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Five-Axis Machine Tool Condition Monitoring Using dSPACE Real-Time System

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Abstract. This paper presents the design, development and SIMULINK implementation of the lumped parameter model of C-axis drive from GEISS five-axis CNC machine tool. The simulated results compare well with the experimental data measured from the actual machine. Also the paper describes the steps for data acquisition using ControlDesk and hardware-in-the-loop implementation of the drive models in dSPACE real-time system. The main components of the HIL system are: the drive model simulation and input – output (I/O) modules for receiving the real controller outputs. The paper explains how the experimental data obtained from the data acquisition process using dSPACE real-time system can be used for the development of machine tool diagnosis and prognosis systems that facilitate the improvement of maintenance activities.

1. Introduction

Modern industry requires fast, accurate and productive CNC machine tools capable to generate workpieces with tight dimension, form, and surface finish tolerances. The cutting processes induce non-linear dynamic behaviour of these machines [1] therefore the classical pre-calibrated methods for error compensation cannot be used in these circumstances. Maj et al [2] described the close interaction between the dynamic behaviour of the mechanical structure, drives, and numerical control to reproduce correctly the characteristics of all components that can limit the machine performance. Then Yeung et al [3] presented the development of a virtual model of a CNC machine tool which requires realistic mathematical models for each CNC component and their logical interconnection. The Virtual CNC allowed the modular integration of trajectory planning and interpolation routines, mathematical models of ball screw and linear drives, friction, feedback sensors, amplifiers, D/A converters and flexible motion control laws. Also there has been significant progress made on modelling various trajectory generation algorithms [4], control laws [5], and physical components of the drives such as motors, amplifiers, ball-screw and linear drives with various friction characteristics [6, 7].

The University of Huddersfield has gained over the years an international reputation due to its extensive research work in the area of machine tool precision accuracy and control engineering. Precise models reflecting the dynamic behaviour of CNC machine tools for various running conditions were developed to ensure an optimal operation of feed drives within CNC machine tools. The lumped parameter models [8], the modular approach [9] and hybrid models with distributed load, explicit damping factors, backlash and friction [10, 11] aimed to represent the dynamic behaviour of the CNC machine tool feed drives when the ball-screw nut was travelling.

Also the Transmission Line Modelling (TLM) technique proved to be useful in replicating these complex interactions occurring when the nut is travelling. The TLM model of ball-screw system [12] included the moving nut, the distributed inertia of the screw, non-linearities (Coulomb friction,

backlash) [13], the simulation synchronisation of axial and torsional forces applied on the nut during its linear movement and the restraints applied by the bearings [14]. The main advantages of TLM technique [15, 16] are the high speed of processing and relatively simple procedures for continuous and discrete models making it suitable for real-time applications [17, 18].

Dougal [19] mentioned that traditional software-based simulation has the disadvantage of being unable to exactly replicate real time operational conditions. One way to bridge the gap between simulation and real conditions is hardware-in-the-loop (HIL) simulation. Several papers have been written outlining the basic fundamentals of HIL simulation [20].

This paper presents the mathematical equations used to develop the mathematical model of the C-axis drive from GEISS five-axis machine existing at the University of Huddersfield. This model is implemented in SIMULINK and the simulated results compare well with the experimental data measured from the actual machine so the proposed model is validated. Also the paper describes the steps for data acquisition using ControlDesk and hardware-in-the-loop implementation of the drive models dSPACE. The main components of the HIL system are: the drive model simulation (executes in real-time and simulates the dynamic characteristics of the drive) and input – output (I/O) modules for receiving the real controller outputs and responding with simulated signals from the drive model back to the controller with the intention to improve the quality of machine operation.

Current trends in mechanical engineering show the growing importance of costs for machine tool life cycles. The producers of machine tools need to pay more attention to their products' life cycle because the customers increasingly focus on machine tool reliability and costs. The present paper explains how the experimental data obtained from the data acquisition process using dSPACE real-time system can be used for the development of a machine tool diagnosis and prognosis system that facilitates the improvement of maintenance activities. The health condition of the physical feed drive components can be constantly assessed by using the monitoring data measured by dSPACE to perform on-line system diagnostics and prognostics and estimation of the remaining useful life.

