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# Study on the correction of cutting force measurement with table dynamometer

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**Abstract**

This paper studies the correction of cutting force measurement with table dynamometer. The cutting force measurement tests and impact tests are carried out to obtain measured cutting forces and measured transfer function between the measured cutting forces and applied forces, respectively. According to the analysis of these experimental data, it is found that the distorted measured cutting forces are caused by the significant errors of cutting forces at two times and three times tooth passing frequency. Using a Kalman filter technique, the distorted measured cutting forces are corrected. The results of cutting force correction are very well and verify the theory that in frequency domain, cutting forces mainly concentrate on tooth passing frequency.


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*Keywords:* Table dynamometer; Kalman filter; Cutting force

## 1. Introduction

Machining process is widely used for producing different kinds of workpieces such as dies, molds and vanes. During machining process, in order to achieve high productivity and better surface quality, processing problems like chatter vibrations, overload and tool wear need to be monitored and solved. Cutting forces reveal to be one of the key information needed to control these problems. Therefore, it is important to obtain accurate cutting forces and a reliable cutting force measurement system is required.

Generally, methods for cutting force measurements can be divided into two categories: direct force measurements and indirect force measurements[1]. The most common direct force measurement is through table dynamometers. Typical table dynamometers are made up of piezoelectric sensors which are assembled between two plates[2]. The main drawback of table dynamometers is that they are very expensive, so table dynamometers are more suitable for experimental use. In order to overcome this problem, some indirect force measurement techniques have been developed[2-5]. Indirect force measurement techniques obtain cutting forces by using some built-in machine sensors or inexpensive sensors to measure different physical quantities like displacement[2,3] or current[4,5], so they are cheaper compared to table dynamometers. However, the accuracy of indirect force measurement techniques is easily influenced by environmental factors such as temperature, humidity and so on.

Whether direct force measurements or indirect force measurements have limited measuring range due to dynamic characteristics of measurement system. The machining process excites machine, workpiece and measurement device assembly to frequencies that come close to or even exceed the measurement system bandwidth, causing significant errors in the cutting force readings due to the structural dynamics[6]. In order to solve this problem, two different approaches have been proposed[1]. The first method is based on direct inversion of the experimentally identified transfer function between applied and measured forces[6-8]. However, the inversion may not exist at times. Another more effective method is through a Kalman filter technique [1,2,9,10]. Using a Kalman filter, the bandwidth of a dynamometer can be extended to an ideal range.


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In this study, table dynamometer is adopted to measure cutting forces. Firstly, experimental data including cutting forces measured by table dynamometer and measured transfer function acquired through impact modal test are analyzed. It is found that because of structural dynamics, in frequency domain, significant cutting force errors are caused at two times and three times tooth passing frequency. Then we use a disturbance Kalman filter compensation technique to obtain accurate cutting forces from distorted measured cutting forces based on the curve-fitted transfer function. Finally, we discuss cutting force correction results and draw conclusions.

## 2. Experimental data analysis

### *2.1. cutting experiment parameters*

Three milling tests are carried out in Hardinge GX710plus CNC machining center. The cutting experiment parameters are given in table 1.

Table 1. Cutting parameters used

| *S*(rev/min) | *D*(mm) | $n_z$ | $a_p$(mm) | $a_e$(mm) | $f_z$(mm/tooth) |
|---|---|---|---|---|---|
| 1000 | 12 | 6 | 1 | 2 | 0.05 |
| 5000 | 12 | 6 | 1 | 2 | 0.05 |
| 6000 | 12 | 6 | 1 | 2 | 0.05 |

Where $S$ is the spindle speed, $D$ is the cutter diameter, $n_z$ is the tooth number, $a_p$ is the axial depth of cut, $a_e$ is the radial depth of cut, and $f_z$ is the feed per tooth. The cutting forces are measured by Kistler 9255B table dynamometer. The machined material is aluminum alloy 7075. The cutting tool is a carbide six-fluted flat end mill.

