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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.

Keywords: Milling, Cutting forces, Experimental measurements

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 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.

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/□m	1000
Rigidity (z direction)	N/□m	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

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.

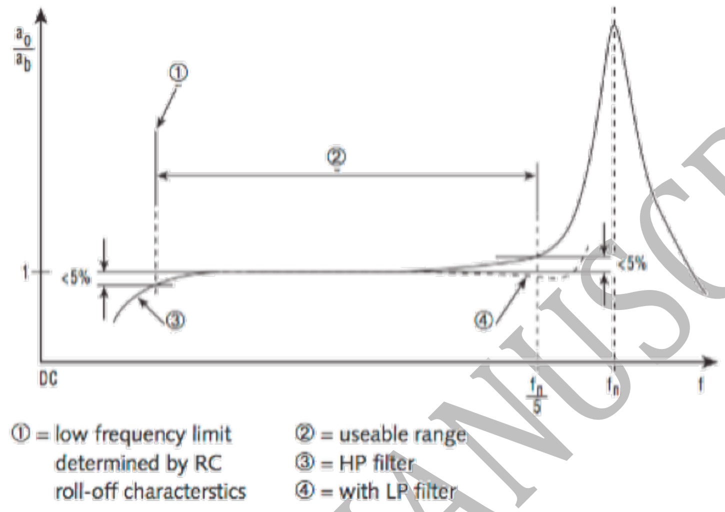


Fig. 1. Typical frequency response curve of a piezoelectric dynamometer.
(Source: Kistler document 20.290e-05.04).

As shown, about 5% amplitude rise can be expected at approximately 1/5 of the resonant frequency (fn). So the expected usable frequency range was 0–500 Hz. In order to experimentally identify the transfer function (i.e. TF) between the measured and applied forces, experimental impact tests were conducted on the system as set up for cutting tests. The dynamometer was mounted on a Mori Seiki NMV 1500 DCG machining center with four M8 hex screws and the workpiece was fixed to the dynamometer with three M8 allen screws.
The workpiece was a simple steel block, flattened once clamped on the dynamometer, in order to be considered totally flat. The shape was chosen to reduce the effects of its flexibility on the transfer functions between the applied cutting forces and the measured signals. Impact tests were conducted along each of the three axis (X, Y, Z) using a Brüel & Kjaer Type 8202 impulse hammer, LMS Scadas III frontend and LMS Testlab 11A software. In Fig. 2, the impact modal test set-up is shown.

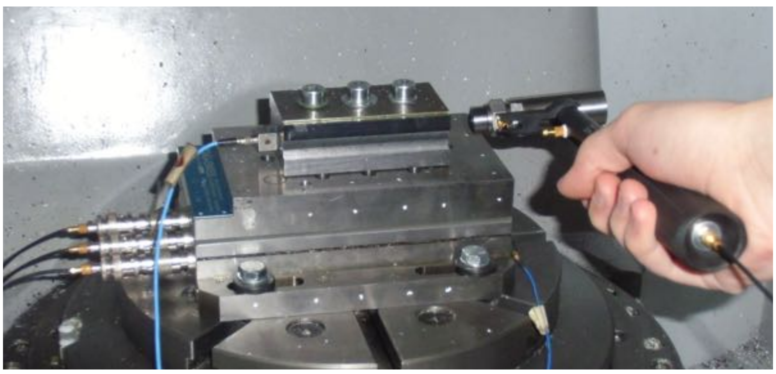


Fig. 2. Experimental impact test.

Impact tests were conducted according to the positive direction of the dynamometer coordinate system: for each axis (i.e. X, Y and Z) the TF between the signal acquired by the dynamometer, and the force applied to the workpiece (measured by the load cell of the hammer) was derived. In order to reduce measurements uncertainties, TFs averaged over 7 impacts were considered for each measurement point. The effect of the position of the excitation point was also evaluated, providing negligible differences.
In order to obtain the correct sensitivities of the table, the hammer was previously calibrated by means of a known pendulous mass, and a calibrated accelerometer, according to Newton's second law. The measured transfer functions are reported in Fig. 3.

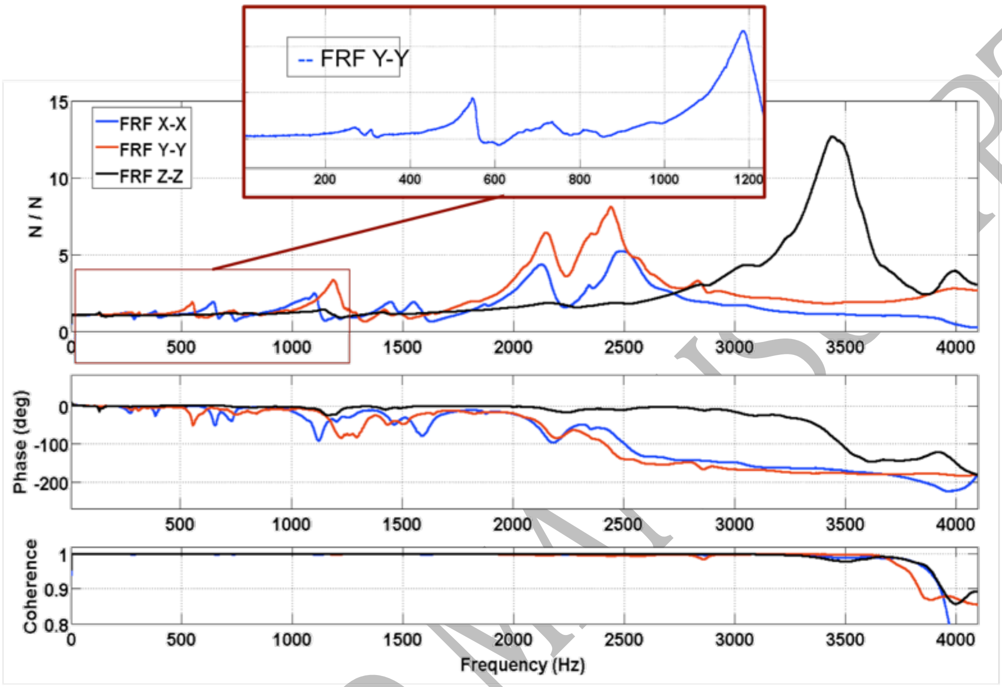


Fig. 3. Measured transfer functions.