Section two shows the results of the analysis of the operation of actual CNC five-axis machine and the derivation of the mathematical equations describing the dynamic behaviour of machine. Section three describes the implementation of C-axis drive model in SIMULINK and the simulated results are compared with the measured data in section four. The next two sections present the steps of performing data acquisition using ControlDesk from dSPACE real-time system and the development of HIL implementation which will use the validated proposed drive model. Section seven describes the experimental data obtained from the data acquisition process using dSPACE real-time system can be used for the development of machine tool diagnosis and prognosis systems that facilitate the improvement of maintenance activities.

2. Analysis of the operation of actual five axis Geiss CNC machine with Siemens 840D controller

Siemens SINUMERIK 840D is an open architecture controller which provides diverse development tools for many applications. It is using the Multiple Protocol Interface (simple version of Profibus) to connect in a single network the processing components, such as the Human-Machine Interface and the Programmable Logic Controller. Figure 1 shows the five-axis machine existing at the University of Huddersfield which has been used for practical measurements. The controller Sinumerik 840D SL (Solution Line) has open architecture and the machine is equipped with the orthogonal trimming head and spindle. Both ends of the axes protrude which permit independent operation with two different tools. The spindle power is 6 kW, the tool is clamped in an ER 16 chuck and the spindle runs on sealed ceramic bearings which are lubricated for life.

In order to perform the data acquisition it is necessary to understand how and where data is processed and transmitted in this five-axis machine. It has direct drives so the servo motors are joined directly to the load with no transmission devices. These torque motors allow the dynamic direction changes for high velocities and have higher values for accuracy and lifetime in comparison to lead screw drives and linear motor drives. Standard servo controllers do not have added force inputs, they

have two encoder inputs motor encoder for a velocity measurement and a second encoder for position measurement at the slider. Direct drives need just one encoder for position and velocity measurement. Modern versions are electrically equivalent to 3-phase brushless, synchronous motors with permanent magnet field excitation. The geometry of the motors is chosen to generate high torques (or forces) output rather than high efficiency. The direct drive technology applies the power to the movement directly, without previous conversion of a mostly rotary movement. The copper losses and electrical time constants remain low, so these motors have a higher number of magnetic poles than a conventional servo motors.

The most significant selection condition is the accelerating ability of the drive. Direct drives, especially torque motors, have often been applied for 5-axis milling machines in the last few years in order to achieve dynamic orientation changes for high path velocities. While ball screw drives and linear motor-driven axes reach comparable dynamic feed axis performance, the torque motor can have clear advantages in dynamics, accuracy and lifetime, compared to gear axes.



a) actual five-axis machine b) rotational B and C axes
Figure 1. Actual five-axis machine and the rotational B and C axes.

Figure 2 shows the main elements of the C-axis drive: position setpoint generator; position controller; speed controller; current (direct torque) controller; 3-phase inverter; induction motor with rotary encoder which generates a feedback signal proportional with the rotor speed. The angular position is obtained by integrating the speed values.

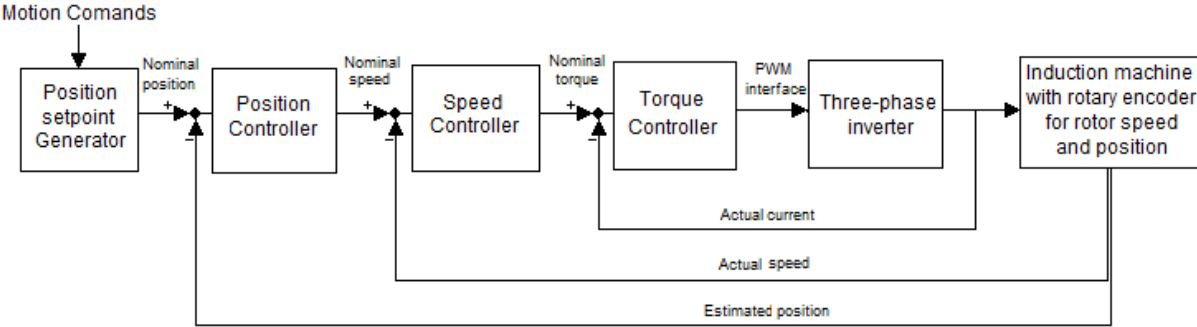


Figure 2. Block diagram representing C-axis drive.

