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Improved dynamic compensation for accurate cutting force measurements in milling applications

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ABSTRACT

Accurate cutting-force measurements appear to be the key information in most of the machining related studies as they are fundamental in understanding the cutting processes, optimizing the cutting operations and evaluating the presence of instabilities that could affect the effectiveness of cutting processes. A variety of specifically designed transducers are commercially available nowadays and many different approaches in measuring cutting forces are presented in literature. The available transducers, though, express some limitations since they are conditioned by the vibration of the surrounding system and by the transducer's natural frequency. These parameters can drastically affect the measurement accuracy in some cases; hence an effective and accurate tool is required to compensate those dynamically induced errors in cutting force measurements. This work is aimed at developing and testing a compensation technique based on Kalman filter estimator. Two different approaches named “band-fitting” and “parallel elaboration” methods, have been developed to extend applications of this compensation technique, especially for milling purpose. The compensation filter has been designed upon the experimentally identified system's dynamic and its accuracy and effectiveness has been evaluated by numerical and experimental tests. Finally its specific application in cutting force measurements compensation is described.

1. Introduction

In recent years many efforts have been put in understanding the cutting processes involved in milling operations in order to achieve more stable cutting conditions, better surface quality, reduce production time, etc. All these tasks are still of main interest in machining related studies, as the abundant and growing literature demonstrates. In each of these research topics, cutting forces reveal to be one of the key information as they can be seen as a control parameter for many phenomena involved in cutting processes. This is one of the reasons why accurate and effective way of measuring cutting forces represent the fundamental instruments in most of the machining related research topics, such as development of efficient feed scheduling algorithm in order to improve productivity, or effective tool condition monitoring techniques, as well as validation of analytical predictive cutting force models and pre-process cutting conditions estimation. Accurate cutting force measurements can be achieved by direct force measurements, by means of designed-on-purpose force transducers, even if some promising indirect cutting force estimation techniques have been described in literature [1]. Different cutting force dynamometers are nowadays commercially available [2,3], even if are mainly used in scientific and research field. The main

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drawback of table dynamometers is that their dynamics is strongly dependent on the workpiece mass, which may change considerably during machining, while spindle-mounted dynamometer could reduce the dynamic stiffness of the spindle system [4] and could complicate tool-changing operations. In order to overcome some of the exposed limitations, many indirect force measurement techniques have been developed in recent years [5–10]. Those techniques aim at estimating cutting forces by measuring different physical quantities. Indirect cutting force measurements could often be achieve by means of built-in machine sensors or low cost sensors and are quite easily implementable in real-time cutting force measurements. Nevertheless in investigating the correlation between measured signals and cutting forces and in validating any of these techniques, direct force measurements are needed; hence accurately and effectively measuring cutting forces is still an up-to-date. Most of the transducers used in direct and indirect force measurements are influenced by vibration of the surrounding system that could drastically affect the accuracy of measured force signals. In addiction cutting force dynamometers could express high distortion in measured signals as cutting force frequencies approach to the transducers' natural frequency. This could be relevant especially when measuring cutting forces in high speed machining. Since these limitations could only be partially overcome by specific and improved dynamometers designs [11,12], some sort of compensation is needed to cleanse the measured force signals from the dynamically induced errors. In order to develop an effective and accurate compensation filter, the transfer function between acting and measured forces should be identified and this is usually accomplished by means of impact modal tests. So far only few compensation techniques have been presented in literature confirming that this is quite a new topic in machining related studies. To cleanse measured force signals from errors induced by vibrations of the surrounding systems, a filtering technique, sometimes referred to as “accelerometric compensation” [2,13], could be used. This technique is actually based on evaluating the mass affected force signals using accelerometric signals, and to subtract them from the measured forces. This method reveals to be quite easily implementable in real time compensation and could be capable of filter even unsteady effects since the accelerations are directly measured. The drawback of this technique is that it is not capable of overcoming limitations imposed by dynamometer's natural frequency, actually limiting possible cutting force measurements to low speed machining. In order to extend the accurately measurable bandwidth, two different approaches have been presented so far. The simplest method is based on direct inversion of the experimentally identified transfer function between acting and measured forces [14–16]. However, this method suffers some limitations since the inversion may not always exist and compensation could be sensible to noise at some frequencies. A more robust approach seems to be offered by the Kalman filter estimation technique [17,18]: Altintas et al. [19–21] reported the benefits given by the use of this compensation technique and the global accuracy seems to be improved compared to the direct inversion method.

This work actually extends the Kalman filter compensation to table dynamometers applications and points out some of those aspects that revealed to be crucial in determining the global compensation accuracy. Particular attention has been indeed focused on identifying the most accurate and performing modal-curve-fitting and discretization algorithms as those steps revealed to be essential in defining filter global efficacy: two specific methods have been developed to extend dynamometer practical usage in measuring milling cutting forces even in high speed milling operations. To validate both the developed compensation filter and the mentioned methods numerical and experimental tests are reported and finally some applications to real cutting force measurements are tested and described. All the numerical computations and digital signal processes operations have been achieved by means of Mathworks Matlab® vR2012A software.

2. Modal test

The proposed method has been applied to a Kistler 9257A table dynamometer, widely used for measuring cutting forces in turning, milling, grinding, etc. In Table 1 the main technical data are summarized.

Piezoelectric sensors may be regarded as under-damped spring mass systems, with a single degree of freedom for each of the measuring axis: the typical frequency response curve is shown in Fig. 1.

Table 1
Kistler 9257A table dynamometer technical datasheet.

Measuring range (Fx, Fy)	N	±5000
Measuring range (Fz)	N	±10000
Overload capacity	%	50
Resolution	N	0.1
Sensitivity Fx, Fy	pC/N	−7.5
Sensitivity Fz	pC/N	−3.5
Rigidity (*x*, *y* direction)	N/μm	1000
Rigidity (*z* direction)	N/μm	2000
Resonant frequency (*z* direction)	kHz	≃3.5
Resonant frequency (*x*, *y* direction)	kHz	≃2.5
Linearity	%	< ±1
Crosstalk	%	<2
Working temperature range	°C	0…70
Weight	kg	6.9