As clearly appears the dynamometer response is strongly affected by the transducer resonances, which are nearby those indicated in the data sheet of the dynamometer (Table 1). In addiction the effect of the modal behavior of the machine tool in the low frequency range is noticeable, which drastically reduces the measureable bandwidth. Hence if no compensation is applied, only cutting forces with a spectrum beneath 200 Hz could accurately be measured.

3. Modal curve fitting

In order to implement the disturbance Kalman filter formulation, as described in [19–21], the experimentally identified transfer function had to be curve-fitted into a more manageable mathematical formulation.

$$\phi(s) = \frac{F_m(s)}{F_a(s)} = \frac{b_1 s^n + b_2 s^{n-1} + b_3 s^{n-2} + \ldots + b_{n-1}}{s^m + a_1 s^{m-1} + a_2 s^{m-2} + \ldots + a_m} \quad (1)$$

where m, n are the desired orders of numerator and denominator polynomials and bi, ai are the coefficients identified by the fitting algorithm. Fm and Fa represent the measured and applied force, respectively. Since the accuracy achieved in this phase has revealed to be crucial in determining the global precision of the compensation filter, different fitting algorithms were tested in this work. In [21], Chae and Park reported the use of a non-linear modal fitting technique known as rational fraction polynomial method (RFP) [22], while in [19,20] an unspecified modal identification algorithm was employed. In this specific application no real interest is focused on identifying system's modal parameters, hence the main goal was to find the most accurate fitting algorithm regardless of modal identification capabilities. The rational fraction polynomial method revealed to be globally in good agreement, even though local accuracy seemed to be unsatisfactory for the stability of the identified system and the computability of the Kalman gain. The best choice proved to be the algorithm based on the damped Gauss–Newton method (DGN) for iterative search [23], with the output of the RFP algorithm being the initial estimate. This algorithm solves the direct problem of minimizing the weighted sum of the squared error between the actual and the desired frequency response points. DGN algorithm slightly improved local accuracy over some frequency ranges and appeared to be more robust in computing stable transfer functions. In addition, allowing transfer function polynomials to be specified, it revealed to be more directly controllable. Moreover using this algorithm more stable TFs can be computed by means of frequency rescaling. To provide a closer link with the experimental set up, the coherences functions has been taken as weight.

3.1. Transfer function limitations

In order to implement the disturbance Kalman filter formulation the system should first be mapped into a state-space form, as follows:

$$\begin{bmatrix} \dot{x}_{s_1} \\ \dot{x}_{s_2} \\ \vdots \\ \dot{x}_{s_{m-1}} \\ \dot{x}_{s_m} \end{bmatrix} = \begin{bmatrix} -a_1 & -a_2 & \cdots & -a_{m-1} & -a_m \\ 1 & 0 & \cdots & 0 & 0 \\ 0 & 1 & \ddots & 0 & 0 \\ \vdots & \cdots & 1 & \vdots & \vdots \\ 0 & 0 & \cdots & 1 & 0 \end{bmatrix} \cdot \begin{bmatrix} x_{s_1} \\ x_{s_2} \\ \vdots \\ x_{s_{m-1}} \\ x_{s_m} \end{bmatrix} + \begin{bmatrix} 0 \\ 0 \\ \vdots \\ 0 \\ 0 \end{bmatrix} \cdot F_a \tag{2}$$

$$\left[F_m \right] = \left[\begin{matrix} 0 & b_1 & b_2 & \cdots & b_n \end{matrix} \right] \cdot \left[\begin{matrix} x_{s_1} & x_{s_2} & \cdots & x_{s_{m-1}} & x_{s_m} \end{matrix} \right]^T$$

where $a_1,\ldots,a_m$ and $b_1,\ldots,b_n$ are the numerator and denominator TF polynomials' coefficients respectively (Eq. 1), while x_s are the state variables. Eq. 2 can be written in a more compact form as:

$$\begin{aligned} \dot{x}_s &= A_s x_s + B_s F_a \\ F_m &= C_s x_s \end{aligned} \tag{3}$$

where Fa and Fm are the applied and measured force respectively.
The state space matrices As and Cs contain both small and large numbers, hence resulting in poorly conditioned matrices. Unfortunately, as clearly visible in Fig. 3, many resonant frequencies are present in the measured frequency range; hence to improve the accuracy of the fitting transfer function (TF), high order polynomials should be employed. This could drastically worsen the matrix conditioning as a consequence of the increased matrices' orders. In numerical processing of the state- space system defined in Eq. (3), the condition of ill-conditioned matrices could result in non-observability of the system (i.e. the observability matrix is not full rank) due to round-off errors, as a consequence numerical filter computation could actually be prevented [18]. In this work these restrictions were experienced for both the x and y direction TFs, actually limiting the filter compensation bandwidth. Practically speaking, given the mentioned stability limitations, it results impossible to develop a compensation filter for the entire measured bandwidth (i.e. 0–4096 Hz), unless some evident local losses of accuracy are neglected. In Fig. 4 the results of the most accurate possible fitting TF is shown. Although the DGN algorithm was used, accuracy resulted not adequate, especially in the low frequency range.

