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Indirect model based estimation of cutting force and tool tip vibrational behavior in milling machines by sensor fusion

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Abstract

Real time prediction of cutting tool condition and machined surface finish have been attractive research objectives over the last decades. However, providing practical and reliable solutions is still a demanding task for milling machine tools. One of the most challenging literature goals is to obtain a robust estimation of the cutting forces through indirect sensor measurements since many process and tool related quantities are indirectly linked to cutting forces. Another challenging issue in machining process monitoring and control is prediction of surface finish and quality. As the vibration plays a major role in the surface generation, this can be done by accurate prediction of the vibrational displacements at the tool tip during machining operation. In this paper, a novel model based estimation of cutting force and tool tip acceleration is designed and tested based on data fusion of different sensors measurements. In this context, two sensors (piezoelectric accelerometer and eddy-current displacement both mounted inside the spindle structure) have been utilized to acquire the experimental signals over a wide range of frequencies.

In order to predict the above mentioned quantities, an optimal state estimator based on Kalman Filter (KF) is used. The models have been obtained by system identification method based on experimental measurements performed on a machine tool. The model based estimator is fed by real data. The results show that the estimation of the impulse force and tool tip acceleration can be achieved accurately in low and high frequency ranges by assigning different weights to the measurement sensors.

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1. Introduction

Real time prediction of cutting tool conditions and machined surface finish have been attractive research objectives over the last decades. However, providing practical and reliable solutions is still a demanding task for milling machine tools. In-process cutting force measurement is one of the most important approaches for monitoring and control of machining process. In this scenario, piezoelectric dynamometers provide the most accurate measurement of cutting forces. However, their usage is limited to the laboratory scales because of the limited size and mounting constraints, high costs, influence of the dynamic behavior on the measured force, etc. In order to overcome the mentioned problems associated to the dynamometer, there have been performed many research studies on the indirect model based cutting force estimation by use of external and internal sensors [1], [2], [3], and [4].

Developments like the integration of force sensors into the machine structure have taken place over the last decade with concepts developed for milling. S.S Park and Altintas [2], [4] used Piezo-electric force sensors that are integrated into the stationary spindle housing, named Spindle Integrated Force Sensor (SIFS), to measure cutting forces. They also presented a method for measuring cutting forces from the displacements of

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rotating spindle shafts using capacitance displacement sensors [1].

Kim and Chang [5] used Cylindrical Capacitive Displacement sensor (CCDS) to estimate cutting forces by measuring spindle displacement. They used CCDS and non-contact magnetic excitation to identify the dynamic characteristic of the spindle tool system during spindle rotation.

Sarhan et al. [6] performed cutting force calculation using spindle-integrated displacement sensors. They used four inexpensive, contamination-resistant eddy-current displacement sensors (S1-S4). Calculating cutting force from spindle displacement involves two major issues: thermal influence and spindle stiffness.

Although, in the above-mentioned research works the cutting force prediction was performed by different sensor configuration, but the prediction based on a multi-sensor approach has been studied in very few cases [3]. Obviously, with a multi-sensor approach it is possible to have more information within a wider frequency range.

Since surface quality is greatly concerned in manufacturing industry, much attention has been paid to the effects of cutting vibration on surface finish.

Altintas [7] and Paris et al. [8] developed cutting process dynamic and kinematic models and applied them in the simulation of surface profile for milling and turning.

Nevertheless, the dynamic cutting process models cannot estimate the exact cutting vibrations with the required precision, since most of them are simplified. Therefore, to have more reliable correlation between surface generation and cutting vibrations, actual vibration of cutting process should be available. Hence, surface roughness and profile in milling can be reconstructed measuring the actual vibrational displacement. Lee et al. [9] investigated the impact of cutting vibration on surface roughness in turning operation by use of on-line measured tool–workpiece relative displacement signals. Nonetheless for milling processes, the relative tool–workpiece displacement is difficult to measure due to combined tool motion of feed and rotation. Hao Jiang et al. [10] developed a method for the simulation of machined surface using on-line measured vibrational displacement signals in peripheral milling. They used four eddy current displacement sensors in the proximity of the tool and workpiece. Nevertheless, due to the architecture of the sensors and to their setup, the effort is limited to the laboratory scales.

In this paper, a hybrid method that includes experimental data is used to simulate the spindle structure dynamic behavior. The model is able to predict tool tip vibrational acceleration and the tool-tip-applied impulse force. A state estimator based on Kalman filter is utilized for the indirect prediction of these quantities starting from the measurements of two sensors. Furthermore, it is possible to assign different weights to the used sensors to have more accurate estimation in both low and high frequency ranges. At the end the results of the simulation are compared with the ones obtained from experimental measurements.