Zirn [21] shows that a pulse width modulated (PWM) voltage source inverter generates a circular rotating field in the stator (rotating field vector Φ). The permanent magnets on the rotor try to align the magnetic rotor axis with the stator field vector. The resulting rotor torque is given by

$$M \approx K_M \cdot I \cdot \sin \beta = K_M(\beta) \cdot I \quad (1)$$

A permanent magnetic rotor tries to align with the iron teeth in a toothed stator. This position-dependent periodic torque, called reluctance or cogging torque, is used for stepping motors. For servo motors, it represents a disturbance and has to be compensated by suitable stator geometry or by lookup compensation tables in the power module. Residual reluctance torque has to be considered in the physical model as a periodic nonlinear function block. Some motor manufacturers give a detailed description of the cogging torque in their data sheets. In most cases, a maximum cogging torque is given as a percentage of the rated torque – this allows approximate consideration of the effect by means of a sinusoidal function. The input voltage U for the motor coil is limited to the intermediate voltage U_z :

$$-U_z \leq U \leq U_z \quad (2)$$

This effect is considered by the saturation block in the physical model. Due to pulse width modulation, the input voltage U follows the command value U_{set} with a certain delay. This delay is taken into consideration in the physical model by a dead time T_{dead} of one pulse period (worst-case estimation):

$$T_{dead} = 1/f_{PWM} \quad (3)$$

The rotor movement generates the back-EMF voltage U_i induced in the coil:

$$U_i \approx K_S \cdot \sin \beta \cdot d\phi/dt = K_S(\beta) \cdot d\phi/dt \quad (4)$$

The current I follows the input voltage U with a delay due to coil inductance (1st-order transfer function with $T_{el}=L/R$). Typical time constants for servo motors are in the range of 10 to 20 ms, i.e. voltage input alone is too slow for dynamic position control. In addition, fast motor movements disturb the current given by the input voltage. The current controller in the power module has to ensure fast current generation with delays of less than 1 ms. If the input command value for the power module is a torque (M_{set}) instead of a current (I_{set}), the input has to be scaled:

$$I_{set} = M_{set}/K_M(\beta) \quad (5)$$

Direct-driven rotary axes can achieve higher control performance, more accuracy, longer lifetime and greater reliability than gear drives. One of the advantages of rotary direct drives is the possibility of exceeding the speed range for special application combinations. The standard maximum speed is limited in accordance with the following relation:

$$\omega_{max} = \frac{U_z}{K_S} \quad (6)$$

where U_z is the intermediate voltage and K_S is the torque constant. If maximum torque is required in the complete speed range, small torque constants in combination with high motor currents are required; this increases the drive costs and current converter volume significantly. Field-weakening is an interesting alternative if higher speeds have to be reached with reduced torque requirements. Therefore the commutation angle yields:

$$M \approx K_M \cdot I \cdot \sin \beta = K_M(\beta) \cdot I \quad (7)$$

It has to be set to smaller values ($\beta < 90^\circ$) to decrease both the back-EMF constant K_S and the torque constant K_M so this is the “field-weakening range”. Although the field of the permanent rotor magnets is not “weakened”, the smaller commutation angle results in the same effect: The motor can achieve higher velocities, but requires more current to produce torque. Typically, the current converter starts the field-weakening operation at maximum speed ω_{Mmax} according to:

$$\omega_{M_{max}} = \omega_{max} - \frac{M_{max} \cdot R}{K_s \cdot K_M} \quad (8)$$

where the motor can achieve the maximum torque. The potential torque, depending on motor parameters and velocity, is given by:

$$M(\omega) = I \cdot K_M(\omega) = \frac{U_Z - \omega \cdot K_S(\omega)}{R} \cdot K_M(\omega) \stackrel{K_M \approx K_S}{=} \frac{U_Z}{R} \cdot K_M(\omega) - \frac{\omega}{R} \cdot K_M^2(\omega) \quad (9)$$