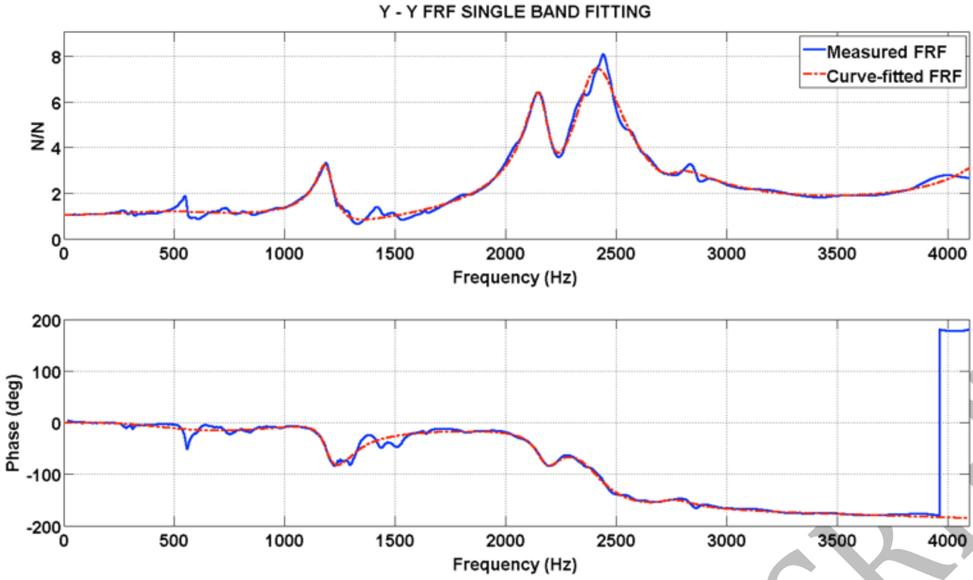


Fig. 4. Curve fitting results over the 0–4096 Hz bandwidth.

In order to overcome the exposed numerical limitations, two different methods were tested; both are based on partitioning the fitting bandwidth in smaller frequency ranges where the fitting TFs result sufficiently accurate.

3.2. Band-fitting method

Since the developed compensation is focused on milling applications, should be clear that in these specific cases no real need exists in compensating the whole bandwidth given that cutting force frequency contributions are limited and directly related to tooth passing frequency (i.e. TPF) [24]. Discrete fitting frequency bands can thus be defined and accuracy could be improved only over those given frequency ranges, since no real force contributions should be presents at different frequencies. This approach is exemplified in Fig. 5, where discrete fitting bands were defined as function of the tooth passing frequency and its harmonics.

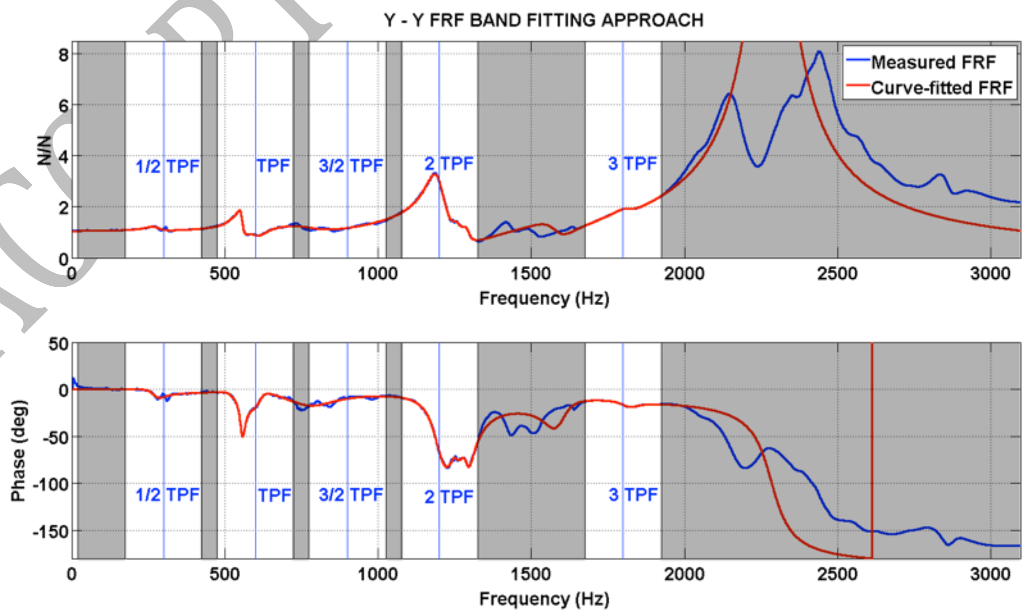


Fig. 5. Band-fitting method example.

As shown accuracy resulted drastically improved in the frequency ranges of interest and numerical limitations could be worked around. This approach could be easily implemented in real time filtering ensuring that no instabilities are presents, otherwise some “out-of-band” frequency contributions could get relevance and neglecting them could result in misleading compensated force measurements. If real-time filtering is not needed, an effective solution could be based on analyzing measured forces frequency spectra in order to identify a posteriori the relevant frequency contributions, hence the fitting frequency ranges needed. By doing so, all the relevant frequency contribution could be considered, included for example the Chatter frequencies, normally unknown a priori.

3.3. Parallel elaboration method

In case of applications requiring maximum accuracy over the whole bandwidth, a different approach could be employed. Given that accurately fitting a wide frequency range is actually limited by numerical restriction, narrower discrete fitting bands can be defined in order to capitalize on the limited TF polynomial orders to achieve the best accuracy possible over those given frequency ranges. The time-domain force signals could hence be partitioned in the frequency domain by means of zero-phase low-pass, band-pass and high-pass filters; each force signal contribution obtained could hence be compensated with a specific filter and then the global time-domain force signal can be computed by simple sums, ensuring no phase shift is present. In Fig. 6 the parallel elaboration fitting method is exemplified. In this case three discrete fitting bands were defined and accuracy is maximized without overcoming polynomial orders limitations.

