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Integration of virtual and on-line machining process control and monitoring

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A B S T R A C T

This paper presents a virtually assisted on-line milling process control and monitoring system. A part machining process is simulated to predict the cutting forces, torque, power, chip load and other process states. The simulated machining states are accessed by a real time monitoring system which detects the tool failure and adaptively adjusts the feed by predicting the forces from the feed and spindle drive motor current supplied by CNC. The integration of virtual simulation with real time measurements avoids false tool failure detection and transient overloads of the tools during adaptive control. The system has been implemented on a CNC machining centre for use in production.

1. Introduction

The recent trend in manufacturing is to develop intelligent, self-adjusting and unattended machining systems to improve the productivity. As reported in past CIRP keynote articles, the reliability of such systems highly depends on the availability of industry friendly sensors [1] and robustness of methods to avoid false alarms and incorrect actions [2].

There have been major efforts in the field of sensor assisted machining. The primary applications focussed on tool wear and breakage monitoring, chatter detection and avoidance, adaptive control of the process forces and dimensional errors, thermal compensation of machines, collision avoidance, and spindle health monitoring. A variety of sensors have been used such as force, vision, acoustic emission, vibration, power, strain, thermocouples and laser devices depending on the application [2]. The reliability of all tool condition and machining process control systems have been suffering mainly because of having difficulties in installing practical and reliable sensors on the machine [3], and not being able to distinguish the actual machining process state from the effects of geometric changes along the tool path [4]. This article presents a new approach: the use of virtual part machining simulation to feed data which is needed to improve the robustness of on-line tool condition monitoring and cutting process control system. The approach is in accordance with Industry 4.0 principles which recommend the integration of digital simulation and sensory data to achieve intelligent manufacturing systems.

The proposed approach has been demonstrated in simultaneous adaptive control of cutting forces and detection of tool failure as shown in Fig. 1. A real time communication link between the CNC and external computer has been developed. The actual motor current, velocity, and acceleration of each drive; tool centreposition of the machine; spindle speed and load; tangential feed and currently executed NC block number are obtained from the CNC in real time, and mapped to the virtually simulated data stored in the external computer. The cutting forces are indirectly measured from the feed drive motor current by compensating the disturbance of structural dynamics of ball screw and table through Kalman filters. The cutting forces in Cartesian axes are estimated by transferring the individual motor torque to tool tip.

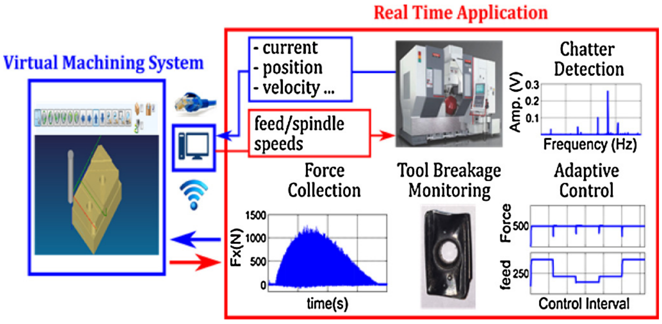

Fig. 1. Parallel execution of virtual and real time system with information exchange.

The tool breakage is detected from the average spindle torque, and the load on the cutting tool is maintained at the desired level by adaptively controlling the feed rate. The chatter is detected and avoided similar to the method given in [5], hence it is not presented here. However, the locations of chatter events are mapped to tool path contained in Virtual model. The robustness of algorithms is ensured by sending the part geometry changes and average force patterns from the stored, virtual part machining system. The system has been experimentally proven on a CNC machining centre.

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2. Prediction of cutting forces from drive currents

The installation of cutting force sensors to the machine would increase the cost and complexity; hence it is preferred to use sensory data available from the CNC directly [6]. The cutting forces are transmitted to feed drive motors as disturbance torque through the drive structure and servo amplifier as shown in Fig. 2. The friction and inertial loads are separated from the measured motor torque (T_m) measurements to predict the cutting torque (T_c) as [7]:

$$T_c = T_m - J_e \frac{d\Omega}{dt} - T_f \qquad (1)$$

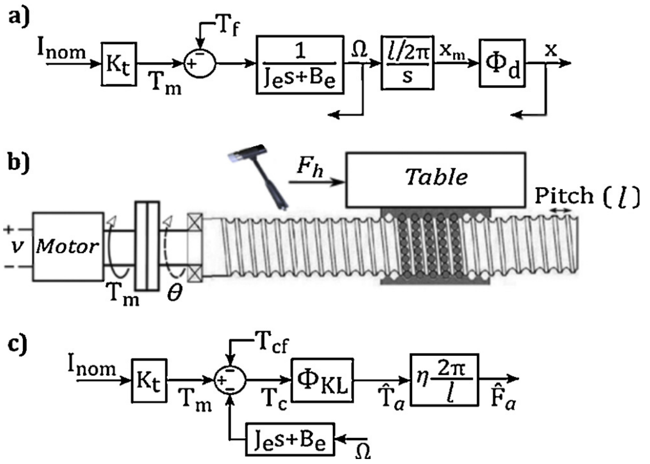

Fig. 2. (a) Disturbance transfer function (ϕ_d), (b) feed drive mechanism, (c) Kalman filter (ϕ_{KL}) compensation (I_{nom} to $\hat{F}_a$) (T_{cf} = coulomb friction).