If a certain torque has to be produced for a speed higher than ω_{Mmax} , the commutation angle has to be reduced until the torque constant is reached

$$K_M(\omega, M) = \frac{U_Z}{2 \cdot \omega} + \sqrt{\frac{U_Z}{2 \cdot \omega} - 4 \cdot \frac{R \cdot M}{\omega}} \quad (10)$$

Equation (10) represents the simplified algorithm implemented in most standard current converters for achieving higher velocities by field-weakening. These mathematical equations describing the dynamic behaviour of the induction machine have been implemented into the SIMULINK model.

3. Implementation of C-axis drive model in SIMULINK

Accurate identification of the feed drives dynamics is an important step in designing a high performance CNC machine which is a mechatronic system (consisting of mechanical and electronic components and software). Figure 3 shows the SIMULINK implementation of the C-axis drive model. The input signals for 'Position Controller' block are nominal angular position and actual position from the motor. This block generates the nominal speed (SP) which is fed to 'Speed Controller' block together with actual motor speed (N) from the rotary encoder and the magnetic compensation constant (MagC). The 'Speed Controller' produces the values for flux and torque which is included in DTC (Direct Torque Controller) together with three-phase voltage V_abc and current I_abc. DTC block generates the command signals for the thyristors gates from the 'Three-phase inverter'. The induction machine receives the electrical energy from the three-phase power supply, diode rectifier, braking chopper and PWM inverter. The block 'Voltage Current Conversion' transforms the torque values into electrical current values. The 'Induction Machine' block produces the values for the rotor angular position, armature currents, rotor speed.

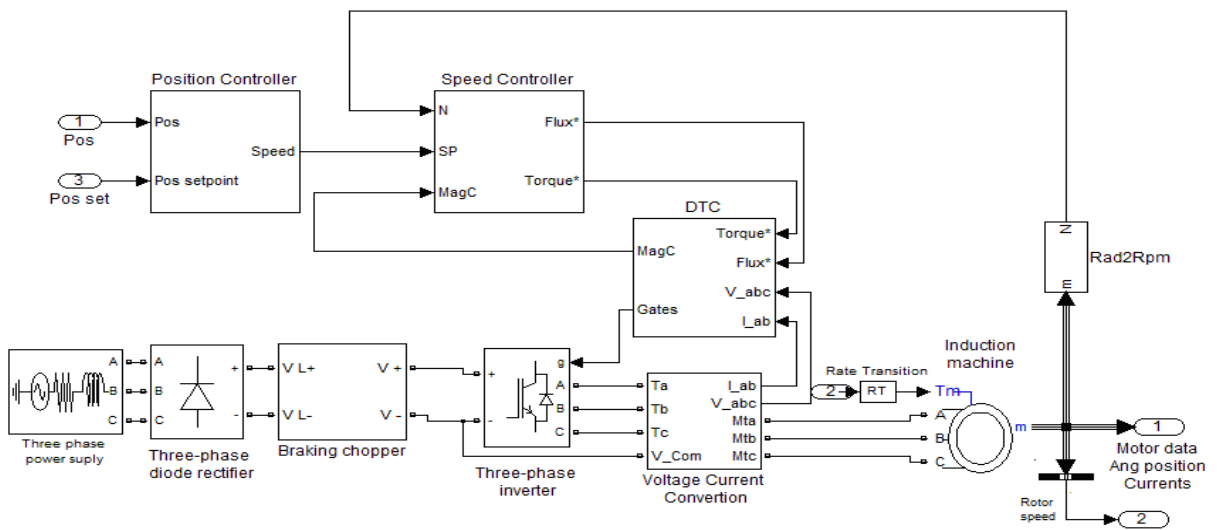


Figure 3. SIMULINK model implementation of the C-axis drive model.