### *2.2. cutting forces analysis*

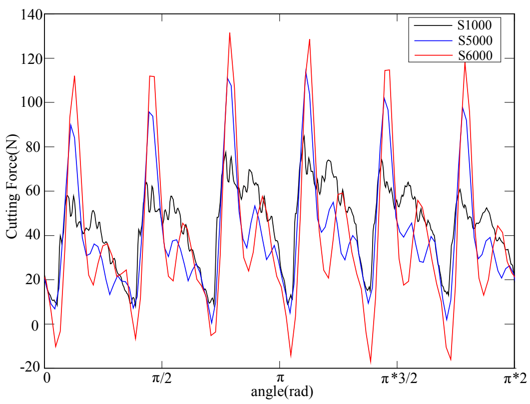


Fig. 1. Measured cutting forces in Y direction

The results of cutting tests are shown in Fig. 1. The measured cutting forces are plotted for the angle rather than time to compare their amplitudes for different spindle speeds. In general, when using the same machined material, the same cutting tool, the same axial and radial feed, and the same feed per tooth in cutting tests, measured cutting forces should be identical[11]. However, as is shown in Fig. 1, the measured cutting forces in Y direction at 5000 rev/min or 6000 rev/min is obviously greater than the measured cutting force in Y direction at 1000 rev/min.

In order to more effectively analyze this problem, we transfer cutting forces in time domain to cutting forces in frequency domain, as is shown in Fig. 2. When the spindle is at 6000 rev/min, the most cutting forces concentrate on two times tooth passing frequency (see Fig. 2(b)). The majority of cutting forces at 5000 rev/min concentrate on two times and three times tooth passing frequency (see Fig. 2(a)). These phenomena contradict the theory that in frequency domain, cutting forces mainly concentrate on tooth passing frequency [11]. However, most of cutting forces at 1000 rev/min concentrate on tooth passing frequency(see Fig. 2(c)), which confirms the aforementioned theory. Therefore, we can reasonably deduce that when the spindle is at 5000 rev/min or 6000 rev/min, significant errors of cutting forces are caused at two times and three times tooth passing frequency because of structural dynamics.

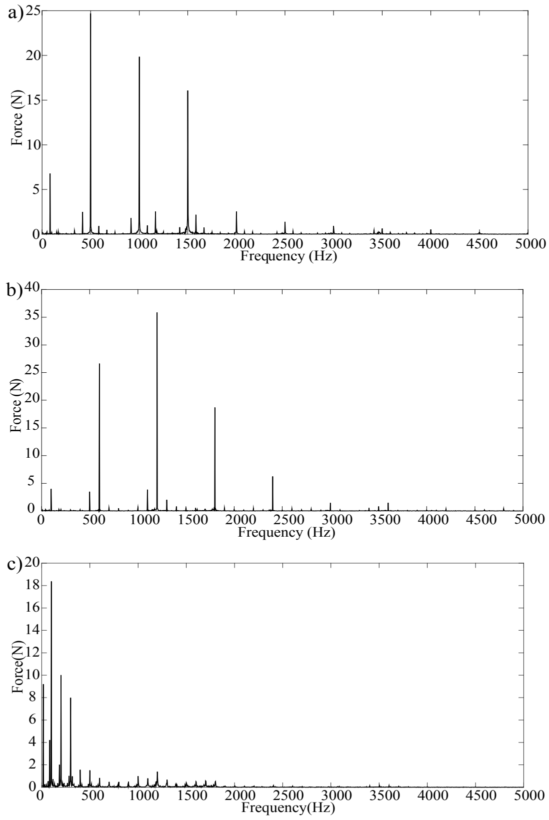


Fig. 2. Y direction measured cutting forces in frequency domain (a) at 5000rev/min (b) at 6000rev/min (c) at 1000rev/min

*2.3. modal test*

In order to obtain the structural dynamics of cutting force measurement system, modal tests should be carried out. Experimental impact tests are conducted to experimentally identify the transfer function between the measured cutting forces and applied forces. The Kistler 9255B table dynamometer is mounted on the Hardinge GX710plus CNC machining center and aluminum alloy 7075 is fixed to the dynamometer. Impact tests are conducted using a PCB impulse force hammer, LMS SCM05 fronted and LMS Test. Lab 13A software. In Fig. 3, the modal test set-up is shown.

