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International Journal of Machine Tools & Manufacture 45 (2005) 993–1008
INTERNATIONAL JOURNAL OF MACHINE TOOLS & MANUFACTURE DESIGN, RESEARCH AND APPLICATION
www.elsevier.com/locate/ijmactool

High frequency bandwidth cutting force measurement in milling using capacitance displacement sensors

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Received 25 October 2004; accepted 30 November 2004

Abstract

This article presents a method of measuring cutting forces from the displacements of rotating spindle shafts. A capacitance displacement sensor is integrated into the spindle and measures static and dynamic variations of the gap between the sensor head and the rotating spindle shaft under cutting load. To calibrate the sensing system, the tool is loaded statically while the deflection of the tool is measured with the capacitance probe. With this calibration, the displacement sensor can be used as an indirect force sensor. However, the measurement bandwidth is limited by the natural modes of the spindle structure. If cutting force frequency contents are within the range of the natural modes of the spindle structure or higher, the measurements are distorted due to the dynamic characteristics of the spindle system. In order to increase the bandwidth of the indirect force sensor by compensating for the spindle dynamics, the design of a Kalman filter scheme, which is based on the frequency response function (FRF) of the displacement sensor system to the cutting force, is presented in this paper. With the suggested sensing and signal processing method, the frequency bandwidth of the sensor system is increased significantly, from 350 to approximately 1000 Hz. The proposed indirect force sensor system is tested experimentally by conducting cutting tests up to 12,000 rpm with a five-fluted end mill. Besides cutting forces, the measured displacements can also be affected by factors such as roundness errors, unbalance at different speeds, or dilatation of the spindle shaft due to temperature variations. Methods to compensate for these disturbing effects are also described in the paper.

Keywords: Displacement sensor; Dynamic compensation; Indirect force sensor; Kalman filter; Milling; Modal curve fitting; Monitoring

1. Introduction

Machining of large and complex integral parts like aircraft ribs, dies, molds, turbine rotors and vanes often requires the removal of large amounts of metal. In order to reduce production time and cost, there is an increasing demand for higher metal removal rates. To achieve high productivity and accuracy, process disturbances like self-excited chatter vibrations, forced vibrations due to unbalance, overload, collision and tool breakage, or excessive tool wear need to be monitored and suppressed. The measurement of cutting forces is the key information needed to monitor, troubleshoot, or control the machining operations. Process optimization can be achieved either by offline simulation or online process monitoring and diagnosis [1,2]. Offline simulation helps to optimize the operation in the planning stage before the actual machining takes place in the shop, or serves as a tool for troubleshooting [3]; whereas online monitoring of the machining process is essential in recognizing disturbances like collision, tool breakage, tool wear, or unstable process conditions such as chatter or tool failure [4]. Adaptive control of machining operations also requires accurate measurement of cutting forces during production [5–8]. In short, a reliable cutting force measurement system, which has a high bandwidth to cover a wide range of cutting speeds, is required.

The most common method to measure cutting forces in machining operations is through table dynamometers. Typical table dynamometers consist of piezoelectric

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doi:10.1016/j.ijmachtools.2004.11.028

Nomenclature

$\delta_{\mathrm{Air\_Cutting}}$	displacement profile measured while air cutting at cutting speed (μm)
$\delta_{\mathrm{Cutting}}$	displacements measured while cutting including disturbing effects (μm)
δ_F	resultant displacement signal caused by cutting forces (μm)
F_δ	force measured indirectly from the displacement sensor (N)
F_a	actual force applied to the tool tip (N)
K_S	static stiffness of the spindle sensor system (N/μm)
G_S	static compliance of the spindle sensor system (μm/N)
$\Phi(s)$	dynamic compliance of the spindle sensor system (μm/N)
f_n	natural frequencies of the spindle structure (Hz)
$\omega_{n,k}$	natural frequencies of the spindle structure (rad/s)
ζ_k	damping ratio of the spindle structure (l)
α_k	compliance equivalent term of the spindle structure (μm/Ns^2)
b_i	numerator coefficient of the transfer function
a_i	denominator coefficient of the transfer function
$\boldsymbol{A}_i$	system matrix
$\boldsymbol{B}_i$	input matrix
$\boldsymbol{C}_i$	measurement or output matrix
x	state vector
u	input vector (here: $u = F_\mathrm{a}$)
z	output vector (here: $z = \delta_F$)
$\boldsymbol{T}$	similarity transformation matrix
$\boldsymbol{W}$	observability matrix
$\boldsymbol{\Gamma}$	system noise matrix
w	process noise
v	measurement noise
$\hat{x}$	estimate for the system state vector from the Kalman filter
$\hat{z}$	estimate for the system output from the Kalman filter (here: $\hat{z} = \hat{\delta}_\mathrm{F}$)
$\hat{\delta}_\mathrm{F}$	estimate for the spindle flange displacement (μm)
$\boldsymbol{K}$	Kalman filter gain matrix
$\boldsymbol{C}_\mathrm{o}$	observer or Kalman filter output matrix
$\hat{z}_\mathrm{o}$	Kalman filter output (here: $\hat{z}_\mathrm{o} = \hat{F}_\mathrm{a}$)
$\hat{F}_\mathrm{a}$	estimate for the actual cutting force from the Kalman filter (N)
$G_{\hat{F}_\mathrm{a}/\delta_\mathrm{F}}$	continuous Kalman filter transfer function (N/μm)
t_d	discrete sampling time (s)
$\boldsymbol{P}$	state estimation error covariance matrix
$\boldsymbol{Q}$	system noise covariance matrix
$\boldsymbol{R}$	measurement noise covariance matrix
$\Delta\vartheta$	temperature variation (K)
α_ϑ	thermal expansion coefficient (1/K)
L	geometric size/length (m)
U	output voltage of the capacitance displacement sensor (mV)
K_U	sensitivity factor of the capacitance displacement sensor (mV/μm)

sensors that are clamped between two plates [9]. Although table dynamometers provide accurate and effective force measurement, they are more suitable for laboratory or experimental use rather than for practical application on production machines, due to the limitation of workpiece size, mounting constraints, high sensitivity to overload, and high costs. Furthermore, the dynamic characteristics of table dynamometers are strongly dependent on the workpiece mass, which may change during machine operation. To overcome limitations of workpiece mass and size, a force sensor can be integrated to the spindle itself instead of installing it on the machine table. For example, Kistler AG [10], Aoyama et al. [11], and Smith et al. [12] proposed rotating force and torque dynamometers. They are attached between the spindle and tool as an adapter, and measure cutting forces very close to the tool. However, the rotating force sensor has an additional mass and overhang, which reduce the dynamic stiffness of the spindle system. A more rigid solution has been proposed, in the form of a force ring sensor integrated to the spindle housing, by Kistler AG in cooperation with several laboratories [13,14]. The ring sensor consists of six piezo quartz elements measuring cutting forces in X-, Y-, and Z-directions. Since the sensors are located away from the tool tip, they are affected by the dynamics of the spindle, which can distort the measurements. Although the spindle integrated force ring sensor provides accurate cutting force sensing when using dynamic compensation, it has high capital and installation costs. A more rugged and cost effective solution is desirable for use in the production environment.

In this study, the radial displacements of the rotating spindle shaft are used to measure cutting forces indirectly via a capacitance sensor installed in the spindle housing. The measurement system is insensitive to overload and not subject to wear because the sensors are not in contact with the rotating spindle. The design satisfies the following criteria for ideal force measurement systems [15,16]:

- No reduction in the static and dynamic stiffness of the machine tool;
- No restriction of working space and cutting parameters;