Recently researchers and companies have built virtual machine tools which aim to represent the behaviour of the actual machines without building physical prototypes. This paper examines the feasibility of using the concepts of virtual machine and virtual machining to increase the effectiveness of real-time simulation processes for CNC machine tool dynamics.

MODELLING AND SIMULATION OF THE DYNAMIC BEHAVIOUR OF CNC MACHINE TOOL FEED DRIVES

For many years the machine tool systems have been modelled as sets of connected stiffness, inertia and damping elements and the electrical drives as assemblies of point-wise capacitors, inductors and resistances (Martin, 1999). But the measured results from the actual machine tool system did not match the simulated results using lumped parameter models.

Whalley et al (2005) observed that all mechanical power transmission systems, for example, containing shafts, couplings, gearing, bearings, load inertia etc, could be similarly configured. The slenderness ratio of the shafts employed tends to be high so the shafts should have distributed topology in order to mass-inertia ratio. However the motor, electrical drive and couplings could be modelled as lumped parameter elements without significant accuracy loss.

Pislaru et al (2004) have built hybrid models considering distributed load, explicit damping factors and measured non-linear effects (backlash, friction) and implemented them in MATLAB / SIMULINK in order to simulate the frequency-domain behaviour of the dynamic non-linear systems which are the CNC machine tools. The parameters of the models were optimised using the generalised eigenvalue method (Holroyd et al, 2003). The hybrid modelling approach was mathematically attractive because the large segmented lumped models were avoided without becoming too involved in the boundary value problems associated with partial differential equations. There was a close match between the simulated resonant frequencies and those measured on the actual machines (Pislaru et al, 2003) subjected to the same input signals but the simulation time was on the order of minutes (considered to be too long for real-time applications).

Moreno-Castaneda et al (2005) analysed the possibility to apply Transmission Line Matrix (TLM) method and Finite Element Analysis (FEA) to digital feed drives. The TLM models contain screw shafts divided into a large number of identical elements and it was necessary to achieve the synchronisation of events during simulation and produce acceptable resolution according to the maximum frequency of interest. A considerable computing effort was required when small time steps are used in the simulation process, but it was possible to reduce the simulation time and calculation power maintaining accurate and reliable results. The models were implemented in C++ and MATLAB / SIMULINK and simulated values for different positions of the moving nut compared well with the measured data when same stimuli are applied to the models and the actual feed drives. The main advantages of the TLM method were reduced simulation time and calculation power, accurate and reliable results for complex hybrid systems. The simulation time was few seconds therefore TLM method proved to be suitable for developing models to run in real-time in order to be used by modern industry.

REAL-TIME SIMULATION OF MACHINE TOOL DYNAMICS

Pritschow and Rock (2004) describe the basic principles for time-deterministic algorithms to deal with aspects of machine dynamics such as: mass, inertia, stiffness, damping, friction, etc. They underline that it is necessary to predetermine the simulation step size and order with respect to the numerical stability of the time-deterministic dynamic non-linear model of the machine.

Pislaru et al (2009) have implemented a comprehensive TLM model for CNC machine tool feed drive into dSPACE real-time system. The one-axis TLM model of ball-screw system included the moving nut, the distributed inertia of the screw, the simulation synchronisation of axial and torsional forces applied on the nut during its linear movement, the restraints applied by the bearings and non-linearities (such as backlash, friction). The simulated results compared well to the experimental data (drive signals, data from analogue, digital, encoder, and PROFIBUS-DP interfaces between the system and the machine drives and controllers) showing the suitability of TLM feed drive models for real-time applications.

Sztendel et al (2009) described the stages for the development of a mechatronic model for the CNC machine tool and creation of a Hardware-in-the-Loop (HIL) platform allowing the real-time simulation and comparison with the experimental results. The hybrid model of the digital feed drive was implemented in SIMULINK while the machine structure model was developed in ABAQUS based on experimental results of modal analysis. It was noted that there are no procedures to link the results of mechanical simulation software packages (such as ABAQUS, SolidWorks) directly to MATLAB and SIMULINK packages.

So it was developed a method where the output of the mechanical model was sent back to the functional simulation tool so a holistic model describing the machine behaviour in static and dynamic conditions is produced. Then this model was implemented in dSPACE real-time system after the experiment control graphical user interface (GUI) is completely developed in dSPACE’s ControlDesk. There are various software packages claiming that they offer quick and reliable links between feed drive models and structural models but their solution is only for an established configuration of the electrical and mechanical parts so they are not suitable for research purposes.

Sztendel et al (2012) has developed a mechatronic model for five axis CNC machine tool and created a Hardware-in-the-Loop (HIL) platform where the model of this machine was used. The simulated results compared well with the experimental ones so the implementation of HIL system (containing the holistic model of CNC machine tool) was validated.

Jonsson et al (2005) introduced the concept of virtual machine for real-time simulation of machine tool dynamics. The concept included a real control system, machine dynamics simulation models and virtual reality model for visualisation. The authors underlined the necessity of a trade-off between productivity and accuracy of the manufacturing process through multidisciplinary optimisation.

Fredin et al (2012) used genetic algorithms and gradient based algorithms to solve the optimisation problem related to mechanical system, control system parameters, servo and drive systems. The results should be analysed by using post processing and data mining techniques. The virtual machine concept allowed the study of the machine dynamic behaviour without building the practical prototype (Altintas et al, 2005).