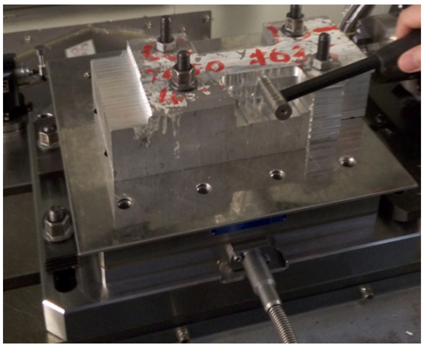

Fig. 3. Experimental impact test set-up

*2.4. curve fitting*

Implementing a disturbance Kalman filter to correct the distorted cutting forces, the experimentally identified transfer function needs to be curve-fitted into a manageable mathematical formulation. The general transfer function is written into polynomial forms as

$$\phi(s)=\frac{F_{\mathrm{m}}(s)}{F_{\mathrm{a}}(s)}=\frac{\mathrm{b}_1 s^{\mathrm{n}}+\mathrm{b}_2 s^{\mathrm{n}-1}+\mathrm{b}_3 s^{\mathrm{n}-2}+\ldots+\mathrm{b}_{\mathrm{n}+1}}{s^{\mathrm{m}}+\mathrm{a}_1 s^{\mathrm{m}-1}+\mathrm{a}_2 s^{\mathrm{m}-2}+\ldots+\mathrm{a}_{\mathrm{m}}} \quad (1)$$

Where $F_{\mathrm{m}}$ is the measured cutting force, $F_{\mathrm{a}}$ is the actual force applied on the workpiece, and $s$ is the variable in frequency domain.

When fitting transfer function curve, the local-fitting method is adopted. Because the majority of cutting forces concentrate on the frequency range of 200Hz to 2100Hz, as is shown in Fig. 2, the transfer function mathematical formulation is curve-fitted from 200Hz to 2100Hz to improve the computation time and the accuracy of the results.

The transfer function mathematical formulation is curve-fitted using a modal curve fitting technique[11] as

$$\phi(s)=\sum_{i=1}^{n}\frac{\alpha_i+\beta_i s}{s^2+\xi_i(2\pi f_{n,i})s+(2\pi f_{n,i})^2} \quad (2)$$

Where $n$ is the number of modes, $\alpha_i$ is the real residue for mode $i$, $\beta_i$ is the imaginary residue for mode $i$, $\xi_i$ is the damping ratio, and $f_{n,i}$ is the natural frequency. Because only cutting forces in Y direction are considered in this paper, we need to fit transfer function curve between measured cutting force in Y direction and the actual force applied on the workpiece in Y direction. The curve-fitted transfer function in Y direction considers 8 modes. Table 2 depicts the identified modal parameters for Eq. (2).

Table 2. Modal parameters for Eq. (2)

| Modes | $f_n$ | $\xi$ | $\alpha$ | $\beta$ |
|---|---|---|---|---|
| 1 | 325 | 0.078 | -85.4 | 227.4 |
| 2 | 581 | 0.054 | -139.5 | 206.98 |
| 3 | 818 | 0.062 | -258.5 | 249.6 |
| 4 | 991 | 0.017 | -104.8 | 98.9 |
| 5 | 1169 | 0.027 | -284.8 | 850.3 |
| 6 | 1294 | 0.016 | -15.03 | 374.6 |
| 7 | 1600 | 0.049 | 1870.9 | -443.5 |
| 8 | 1837 | 0.015 | -412.8 | -125.4 |

The measured transfer function and curve-fitted transfer function are plotted in Fig. 4. Ideally, the magnitude of transfer function should be 1, but it's not the truth, especially for the bandwidth of 1100Hz to 1800Hz.