where J_e and Ω (rad/s) are the equivalent feed drive inertia felt at the motor and motor velocity, respectively. The motor torque is proportional to the current $T_m = K_t i$ where K_t [N m/A] is the torque constant and i [A] is the measured current. The friction torque is modelled as $T_f = B_e\Omega + T_{cf}$ where B_e and T_{cf} are the viscous and coulomb components, respectively. Lu Gre friction model has been used to capture the Coulomb friction, Stribeck effect, hysteresis and pre-sliding displacement [8] of the drive as shown in Fig. 3a. The friction and equivalent inertia of all drives have been identified from the velocity and current values supplied by CNC while moving the drives at different velocities. The cutting force is predicted from the cutting component of the torque as:

$$F_c = T_c \eta \frac{2\pi}{l} \qquad (2)$$

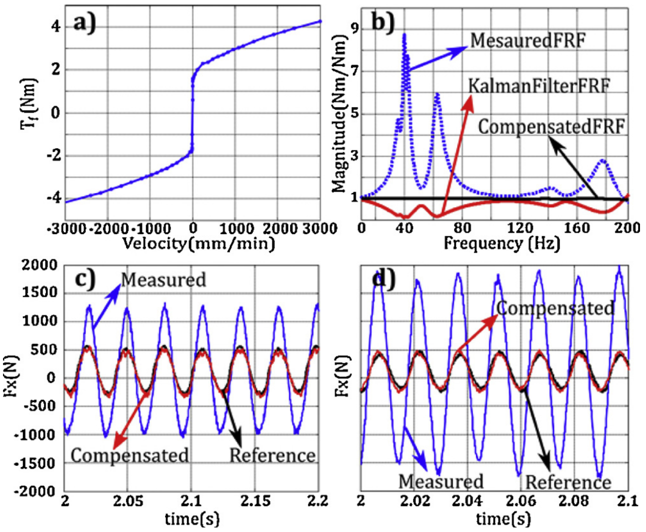

Fig. 3. (a) LuGre friction curve (X axis), (b) identified and Kalman filter compensated FRF, (c, d) comparison of estimated cutting forces from feed drive current and reference forces measured from dynamometer, axial depth = 4 mm, radial depth = 20 mm, feed = 0.2 mm/tooth; (c) 1000 rpm (f_t = 33.3 Hz), (d) 2000 rpm (f_t = 66.6 Hz).

where l is the screw lead (pitch) and η is the efficiency.

However, the cutting force acting on the tool tip is distorted by the structural dynamics of the feed drive system before reaching at the motor's current amplifier as a disturbance torque. The Frequency Response Function (FRF) of the structural disturbance has been measured by applying impulse excitation at the table while measuring the current and angular position of the motor shaft from the CNC (Fig. 2b).

$$\Phi_d(\omega) = \frac{T_c(\omega)}{T_m(\omega)} \qquad (3)$$

A sample measurement of disturbance FRF is shown in Fig. 3b for x axis of the machine. The modes at 40, 64 and 175 Hz distort the magnitude and phase, and deviate the magnitude from the desired unity, leading to incorrect measurement of the force when the tooth passing frequency (i.e. spindle speed times number of teeth) and harmonics are beyond 10 Hz. Although the current amplifier of the CNC has 1000 Hz bandwidth, unless compensated, the structural dynamics of the drive reduces the bandwidth of the force prediction from motor current to 10 Hz or 600 rev/min spindle speed when one tooth is used on the cutter.

The disturbance FRF is fitted to a transfer function as:

$$\Phi_d(s) = \frac{T_c(s)}{T_m(s)} = \sum_k \frac{\alpha_k}{s^2 + 2\varsigma_k\omega_{nk}s + \omega_k^2} \qquad (4)$$

where $\alpha_k, \varsigma_k, \omega_{nk}$ are the residue, damping and natural frequency of mode k.

The disturbance caused by the structural modes has been compensated by passing the measured motor torque from a Kalman filter which has a transfer function of [9];

$$\Phi_{Kl}(s) = \frac{\hat{T}_a(s)}{T_c(s)} = \sum_k \frac{\alpha_{Kl}}{s^2 + 2\varsigma_{Kl}\omega_{Kl}s + \omega_{Kl}^2} \qquad (5)$$

where $\hat{T}_a$ is the estimated actual torque transferred from tool tip to the drive and actual tool tip force ($\hat{F}_a$) is found from Eq. [2].

The FRF of the cutting force prediction from the drive current is shown in Fig. 3b, where the compensated system magnitude approached to unity and the bandwidth has been increased to 200 Hz. As a result, the cutting forces can be predicted accurately from the current monitored from the CNC at tooth passing frequencies up to 200 Hz. A sample cutting force prediction is compared against the dynamometer measurements in Fig. 3c–d.

3. Virtual model assisted process monitoring and control

The predicted cutting forces from feed drive motors are used for tool breakage detection and adaptive force control. The machine was a Quaser UX600 CNC machining centre. The real-time algorithms are run on an external PC (Intel® Core™ i7-3.40 GHz CPU, 8 GB RAM) which communicates with the Heidenhein CNC via TNC Ethernet connection. A multi-threaded real time code is developed in C++ using the LSV-2 communication protocol which collects commanded, noise free digital motor currents, drive speeds, tool centre point position, spindle speed, and tangential velocity between 330 Hz and 10 kHz sampling frequency. External PC can vary the spindle and feed speeds at 10 Hz interval which is sufficient for the targeted tool condition and process monitoring/control tasks which are outlined as follows.

3.1. Virtual model – real time application integration

Prior to the cutting operation, part machining process is simulated using MACHpro® Virtual Machining System [10] to calculate cutter–workpiece engagement (CWE), cutting forces, torque, power and the machining process states along the tool-path [11]. These machining states are stored in a file and accessed by the real time machining process monitoring and control system as a virtual feedback to avoid false tool failure detection and to prevent transient force peaks during adaptive control. In addition, the

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