The speed controller is based on a PI regulator which generates a torque set point applied to the direct torque controller. DTC estimates the motor flux components and the electromagnetic torque. The SIMULINK implementation uses the blocks from SimPowerSystems library. The power supply adjusts the AC input voltage to the intermediate circuit voltage. One intermediate circuit supplies several axis power modules, which makes possible the storage of braking energy and energy exchange between different axis operations. Braking chopper is used to absorb the energy produced by a motor deceleration. A, B, C are the three phase terminals of the drive.

Figure 4 shows the simulated angular position produced by the block 'Induction machine' from the SIMULINK implementation (see Figure 3). A triangular signal was applied as a demand to the 'Position Controller' block and the model simulates the rotor angular position. The values for the demand signal were chosen in accordance with the measured experimental data from the actual five-axis machine.

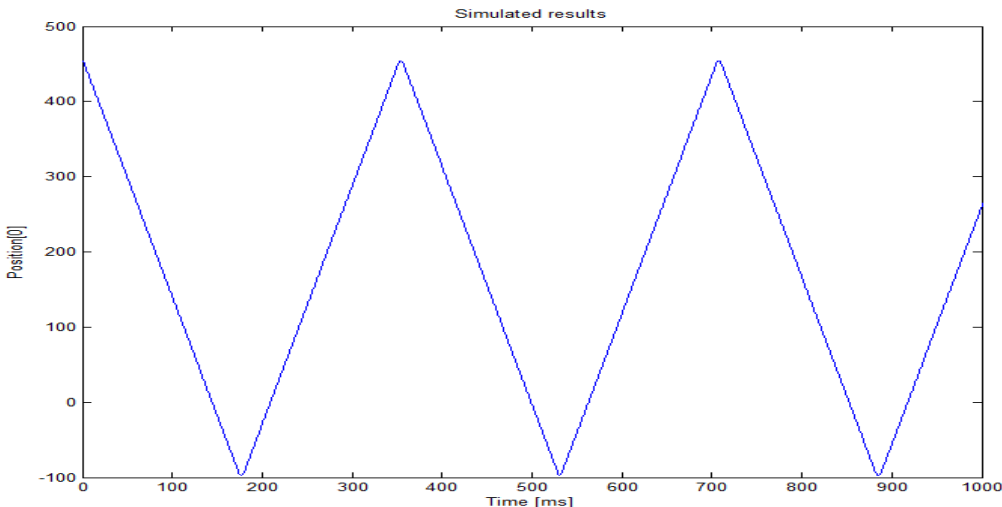


Figure 4. Simulated results obtained using SIMULINK model.

4. Comparison between simulated and measured results

The servo trace built-in function of the SINUMERIK 840D SL controller is used to measure the data from the actual five-axis machine. Manual commands are applied to achieve rapid traverse movements of the C-axis. Output signals are provided via rotary encoder mounted on the motor. The approach behaviour at various speeds has been checked using the HMI Advanced servo trace software. Servo trace provides a graphically assisted analysis of the time response of position controller and drive data and offers functions for recording and graphically illustrating the temporal characteristics of values for servo signals, e.g. actual position value, following error etc.

The measured values for the angular position of the actual servomotor are presented on Figure 5.