Fig. 4 illustrates the reason why in frequency domain, the majority of cutting forces in Y direction concentrate on two times and three times tooth passing frequency, as is shown in Fig. 2(a) and Fig. 2(b). For example, when the spindle is at 6000 rev/min, the magnitude at the tooth passing frequency(600Hz) is about 1. However, the magnitudes at two times and three times frequency tooth passing frequency(1200Hz and 1800Hz) are far more than 1 so that it brings significant errors to measured cutting forces. Therefore, when judging whether the measured cutting forces are accurate or not, we should not only focus on the impact of magnitude of transfer function at tooth passing frequency, but also the impact of magnitudes at two times and three times frequency tooth passing frequency.

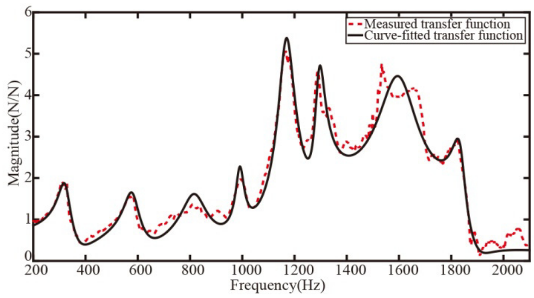


Fig. 4. Transfer function of cutting force measurement system in Y direction

## 3. Cutting force correction method

In this study, a Kalman filter technique[9,10] is utilized to correct the distorted measured cutting forces.

In order to design the Kalman filter, the curve-fitted transfer function in Y direction should be mapped into state space form, as follows:

$$\underbrace{\begin{bmatrix}\dot{x}_1\\ \dot{x}_2\\ \vdots\\ \dot{x}_{16}\end{bmatrix}}_{\dot{x}} = \underbrace{\begin{bmatrix}-\mathrm{a}_1 & -\mathrm{a}_2 & \cdots & -\mathrm{a}_{16}\\ 1 & 0 & \cdots & 0\\ \vdots & \ddots & 0 & \vdots\\ 0 & \cdots & 1 & 0\end{bmatrix}}_{A_\mathrm{s}} \underbrace{\begin{bmatrix}x_1\\ x_2\\ \vdots\\ x_{16}\end{bmatrix}}_{x} + \underbrace{\begin{bmatrix}1\\ 0\\ \vdots\\ 0\end{bmatrix}}_{B_\mathrm{s}} F_\mathrm{a}, \quad (3)$$

$$[F_\mathrm{m}] = \underbrace{[\mathrm{b}_1 \;\; \mathrm{b}_2 \;\; \cdots \;\; \mathrm{b}_{16}]}_{C_\mathrm{s}} \underbrace{\begin{bmatrix}x_1\\ x_2\\ \vdots\\ x_{16}\end{bmatrix}}_{x}$$

Where $\mathrm{a}_i$ and $\mathrm{b}_i$ are the numerator and denominator curve-fitted transfer function polynomial coefficients respectively(they are given in Eq. (2)), $x$ is the state variable.

The matrices $A_\mathrm{s}$ and $C_\mathrm{s}$ contain both very large and very small numbers, which may result in poor conditioning during the calculation process[10]. In order to deal with this problem, the system is transformed into an equivalent system using a similarity transformation:

$$x_\mathrm{n} = Tx, \quad A_\mathrm{n} = TA_\mathrm{s}T^{-1}, \quad B_\mathrm{n} = TB_\mathrm{s}, \quad C_\mathrm{n} = C_\mathrm{s}T^{-1} \quad (4)$$

Eq. (3) will be rearranged as

$$\dot{x}_\mathrm{n} = A_\mathrm{n}x_\mathrm{n} + B_\mathrm{n}F_\mathrm{a}, \quad F_\mathrm{m} = C_\mathrm{n}x_\mathrm{n} \quad (5)$$