2. Experimental tests and system modelling

The following sub-sections presents the experimental tests performed on the machine and the developed model which is called system plant.

2.1. Experimental tests and System identification process

In order to apply the Kalman filter to estimate the tool-tip-applied force and the tool tip vibration, a model for the spindle structure displacement is developed starting from the system identification. In this context, an impulsive force F_a was applied on the tool tip with an instrumented hammer. The displacement response signals comprise the accelerometers mounted on the tool tip (point 1), spindle housing (point 2), and eddy current probe measuring the relative displacement of spindle shaft and housing (point 3) (all points refers to Figure 1).

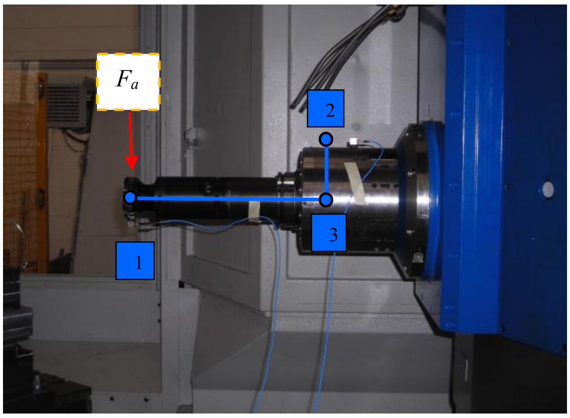

Figure 1: simplified map of sensors position

Table 1 presents the list of the sensors used to perform the measurements.

Table 1: adopted sensors

1	Accelerometer on the tool tip (external)
2	Accelerometer on the spindle housing (internal)
3	Eddy current relative displacement sensor (internal)

Figure 2 shows frequency responses of the spindle housing, relative displacement sensor and tool tip displacement applying short impact force to the tool tip. According to the figure, the experimentally measured Frequency Response Functions (FRFs) are approximated to be an eight degrees-of-freedom system considering low frequency and high frequency eigenmodes (see Table 2). Later on, they are used to develop the system plant model.

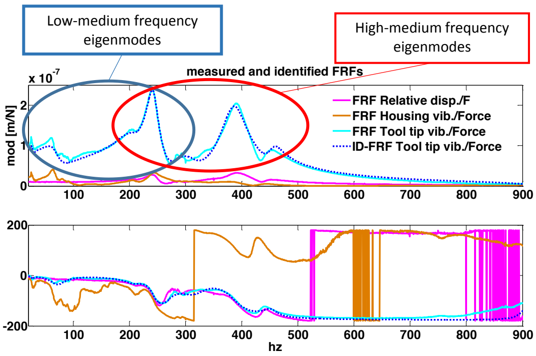

Figure 2: Measured and identified Frequency Response Functions

The identified system plant adequacy can be appreciated looking at Figure 2 and Figure 3. In the former, the matching between the measured and identified FRFs at the tool tip can be observed. In the latter, the comparison between the relative displacement sensor responses to a force pulse is reported.

Table 2: Identified eigenmodes

Mode	Freq. [Hz]	Damping ratio [%]
1	27.6	6.14
2	69.35	22.83
3	205.9	11.25
4	243.1	4.76
5	302.2	9.49
6	386.2	6.11
7	455.34	3.36
8	921.1	1.32

According to Figure 2 the low frequency eigenmodes are related to the structure the machine tools (machine tool column and spindle housing), while the high frequency eigenmodes pertain to the spindle shaft dynamic behavior. As a result, the spindle housing accelerometer was utilized to measure the low frequency vibrational modes, while the relative spindle shaft displacement sensor is responsible for capturing the high frequency vibrational modes.

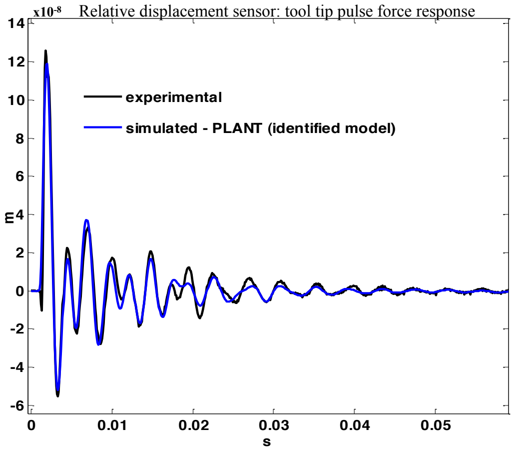

Figure 3: Experimental-numerical (identified model) relative displacement sensor comparison

To further above, the identified spindle housing acceleration is verified by the measured acceleration as is shown in Figure 4.