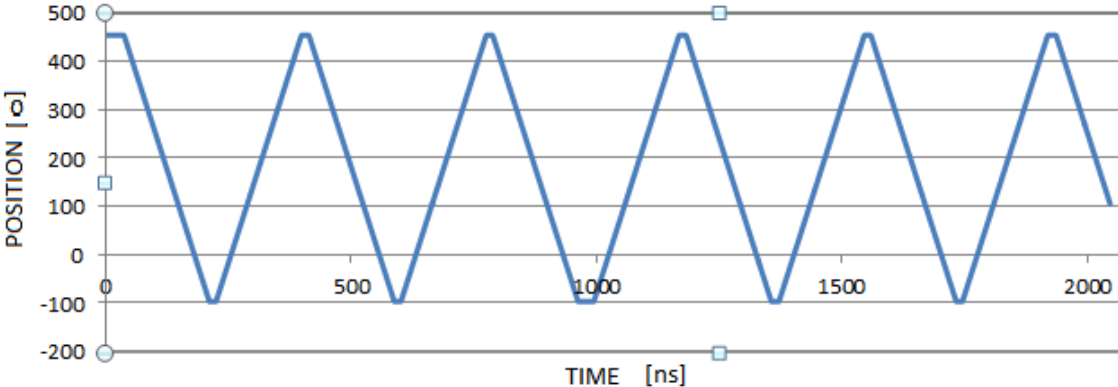


Figure 5. Measured rotor angular position using ServoTrace tool.

The simulated results (Figure 4) compare well with the measured data from the controller of the actual machine (Figure 5). This represents the first step in developing a full model of the five-axis machine including the horizontal, vertical and rotary axes drives.

5. Data acquisition using ControlDesk

It is intended to use the developed model into hardware-in-the-loop (HIL) implementation using dSPACE real-time system existing at the University of Huddersfield.

Real time implementation of drive models includes five main steps [18]:

1. construct the block diagram in SIMULINK and run the model
2. perform signal conditioning for the RTI implementation
3. use RTI for automatic implementation of SIMULINK model on dSPACE hardware
4. generate C code for the RTI implementation using Real Time Workshop (RTW) within MATLAB environment
5. develop GUI within ControlDesk

There are few Data Acquisition Instruments that keep track of continuous and binary variables: the plotter, XYPlot, LogicAnalyzer, and PloterArray instruments. A time trace capture collects data on the simulation platform and is the source of the data signals displayed in plotter instruments. The following topics explain how to use the Data Acquisitions Instruments.

The CaptureSetting instrument allows you to set data capture parameters for the different services specified in the model. Each tab in the Capture Settings Window corresponds to a service. The tab is labelled platform type – the name of the system description file – service number. For each service defined in the program, capture start/stop and all capture conditions (in particular trigger conditions) can be controlled individually. The settings of each captureSettings instrument may be applied to any data acquisition instrument. This lets you specify different sets of data capture parameters and apply these sets to several data acquisition instruments.

The Capture Settings Window is used to control the captured data in ControlDesk. This contains one or more pages: the CaptureSettings instruments. It allows setting data capture parameters for different variables specified in the model. It's possible to save the data as a MAT, CSV or IDF file.

The simulator variables connected to data acquisition instruments can be identified by the icon displayed in the first column (Connected). The connected variables will always be used for data capture. Invalid data connections (source or target of the data connection is removed) are displayed in red. The Capture Settings window with the corresponding service is displayed and each button corresponds to a service that is specified in the loaded application or SIMULINK simulation.

Trigger property page allows specifying the settings of the trigger signal, (e.g. the delay, rising or falling edge, and the trigger level). Data capturing starts immediately after the animation starts, if the checkbox auto start is selected. Otherwise, in the capture Settings Window click start/stop to manage data capturing manually.

One procedure for data acquisition using ControlDesk from dSPACE system was developed for three-axis CNC machine tool [17, 18]. A similar approach will be applied when the measured data from five-axis machine will be included in dSPACE system in the future.

6. Development of HIL implementation

HIL (hardware-in-the-loop) simulation is a technique that combines real and virtual components into an operational configuration to allow simulation and test of dynamic behavior of complex systems under varied conditions.

HIL simulations have given the engineers the ability to simulate a variety of scenarios that may be too difficult, time consuming or expensive to do on a machine prototype. This advanced testing capability has proven to significantly improve the quality of the released software. Our verification test process follows the System Engineering V. An HIL system can have several components within it. The main part is the plant model simulation, which executes in real-time and simulates the dynamic

characteristics of the plant. I/O modules are used to receive the controller outputs and respond with simulated signals from the plant back to the controller.