The aim of using the Kalman filter is to obtain the actual cutting force, $F_\mathrm{a}$, applied on the workpiece. Since the Kalman filter only yields estimates for state vector and output, the state-space system should be expanded including the actual force, $F_\mathrm{a}$, in the state vector[2]. It is assumed that the cutting forces can be treated to be piecewise constant when the sampling frequency is quite high relative to the tooth passing frequency so that the derivative of the input, $F_\mathrm{a}$, is the function of system noise, $w$[9]. The expanding equations are as follows:

$$\underbrace{\begin{bmatrix}\dot{x}_{\mathrm{n}(16\times1)}\\ \dot{F}_{\mathrm{a}(1\times1)}\end{bmatrix}}_{\dot{x}_\mathrm{e}} = \underbrace{\begin{bmatrix}A_{\mathrm{n}(16\times16)} & B_{\mathrm{n}(16\times1)}\\ 0_{(1\times16)} & 0_{(1\times1)}\end{bmatrix}}_{A_\mathrm{e}} \underbrace{\begin{bmatrix}x_{\mathrm{n}(16\times1)}\\ F_{\mathrm{a}(1\times1)}\end{bmatrix}}_{x_\mathrm{e}} + \Gamma_{(17\times1)}w_{(1\times1)} \quad (6)$$

$$F_{\mathrm{m}(1\times1)} = \underbrace{\begin{bmatrix}C_{\mathrm{n}(1\times16)} & 0_{(1\times1)}\end{bmatrix}}_{C_\mathrm{e}} \underbrace{\begin{bmatrix}x_{\mathrm{n}(16\times1)}\\ F_{\mathrm{a}(1\times1)}\end{bmatrix}}_{x_\mathrm{e}} + v_{(1\times1)}$$

Where $\Gamma$ is the system noise matrix. $v$ denotes measurement noise.

The state vector can be estimated through this expanded Kalman filter as:

$$\begin{aligned}\dot{\hat{x}}_\mathrm{e} &= A_\mathrm{e}\hat{x}_\mathrm{e} + K(F_\mathrm{m} - \hat{F}_\mathrm{a}) = A_\mathrm{e}\hat{x}_\mathrm{e} + K(F_\mathrm{m} - C_\mathrm{e}\hat{x}_\mathrm{e})\\ &= (A_\mathrm{e} - KC_\mathrm{e})\hat{x}_\mathrm{e} + KF_\mathrm{m}\\ \hat{F}_\mathrm{a} &= C_0\hat{x}_\mathrm{e}, \quad \text{with} \quad C_0 = \begin{bmatrix}0_{(1\times16)} & 1\end{bmatrix}\end{aligned} \quad (7)$$

Where $K$ is the Kalman filter gain. $\hat{F}_\mathrm{a}$ is an estimate for the actual cutting force $F_\mathrm{a}$(or the corrected measured cutting force). The transfer function of this Kalman filter can be derived from Eq. (7):

$$\hat{F}_\mathrm{a} = \left\{\frac{C_0 adj\left[sI - (A_\mathrm{e} - KC_\mathrm{e})\right]}{\det\left[sI - (A_\mathrm{e} - KC_\mathrm{e})\right]}K\right\}F_\mathrm{m} = G_{\hat{F}_\mathrm{a}/F_\mathrm{m}}F_\mathrm{m} \quad (8)$$

In the Eq. (8), only Kalman filter gain, $K$, is the unknown variable. The Kalman filter gain is identified by minimizing the state estimation error($\hat{x}_\mathrm{e} - x_\mathrm{e}$) covariance matrix $P$, which is the solution of the following time variant Riccati equation[9,10]:

$$\begin{aligned}\dot{P} &= A_\mathrm{e}P + PA_\mathrm{e}^\mathrm{T} + \Gamma Q\Gamma^\mathrm{T} - PC_\mathrm{e}^\mathrm{T}R^{-1}C_\mathrm{e}P\\ K &= PC_\mathrm{e}^\mathrm{T}R^{-1}\end{aligned} \quad (9)$$

It is assumed that system and measurement noise are uncorrelated zero-mean white noise signals with covariance matrices are as given below:

$$Q = E\left[ww^\mathrm{T}\right] > 0, \quad R = E\left[vv^\mathrm{T}\right] \geq 0, \quad E\left[wv^\mathrm{T}\right] = 0 \quad (10)$$

The measurement noise covariance matrix, $R$, is determined from the average electrical RMS reading when the machine is stationary and the average differences in air cutting force fluctuations, while the system noise covariance matrix, $Q$, is tuned to accommodate the compensations[9]. For this case, the measurement, system noise covariance, and the system noise matrix are as follow:

$$R = [2.6], \quad Q = [9e11], \quad \Gamma = \begin{bmatrix}0_{(1\times16)} & 1\end{bmatrix}^\mathrm{T} \quad (11)$$

Therefore, the Kalman filter gain, $K$, can be determined with the aforementioned equations. Based on the Eq. (8) and measured cutting forces in frequency domain, the corrected cutting forces can be obtained.