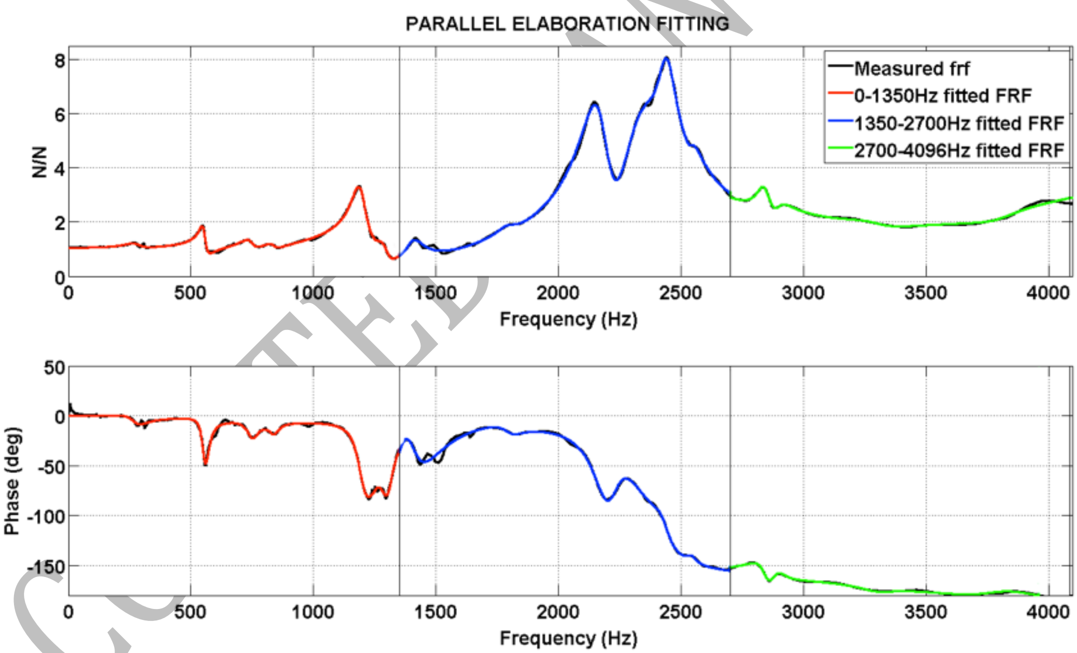


Fig. 6. Parallel elaboration fitting.

This method seems to be more generally applicable and quite effective, as long as high order filters are used for partitioning the time-domain force signals. High order filter computation could become a time-consuming operation when high sampling frequencies are employed, actually preventing their usage in practical applications. In those cases lower order filters must be used instead; this could considerably affect compensation accuracy in proximity of cut-off frequencies. The global compensation accuracy is hence directly related to the characteristics of the pre-process filters employed for partitioning the measured force signals.

Further improvements in fitting accuracy and robustness could possibly be achieved by using orthogonal sets of polynomials for the fitting TFs, instead of power functions polynomials, as here described. Future activities will be focused on the implementation of such polynomial sets in the fitting algorithm.

4. Disturbance Kalman filter implementation

The disturbance Kalman filter formulation allows disturbances to be estimated in presence of some sort of modeled measurement errors. In this case the interest is focused on evaluating the actual cutting force given some dynamic noise affected measurements. In order to implement the disturbance Kalman filter formulation, the state-space system defined in Eqs. (2) and (3) has to be expanded including the applied force, Fa, in the state vector, as follows:

$$\underbrace{\begin{bmatrix} \dot{x}_{s_1} \\ \dot{x}_{s_2} \\ \vdots \\ \dot{x}_{s_{m-1}} \\ \dot{x}_{s_m} \\ \dot{F}_a \end{bmatrix}}_{\dot{x}_e} = \underbrace{\begin{bmatrix} -a_{s_1} & -a_{s_2} & \cdots & -a_{s_{m-1}} & -a_{s_m} & -b_{s_1} \\ 1 & 0 & \cdots & 0 & 0 & 0 \\ 0 & 1 & \ddots & 0 & 0 & \vdots \\ \vdots & \cdots & 1 & \vdots & \vdots & 0 \\ 0 & 0 & \cdots & 1 & 0 & 0 \\ 0 & 0 & 0 & \cdots & 0 & 0 \end{bmatrix}}_{A_e} \underbrace{\begin{bmatrix} x_{s_1} \\ x_{s_2} \\ \vdots \\ x_{s_{m-1}} \\ x_{s_m} \\ F_a \end{bmatrix}}_{x_e} + \underbrace{\begin{bmatrix} 0 \\ 0 \\ \vdots \\ 0 \\ 0 \end{bmatrix}}_{\Gamma} w \qquad (4)$$

$$[F_m] = \underbrace{\begin{bmatrix} 0 & c_{s_1} & c_{s_2} & \cdots & c_{s_n} & 0 \end{bmatrix}}_{C_e} \begin{bmatrix} x_{s_1} & x_{s_2} & \cdots & x_{s_{m-1}} & x_{s_m} & F_a \end{bmatrix}^T + v$$

or:

$$\begin{aligned} \dot{x}_e &= A_e x_e + \Gamma w \\ F_m &= C_e x_e + v \end{aligned} \qquad (5)$$