Modeling provides the ability to begin simulating control behavior while hardware prototypes are still unavailable. In addition, models from previous designs may be reused to further reduce the effort necessary to produce a model. If prototype or existing hardware is available, the modeling effort may be complemented by using real-world input/output data to produce models with system identification techniques.

The “Real Time Interface” is used to interface with the SIMULINK environment. In addition, the dSPACE adds patented user interface tools for viewing and controlling data in the SIMULINK environment. Users of the SIMULINK software can use dSPACE to perform offline simulations on a desktop or download the dynamic model to a real-time system for rapid control prototyping or HIL testing.

Because software simulations cannot account for all of the unique behaviors of an actual dynamic environment, a hardware prototype is developed to aid in the testing of the control algorithm in real time. This rapid control prototyping is the next, main stage of the control design V diagram. Real-Time Workshop® generates and executes stand-alone C code for developing and testing algorithms modeled in SIMULINK and Embedded MATLAB code. The controller design is tested in a real-time environment and connected to the real or simulated plant. This step provides excellent verification and validation feedback on the fidelity of the modeling effort and the resulting control design early in the design flow. Further refinements to the controller and hardware designs and requirements can be made prior to finishing the design of the production systems. Following this stage, the controller is implemented on target hardware that is dSPACE DS1005 or it can be some custom hardware.

In HIL testing, the designer can simulate real-time behavior and characteristics of the final system to verify the production system controller without the need for the physical hardware or operational environment. As seen in the figure, the control code is running on the target controller hardware while the plant is simulated in real time on a test computer. ControlDesk handles every facet of the HIL usage process, from providing customizable user interfaces, to managing the model execution and all hardware configurations, to providing extensions to the HIL environment.

During this testing phase, it is important to test the complete functionality of the controller. While you can connect the target hardware with the actual plant, testing against a simulated plant such as an engine offers several advantages. An HIL tester is far more cost-efficient and easier to reproduce than a physical engine. The simulated engine also can simulate a variety of operating conditions or even fault conditions, such as engine stall, that would be difficult, costly, and/or dangerous with the actual plant. In order to get the real time information from the NC control side, the interface must be able to access the data from Siemens SINUMERIK 840D during the operation, collect the necessary information and pass it in real time to dSPACE 1005 DSP board. After the desired model configuration is built for the dSPACE target hardware, and tested successfully, the experiments are saved and are run directly using ControlDesk without repeating the model building process.

7. Using dSPACE real-time data for the development of machine tool diagnosis and prognosis systems

Feed-drives are directly implicated into the machining process. The accuracy, reliability and availability of the machine-tools depend on mechatronic devices that drive the tools. Generally, the direct drive motor faults and the drive chain faults are due to wear, heating, ageing. The usual condition monitoring system of a CNC machine-tool is limited particularly to the machine-tool auxiliary component. Data about the machine auxiliary component failures or malfunctions monitoring is insufficient to make the machine-tool more accurate, more available and more reliable and to produce good quality work-pieces.

The effectiveness of a condition-monitoring system relies on two elements - sensors and the signal processing with simplification methods required to extract usable information. If the monitoring of the feed-drive is running during the machining process, changes into some parameter values could be due

to changes in the cutting process. So, the monitoring of the feed-drive is only considered while there is no machining process. Monitoring systems should make a distinction between normal operational state and abnormal states so model does not include any cutting data and its suggested to use it only during the rapid commands between cutting cycles.

Different functions or activities like scheduling, maintenance, adaptive controls, diagnosis requires reliable information about the machine state and about its main components. The drive models which present original (not current state of the machine) have been used to analyse the dynamic behaviour of the machining system for in-process monitoring and control of dynamic stability. The analysis provided a great help for taking decisions and corresponding actions: stopping operation or changing operation, setting up, maintenance (i.e. reliable information reduces the risk of stopping operation due to false fault detection).