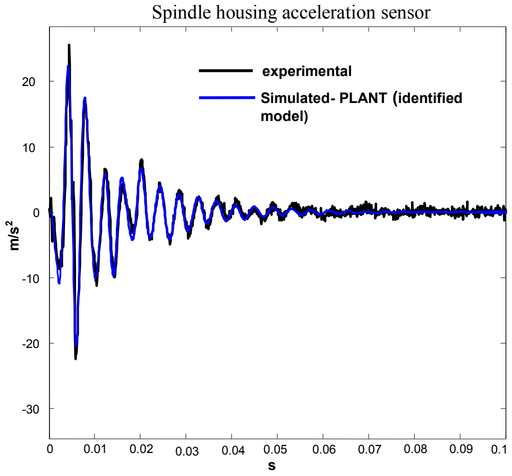

Figure 4 : Experimental-numerical (identified model) spindle housing acceleration sensor comparison

2.2. Dynamic model of the spindle integrated sensors

In order to design the Kalman filter (KF), spindle dynamic model is represented in state space form that yields,

$$\begin{aligned} \dot{x}_{(16\times1)} &= A_{(16\times16)} x_{(16\times1)} + B_{(16\times1)} u_{(1\times1)} \\ y_{(2\times1)} &= C_{(2\times16)} x_{(16\times1)} \end{aligned} \tag{1}$$

where x is the state vector having sixteen states (eight degrees-of-freedom), $u = F_a$, is the input vector or the actual force applied to the tool and $y = \delta F$ is the vector that contains the measurements of the shaft relative displacement and the housing accelerometer.

The observability matrix W has to be full rank, which guarantees the observability of the system [1]:

$$W = \left[C_n^T \, A_n^T \, C_n^T \ldots \left(A_n^{n-1} \right)^T C_n^T \right] \quad (2)$$

2.3. Kalman filter configuration

A Kalman filter is implemented as a model based disturbance observer for indirect measurement of impulse forces and tool tip acceleration in this paper. The principal objective of using the Kalman filter is to indirectly predict the force while compensating the influence of the structural dynamics of the spindle due to its natural modes and to extend the measurement bandwidth [1].

Since the Kalman filter only yields estimates for state vector $\hat{x}$ and output $y = \delta F$, the system model in Eq. (1) is expanded with the actual force F_a as an additional unknown state in the state vector.

$$\begin{aligned} \dot{x}_{e(17\times1)} &= A_{(17\times17)} x_{e(17\times1)} + G_{(17\times1)} w_{(1\times1)} \\ y_{(2\times1)} &= C_{e(2\times17)} x_{e(17\times1)} + v_{(2\times1)} \end{aligned} \quad (3)$$

where G is the system noise matrix, both w and v are assumed to be zero-mean white Gaussian noise inputs and $Q = E\,[w\,w^T]>0$, $R=E\,[v\,v^T]>0$ are their covariance matrices, respectively.

2.4. Kalman gain calculation

A Kalman filter is an optimum observer designed to minimize state estimation errors, $\hat{x} = \hat{x} - x$, due to system and measurement noise. The Kalman filter gain matrix is identified by minimizing the state estimation error covariance matrix, $P = E\,[\hat{x}\ \ \hat{x}^{T}]$ [1]. The minimum state estimation error covariance matrix P can be evaluated by solving the following time variant Riccati equation [11]:

$$\dot{P} = A_e P + P A_e^T + G Q G^T - P C_e^T R^{-1} C_e P \quad (4)$$

And the Kalman gain is obtained as:

$$K = P C_e^T R^{-1} \quad (5)$$

After finding the gain K, the force can be estimated through a disturbance Kalman filter designed for the expanded model that yields,

$$\begin{aligned} &\dot{x}_{\mathrm{e}} = A_e \hat{x}_e + K(\mathrm{y} - \hat{\mathrm{y}}) = A_e \hat{x}_e + K(\mathrm{y} - C_e \hat{x}_e) = \\ &= \left(A_e - K C_e \right) \hat{x}_e + K y \\ &\hat{y}_0 = C_0 \hat{x}_e = \left[\hat{a}_{TT} \ \hat{F}_a \right]^T \end{aligned} \quad (6)$$

where $\hat{y}_0$ is the output matrix of the Kalman filter including the estimation of tool tip acceleration $\hat{a}_{TT}$ and applied force $\hat{F}_a$.

2.5. Model schema and simulation

Figure 5 shows the schematic procedure used to validate the prediction capabilities of the designed Kalman filter. According to the figure, the inputs to the filter are the experimental measurement of the spindle housing acceleration and the spindle relative displacement. The predicted tool tip acceleration and tool tip pulse force (Eq.3) are compared to the experimental ones.