## 4. Results and discussion

Fig. 5 and Fig. 6 depict the measured and corrected cutting forces in Y direction when the spindle is at 5000 rev/min and 6000 rev/min respectively.

As is shown in Fig. 5(a) and Fig. 6(a), the amplitudes of the corrected cutting forces at 5000 rev/min and 6000 rev/min are approximately equal to each other, and their amplitudes are also approximately equal to the amplitude of measured cutting force in Y direction at 1000 rev/min. These results prove that the distorted measured cutting forces have been corrected to the accurate cutting forces.

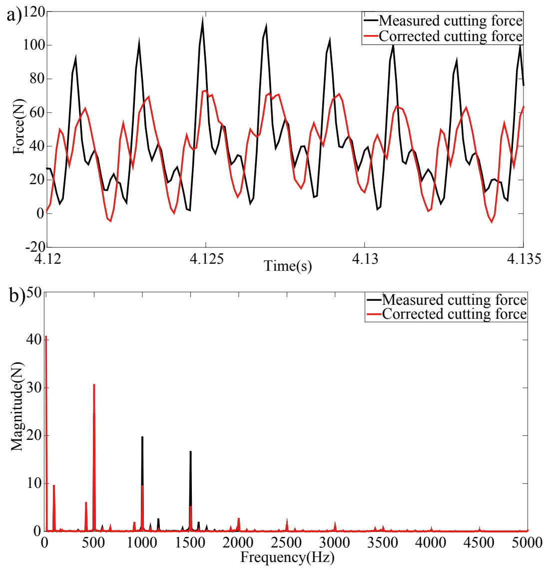


Fig. 5. Cutting forces at the spindle speed of 5000rev/min (a) in time domain (b) in frequency domain

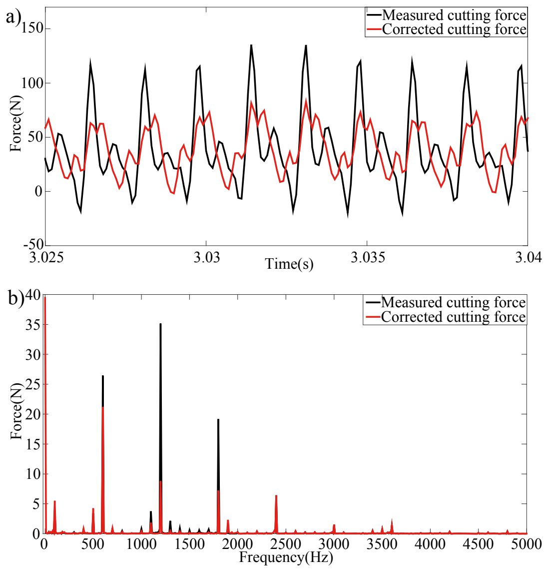


Fig. 6. Cutting forces at the spindle speed of 6000rev/min (a) in time domain (b) in frequency domain

In Fig. 5(b) and Fig. 6(b), it can be seen that in frequency domain, the majority of corrected cutting forces concentrate on the tooth passing frequency. The results verify the theory that in frequency domain, cutting forces mainly concentrate on tooth passing frequency [11].

## 5. Conclusion

This paper presents some research on the correction of cutting force measurement with table dynamometer. According to the analysis of experimental data, it can be concluded that when judging whether the measured cutting forces are accurate or not, not only the impact of magnitude of transfer function at tooth passing frequency should be concerned, the impact of magnitudes of transfer function at two times even three times tooth passing frequency should also be concerned. Using a Kalman filter, the distorted measured cutting forces have been corrected. The results of cutting force correction are very well and verify the theory that in frequency domain, cutting forces mainly concentrate on tooth passing frequency.

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