Jędrzejewski and Kwaśny [22] diagnosed a variety of drive conditions and diagnostic signals with an expert system and neural networks. They developed one drive self-diagnosing system consisting in on-line temperature- and power-based monitoring supplemented by detailed off-line diagnostics backed by artificial intelligence tools and knowledge bases and invoked in need only. The detailed diagnostics is based on power and acoustic noise measurements and involves data base propagation, a customized diagnosing algorithm, a mechanism of automatic inferring using fuzzy logic procedures and simulation of the inferring mechanism by a neural network. .

The failure of critical components in industrial systems may have negative consequences on the availability, the productivity, the security and the environment. To avoid such situations, the health condition of the physical system, and particularly of its critical components, can be constantly assessed by using the monitoring data to perform on-line system diagnostics and prognostics. Tobon-Mejia et al [23] used Bayesian networks for machine tool wear diagnostic and prognostic. In the metal cutting process, tool condition is the most crucial and determining factor to machine tool automation. Abnormal tool condition in a machining operation can be divided into three major types: tool breakage, tool wear, and tool-workpiece chatter. The assessment of machine health condition and estimation of remaining useful life (RUL) had been performed in two phases: off-line phase (raw data provided by the sensors are processed to extract reliable features) and on-line phase (constructed models are exploited to identify the tool's current health state, predict its RUL and the associated confidence bounds).

Modern monitoring systems employ smart actuators instead of traditional drives (spindles and feed-drives) so data processing abilities are used to implement monitoring and control tasks [24]. The data processing abilities of smart actuators are also exploited in order to create a new decision level where the machine reacts to disturbances that the monitoring tasks detect. The cooperation between the computational objects (the smart spindle, the smart feed-drives and the CNC unit) enables smart drives to carry out functions for accommodating or adapting to the disturbances.

The data measured with the dSPACE real-time systems will be used for real-time/online machine fault detection and prognostic monitoring and critical machinery facility maintenance. More study will be performed regarding the methodologies for real-time machine fault detection, lifetime prediction and optimal control to reduce faults especially for high-speed machining processes where the deformations of cutters, machine tools, and workpieces are caused by cutting force, thermal effect and chatter vibration. In high-speed machining, the combination of high quality and novel cutters with high-speed spindles and velocity/acceleration motion bases allows the tool to traverse the part path in minimal time and enables machining of hard and brittle materials with a high precision finish that is impossible to achieve by conventional machining. Optimum performance of these complex processes relies on the availability of the data about process conditions for process monitoring and feedback to the process controller. Also this task demands in-process reliable sensing systems coupled with robust signal processing techniques to extract useful information from a machining process.

8. Conclusions

This paper presents the development of the lumped parameter model of C-axis drive for five-axis CNC machine existing at the University of Huddersfield. The analysis of the operation of actual CNC five-axis machine is presented and the derivation of the mathematical equations describing the dynamic behaviour of machine is explained. The model is implemented in SIMULINK using SimPowerSystems toolbox. The simulated angular rotor position compare well with the experimental data measured from the actual machine so the proposed model is validated. Also the paper describes the steps for data acquisition using ControlDesk and hardware-in-the-loop implementation of the drive models in dSPACE. The main components of the HIL system are: the drive model simulation (executes in real-time and simulates the dynamic characteristics of the drive) and input – output (I/O) modules for receiving the real controller outputs and responding with simulated signals from the drive model back to the controller with the intention to improve the quality of machine operation. Also the paper explains how the experimental data obtained from the data acquisition process using dSPACE real-time system can be used for the development of machine tool diagnosis and prognosis systems that facilitate the improvement of maintenance activities.

Further research will be done to develop a full model of the five-axis machine including the horizontal, vertical and rotary axes drives which will be included in HIL implementation using dSPACE real-time system. This will represent an important contribution to the condition monitoring techniques which could be used to improve the five-axis machine performance.

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