where, ν is the measurement noise. Eq. (5) results valid as long as the sampling frequency is quite high, compared to the tooth passing frequency, hence the applied forces can be treated to be piecewise constant and their derivative results only a function of process noise, w.
The expanded state vector, x_e, can be estimated through the Kalman filter formulation as follows:

$$\begin{aligned} &\dot{x}_e = A_e\hat{x}_e + K(F_m - \hat{F}_a) = A_e\hat{x}_e + K(F_m - C_e\hat{x}_e) = \\ &= (A_e - KC_e)\hat{x}_e + KF_m \\ &\hat{F}_a = C_0\hat{x}_e \end{aligned} \qquad (6)$$

where $C_0 = \{0\ 0\ \dots\ 0\ 1\}$, *K* is the Kalman filter gain and $\hat{F_a}$ is an estimate for the actual cutting force, F_a. The Kalman gain, *K*, is identified by minimizing the state estimation error covariance matrix $P=E[\varepsilon\varepsilon^T]$, were $\varepsilon = x_e - \widehat{x_e}$ is the estimation error. The minimum state estimation error covariance matrix *P* can be evaluated by solving the associated time variant Riccati equation:

$$\dot{P} = A_e P + PA_e^T - PC_e^T C_e P^T R^{-T} + \Gamma Q \Gamma^T = 0 \qquad (7)$$

where *R* and *Q* are the evaluated measurement and process noise covariance matrices respectively. The measurement noise covariance was evaluated by means of cutting operations with-out tool engagement, and resulted in *R*=0.0519, while the value of process noise co-variance Q was computed through filter tuning and resulted in *Q* = 2e16. Once eq. 7 is solved, the value of Kalman filter gain, *K*, can be computed as:

$$K = PC_e^T R^{-1} \qquad (8)$$

The continuous-time compensation filter, defined by Eq. (6), is then fully defined, and compensation effectiveness can be verified by checking whether the product of Kalman filter and sensor transfer functions approaches to unity over a wide frequency range. In order to use the computed continuous-time compensation filter in digital signal processing, a discretization algorithm must be used. Different algorithms were tested since discretization accuracy could drastically affect filter effectiveness. The best results in preserving filter dynamics were obtained by means of the bilinear, Tustin, approximation with frequency pre-warping [25]. The actual acting forces could hence be reconstructed by recursively filtering the measured forces with the discrete-time filter so defined.

5. Experimental validation

In order to test filter accuracy and effectiveness, specific experimental validation tests were performed: different force input signals were generated by means of a Brüel & Kjær 4809 shaker. A PCB 288D01 impedance head was inserted between stinger and workpiece in order to measure the input reference force signals. The experimental test setup is shown in Fig. 7.

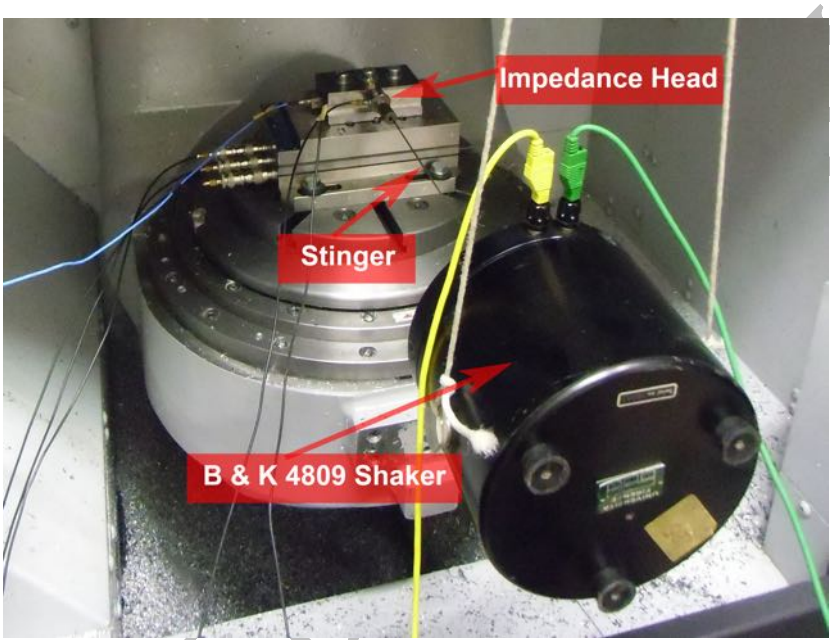


Fig. 7. Experimental validation tests setup.

In order to investigate filter behavior at some specific frequencies and over broad frequency ranges, both pure sine wave and chirp sine sweep excitations were employed (Figs. 8 and 9).