Abdul Kadir et al (2011) produced a comprehensive review of existing approaches (virtual reality, hardware interactions, web-based techniques, STEP-NC methodologies) used to support virtual manufacturing. They underlined the features of an effective virtual system such as “neutral data to support interoperability, realistic visualisation, incorporation of shop-floor information through hardware interaction, high-level data to support multi-directional data flow, networked capability to assist collaboration”.

Neugebauer et al (2007) mentions about “intelligent” machine tools with electronically enhanced functions, self-optimising and adaptronic components, model-supposed compensation of machine errors and process control. The fundamental expansion of design technologies using “virtual machine tool” concepts will ensure the complete transformation of the paradigm “reliability despite mechatronics” into “reliability by means of mechatronics”.

CONCLUSIONS

TLM models, mechatronic approach, virtual machine and machining concepts represent possible solutions to the current research challenges in the design, analysis and real-time control of CNC machine tools. Effective real-time simulation techniques for CNC machine tool dynamics could be employed into the development of models comprising the most relevant aspects of the machining processes which will be able to predict the quality of workpiece without the time, money and resources required to carry out physical trials which ultimately lead to cheaper development costs. Users of the enhanced manufacturing systems will benefit due to the efficiency savings and the society will benefit directly from cheaper products and enhanced functionality.

REFERENCES

1. ARC Advisory Group – Mechatronic Development Process for the Machine Tool Industry. ARC White paper, September 2010.
2. K. Martin, M. Ebrahimi M - Modelling and Simulation of the Milling Action, Proc. IMechE, Part B: Journal of Engineering Manufacture, Vol. 213, 1999, pp. 539-554.
3. R. Whalley, M. Ebrahimi and A. Abdul-Ameer - Hybrid Modelling of Machine Tool Drives, International Journal of Machine Tools and Manufacture, Vol. 45, Issue 14, 2005, pp. 1560 – 1576.
4. Pislaru, D. G. Ford, G. Holroyd – Hybrid Modelling and Simulation of a CNC Machine Tool Axis Drive. Proc. IMechE, Part I: Journal of Systems and Control Engineering, vol. 218, issue I2, 2004, pp. 111-120
5. G. Holroyd, C. Pislaru, D. G. Ford – Determination of Stiffness and Damping Sensitivity for Computer Numerically Controlled Machine Tool Drives. Proceedings of the Inst. Mech. Engrs (IMechE), Part C, Journal of Mechanical Engineering Science, vol. 217, 2003, pp. 1165 – 1177.
6. C. Pislaru, J. M. Freeman, D. G. Ford – Modal Parameter Identification for CNC Machine Tools Using Wavelet Transform. International Journal of Machine Tools and Manufacture, vol 43, no 10, 2003, pp. 987 – 993.
7. Moreno-Castaneda, V., Pislaru, C. and Ford, D. (2005) ‘Modelling and simulation of the dynamic behaviour of a ball screw system using transmission line modelling technique*’.* Proc. 7th Int. Conf. on on Laser Metrology, Machine Tool, CMM & Robotic Performance (Lamdamap 2005), Cranfield, pp. 210 - 219.
8. Y. Altintas – Manufacturing Automation: Metal Cutting Mechanics, Machine Tool Vibrations, and CNC Design, Cambridge University Press, 2011.
9. G. Pritschow, S. Rock – “Hardware in the Loop” Simulation of Machine Tools. Annals of CIRP – Manufacturing Technology, vol, 53, no. 1, 2004, pp. 295 – 298.
10. Pislaru, C., Ford, D.G., Sztendel, S., Myers, A. - Optimisation of Real-Time Implementation for High Speed Drives Models. Proc. 9th Int. Conf. on Laser metrology, machine tool, CMM and robotic performance (LAMDAMAP 2009), 30 June - 2 July 2009, Brunel University, pp. 138-146.

11. Sztendel, S., Pislaru, C., Poxton, A., Ford, D.G., Myers, A. - Developing Mechatronic Models of Modern CNC Machine Tools For Real-Time Implementation. Proc. 9th Int. Conf. on Laser metrology, machine tool, CMM and robotic performance (LAMDAMAP 2009), 30June - 2 July 2009, Brunel University, pp. 147-155.
12. Sztendel, S., Pislaru, C., Longstaff, A., Fletcher, S. and Myers, A. - Five-Axis Machine Tool Condition Monitoring Using dSPACE Real-Time System, Journal of Physics: Conference Series , vol 364, 2012, p. 012091.
13. A. Jonsson, J. Wall, G. Broman – A Virtual Machine Concept for Real-Time Simulation of Machine Tool Dynamics. International Journal of Machine Tools and Manufacture, vol 45, 2005, pp. 795 – 801.
14. J. Fredin, A. Jonson, G. Broman – Holistic Methodology Using Computer Simulation for Optimisation of Machine Tools. Computers and Industrial Engineering, vol 63, 2012, pp. 294 – 301.
15. Y. Altintas, C. Brecher, M. Weck, S. Witt – Virtual machine Tools, Annals of CIRP, vol. 54, no. 2, 2005, pp. 651 – 673.
16. A. Abdul Kadir, X. Xu, E. Hammerle – Virtual Machine Tools and Virtual Machining – A Technological Review. Robotics and Computer-Integrated Manufacturing, vol. 27, 2011, pp. 494 – 508.
17. Neugebauer, B. Dekena, K. Wegener – Mechatronic Systems for Machine Tools. Annals of CIRP – Manufacturing Technology, vol. 56, no. 2, 2007, pp. 657 – 686.