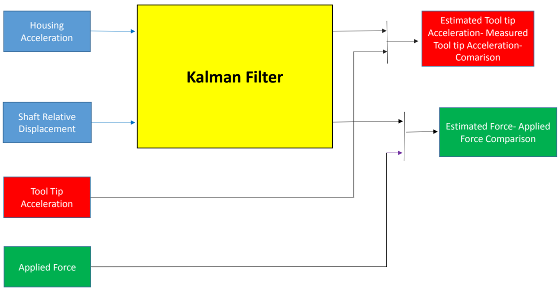

Figure 5: Schematic of the performed measurements and prediction

3. Results and discussions

This section presents the results of the current research work and further discusses impulse force and tool tip acceleration estimation. In this scenario several simulations have been conducted to tune the process noise covariance matrix Q and measurement noise covariance matrix R.

3.1. Estimation of impulse force

Impulse force is estimated indirectly using acceleration and displacement measurement sensors. Figure 6 shows the results of the impulse force estimation and its comparison with the applied short impact force. An external pulse force was used as an excitation instead of proper cutting forces due to its property of being able to excite several machine eigenmodes.

According to the figure, force estimation in blue color closely follows the applied impulse force in black color.

In this paper, the impulsive force is predicted offline, but the effort can be expanded to real-time cutting force estimation as it is the most important indicator linked to cutting tools, machining process and machine tool components failures. With the estimation of cutting forces, it is possible to monitor machining operations.

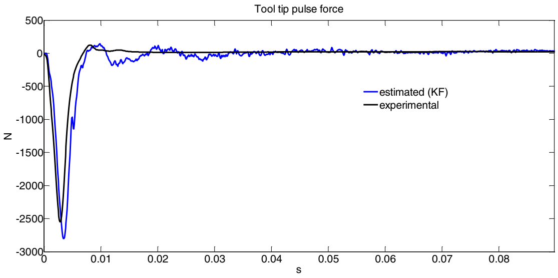

Figure 6: external pulse force estimation through Kalman Filter

3.2. Estimation of tool tip displacement in time domain

In this sub-section, the results of the estimation of the tool tip acceleration (due to the availability of an accelerometer at tool tip, see Figure 1) are compared with the experimental one. The estimated tool tip acceleration has been achieved by considering the measure of two sensors: spindle housing accelerometer and spindle shaft-housing relative displacement eddy current sensor. In this context, the spindle housing acceleration is responsible for capturing the low frequency contents while the eddy current displacement sensor is used for getting the high frequency contents. Hence, by assigning different weights to the mentioned sensors, it is possible to emphasize on desired frequency range.

After a tuning phase, the sensors performance was balanced assigning appropriate values to the process noise covariance, *Q,* and the measurement noise covariance matrix, *R*, which are as follows,

$$Q = 5\times10^{15}\ ;\ R = \begin{pmatrix} 1 & 0 \\ 0 & 5\times10^{-10} \end{pmatrix} \quad (7)$$

Figure 7 presents the results of the estimation of the tool tip acceleration and its comparison with the experimental one in time domain. Referring to the obtained results in time domain, it is possible to correctly estimate the tool tip vibrational behavior both in low and high frequencies by assigning different weights to the mentioned sensors and capturing the vibration within the frequency spectrum of interest.

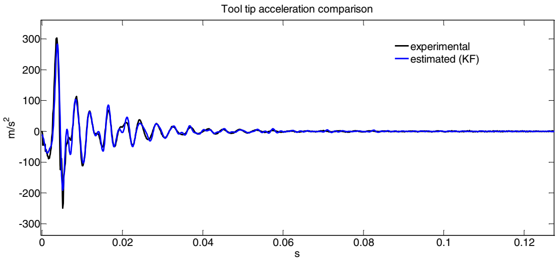

Figure 7 : Tool tip acceleration estimation through Kalman Filter

Real-time estimated tool tip acceleration can be further utilized to detect the machined surface profile since vibrations at the tool tip play the major role in the surface profile generation. This approach will be implemented on a real-time platform and it will be tested during milling operations.

4. Conclusion

In this paper, a novel model based cutting force and tool tip acceleration estimation has been designed and tested. To obtain this result, different sensors are used and the information fused the obtained desired values and indicators. In this context, two sensors (i.e. piezoelectric accelerometer and eddy-current displacement sensor mounted inside the spindle structure) are utilized in order to capture the measurement data over a wide frequency range (both low and high frequency contents). In order to predict the above mentioned quantities an optimal state estimator, (Kalman filter) is used. The models used for the estimation have been obtained by system identification based on experimental modal analysis performed on the machine tool. The following conclusions are drawn:

- The identified model for the system is in good agreement with the information achieved by the experimental measurements.
- The impulse force that is estimated from indirect measurement closely follows the simulated applied impact force.
- The tool tip acceleration is estimated from the spindle housing accelerometer and eddy current displacement sensor. The results are in good compromise with the ones obtained.

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