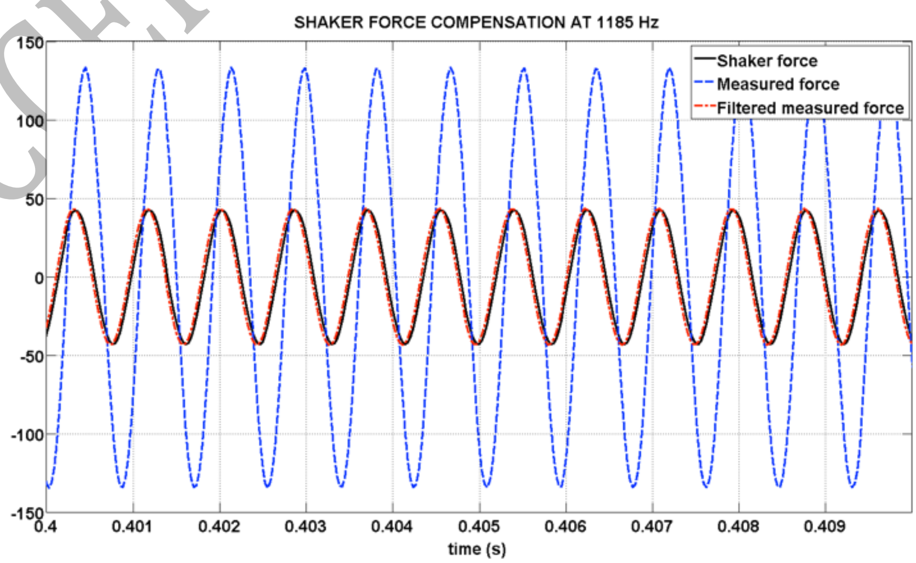
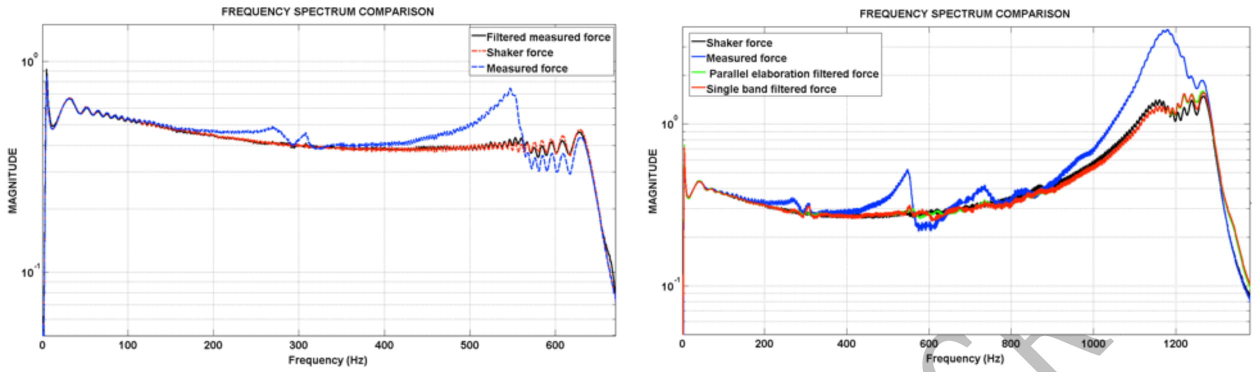


Fig. 8. 1185 Hz pure sine wave experimental test results.

In analyzing the chirp sine wave excitation tests results, the comparison of the exerted, measured and compensated forces frequency spectra results more informative. Some of the results are shown in Fig. 9. In particular for the 10–1300 Hz chirp sine sweep test the parallel elaboration method was employed as well, in order to investigate accuracy improvements over some specific frequencies, in particular around 300 Hz, where the single band fitted TF showed some local loss of accuracy.



a) b)

Fig. 9. Chirp sine sweep tests frequency spectra comparisons: (a) 10–650 Hz and (b) 10–1300 Hz.

All the experimental validation tests confirmed the compensation filter performances both at some single frequencies and over broad frequency ranges. Parallel elaboration method has demonstrated to be a good solution in improving accuracy at some specific frequencies if a broad compensation band is needed.

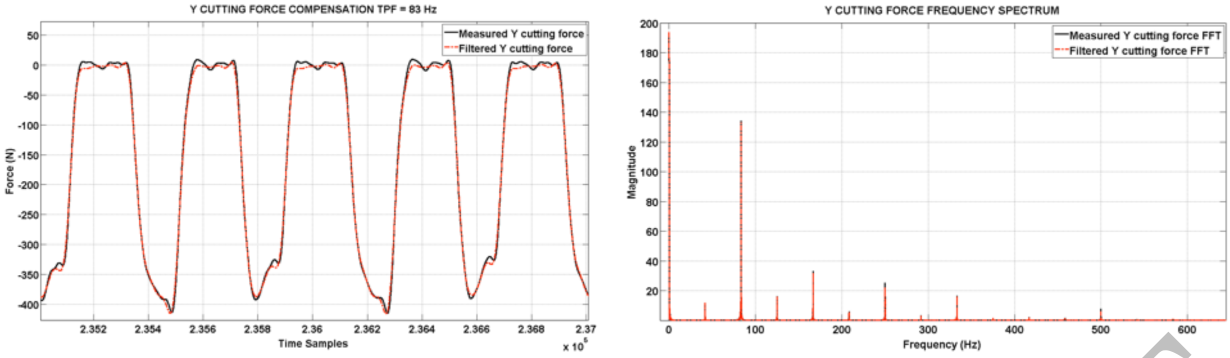
6. Cutting force compensations

Three different cutting tests were performed in order to evaluate the effect of the filter on real cutting forces, considering two different spindle speeds: one corresponding to a low TPF (i.e. 83 Hz), where almost no compensation is needed, the other at higher TPF (i.e. 275 Hz). Flank milling and side milling operations were considered. Cutting tests performed are summarized in Table 2.

Table 2: Cutting tests specifications (Ap and Ae stand for axial and radial depth of cut, respectively).

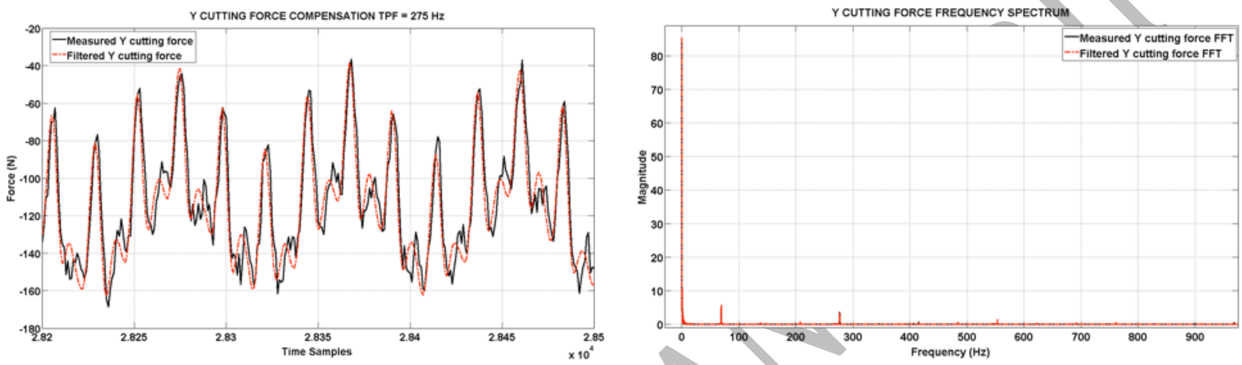
Test N°:	Operation	Tool	Ap	Ae	Feed (mm/min)	Spindle speed (Rpm)
1	Flank Milling	Osawa G2CS2 - Φ10x10x25x75	9 mm	1 mm	500	2500
2	Flank Milling	Osawa G2CS4 - Φ6x6x15x50	6 mm	0.5 mm	1000	4150
3	Side Milling	Osawa G2CS4 - Φ6x6x15x50	6 mm	0.5 mm	1000	4150

In Figs. 10–12 the measured cutting forces (dark lines) in the feed direction (i.e. Y-axis) are compared to the compensated signals (red lines) for the three cutting tests considered.



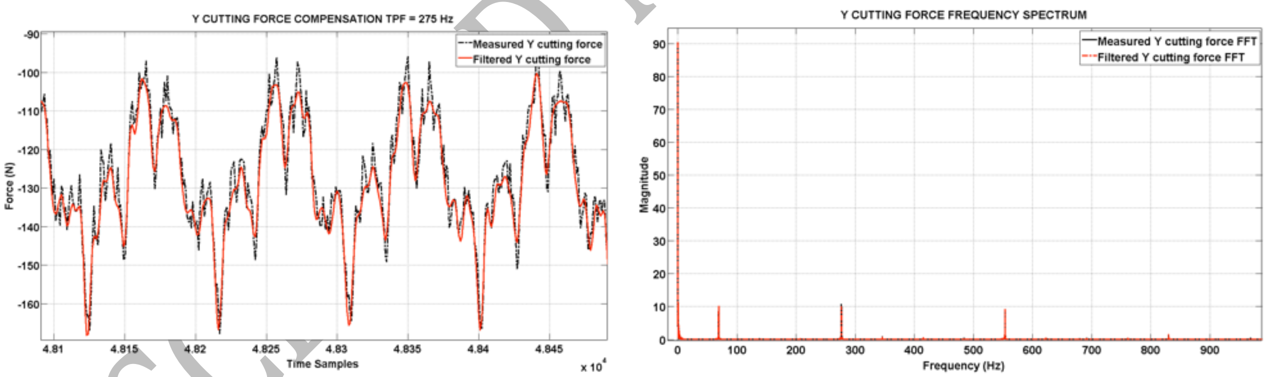
a) b)

Fig. 10. Cutting test 1, Y direction measured and compensated forces: time domain (a) and frequency domain (b) comparison.



a) b)

Fig. 11. Cutting test 2, Y direction measured and compensated forces: time domain (a) and frequency domain (b) comparison.



a) b)

Fig. 12. Cutting test 3, Y direction measured and compensated forces: time domain (a) and frequency domain (b) comparison.

By analyzing the provided results, the requirement of dynamic compensation is confirmed even in the nominally usable frequency range of the dynamometer (refers to Fig. 1 and Table 1), if very accurate cutting force measurements are needed, although for low speed machining operations only slight differences can be observed, as shown for the test 1. It is interesting to underline that this result is consistent with the dynamometer response, which is almost linear in the low frequency range: in this domain (i.e. lower spindle speeds), compensation should produce no relevant alteration of the measured force signals.

More relevant distortions should be experienced if higher TPFs are used, as suggested by the FRF measurements, nevertheless the developed filtering technique appears to be promising in compensating force measurements even in high speed machining operations. Future experiments will be carried out to demonstrate the importance of compensation at higher spindle speeds, as in high speed milling.

7. Conclusion

This paper proposes a filtering technique aimed at dynamically compensating noise affected force signals measured by table dynamometers. As shown by experimental impact modal tests, measurable bandwidth of the Kistler 9257A table dynamometer is drastically reduced by the effects of the modal behavior of the surrounding system and by workpiece mass. In practical applications measurable bandwidth would allow only cutting force measurements in low speed machining operations, if no dynamic compensation is applied. Following the work of Altintas et al. a compensation filter based on the disturbance Kalman filter formulation was developed and two different approaches were developed to overcome limitations imposed by numerical processing of the filter, especially suitable for milling operation. The performed numerical and experimental validation tests demonstrated filter accuracy and effectiveness over a broad frequency range, and confirmed that band fitting and parallel elaboration methods represent a good solution in extending the compensable bandwidth without facing numerical limitations. Real cutting force measurements applications shown the necessity of dynamic compensation even at low tooth passing frequencies and confirmed filter effectiveness. Band fitting method and parallel elaboration method actually extend the measurable bandwidth even above transducers' natural frequency, allowing accurate cutting force measurements even in high speed machining operations. The only limitation is related to the implicit assumption that during the cutting phase the measured TFs do not change significantly in the frequency range of measure, due to the material removal.

Future activities will be carried out to demonstrate technique effectiveness in high speed machining applications and to evaluate the implementation of orthogonal sets of polynomials for the fitting TFs in order to improve filter computation robustness and accuracy.

The use of Kalman filter dynamic compensation could find large applications in most of the machining related research topics in which accurate cutting force measurements are needed, such as development of effective tool condition monitoring techniques or optimized feed-scheduling algorithms.

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References

[1]. G Stepan, Z. Dombovari, J. Munoa, “Identification of cutting force characteristics based on chatter experiments”, CIRP Annals - Manufacturing Technology, 60 (2011) 113-116.

[2]. Y. Altintas, A. Kirchheim, F. Klocke et Al., “Sensors and Signal Analysis in High Performance Cutting”, International Conference High Performance Cutting (HPC), Aachen Germany, 2004.

[3]. M. Milfelner, F. Cus, J. Balic, “An over-view of data acquisition system for cut-ting force measuring and optimization in milling”, Journal of Materials Processing Technology 164–165 (2005) 1281–1288.

[4]. A. Albrecht, S. S. Park, Y. Altintas, G. Pritschow, “High frequency bandwidth cutting force measurement in milling using capacitance displacement sensors”, International Journal of Machine Tools & Manufacture 45 (2005) 993–1008.

[5]. S. Auchet, P. Chevrier, M. Lacour, P. Lipinski, “A new method of cutting force measurement based on command voltages of active electro-magnetic bearings”, International Journal of Machine Tools & Manufacture 44 (2004) 1441–1449.

[6]. Tae-Yong Kima, Joongwon Woob, Dongwon Shinc, Jongwon Kimd, “Indirect cutting force measurement in multi-axis simultaneous NC milling processes”, International Journal of Machine Tools & Manufacture 39 (1999) 1717–1731.
[7]. Young-Hun Jeong, Dong-Woo Cho, “Estimating cutting force from rotating and stationary feed motor currents on a milling machine”, International Journal of Machine Tools & Manufacture 42 (2002) 1559–1566.
[8]. J.H. Kim, H.K. Chang, D.C. Han, D.Y. Jang, “Cutting Force Estimation by Measuring Spindle Displacement in Milling Process”, CIRP Annals - Manufacturing Technology DOI:10.1016/S0007-8506(07)60051-1.
[9]. S. A. Spiewak, “Acceleration Based In-direct Force Measurement In Metal Cutting Processes”, Int. J. Mach. Tools Manufact. Vol. 35, No. 1, pp. 1-17, 1995.
[10]. Tae-Yong Kim, Jongwon Kim, “Adaptive Cutting Force Control For A Machining Center By Using Indirect Cutting Force Measurements”, Int. J. Mach. Tools Manufact. Vol. 36, No. 8, pp. 925-937, 1996.
[11]. S. Yaldiz, F. Unsacar, H. Saglam, H. Isik, “Design, development and testing of a four-component milling dynamometer for the measurement of cutting force and torque”, Mechanical Systems and Signal Processing 21 (2007) 1499–1511.
[12]. G. Totis, G. Wirtz, M. Sortino, D. Veselovac, E. Kuljanic, F. Klocke, “Development of a dynamometer for measuring individual cutting edge forces in face milling”, Mechanical Systems and Signal Processing 24 (2010) 1844–1857.
[13]. N. Tounsi, A. Otho, “Dynamic cutting force measuring”, International Journal of Machine Tools & Manufacture 40 (2000) 1157–1170.
[14]. F. Girardin, D. Remond, J. Rigal, “High Frequency Correction of Dynamometer for Cutting Force Observation in Milling”, Journal of Manufacturing Science and Engineering, Vol. 132, June 2010.
[15]. L. R. Castro, P. Viéville, P. Lipinski, “Correction of dynamic effects on force measurements made with piezoelectric dynamometers”, International Journal of Machine Tools & Manufacture 46 (2006) 1707–1715.
[16]. E. D. Haugse, G. C. Foss, D. W. Princehouse, “Dynamic Calibration of a Dynamometer”, IMAC XIV - 14th Inter-national Modal Analysis Conference, 1996.
[17]. G. Welch, G. Bishop, “An Introduction to the Kalman Filter”, SIGGRAPH 2001 Course 8 lecture notes, University of North Carolina at Chapel Hill.
[18]. M.S. Grewal, A.P. Andrews, “Kalman Filtering: Theory and Practice using Matlab, 2nd edition”, John Wiley & Sons, Inc. ISBNs: 0-471-39254-5 (Hardback); 0-471-26638-8 (Electronic).
[19]. S.S. Park, Y. Altintas, “Dynamic Compensation of Cutting Forces Measured From the Spindle Integrated Force Sensor System”, ASME IMECE2002 DSC Conference, New Orleans, November 2002.
[20]. S.S. Park, “High Frequency Bandwidth Cutting Force Measurements in Milling Using Spindle-Integrated Force Sensor System”, Ph.D. Thesis, Department of Mechanical Engineering, University of British Columbia, 2004.
[21]. J. Chae, S.S. Park, “High frequency bandwidth measurements of micro cutting forces”, International Journal of Machine Tools & Manufacture 47, 1433–1441, 2007.
[22]. M.H. Richardson, D.L. Formenti, "Parameter Estimation from Frequency Response Measurements using Rational Fraction Polynomials", Proceedings of the 1st International Modal Analysis Conference, November 1982.
[23]. Dennis, J.E., Jr., and R.B. Schnabel, “Numerical Methods for Unconstrained Optimization and Nonlinear Equations”, Englewood Cliffs, NJ: Prentice-Hall, 1983.
[24]. Y. Altintas, “Manufacturing Automation, metal cutting mechanics, machine tool vibration and cnc design, 2nd edition”, Cambridge University Press, ISBNs: 978-1-107-00148-0 (Hardback), 978-0-521-17247-9 (Paperback).
[25]. N. F. Macia, G. J. Thaler, "Modeling and Control of Dynamic Systems", Delmar Publishers Inc, ISBN: 978-1401847609.