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Improved inverse filter for the correction of distorted measured cutting forces

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ABSTRACT

The cutting forces sampled from machining processes may be distorted by the dynamic response of measuring system. Traditional methods, whether discrete inverse filter or Kalman filter, may result in accuracy loss due to inaccurate approximation of transfer function. This paper proposes an improved inverse filter to achieve accurate and efficient correction of the distorted cutting forces. Failure behaviors of traditional methods are analyzed in-depth first, and then, a spline curve-based interpolation scheme is proposed to approximate the transfer function of the measuring system. The transfer function corresponding to the frequencies of the measured cutting forces obtained by this method can be close to the actual response of the cutting system to the most degree. As a result, the corrected cutting forces can well reflect the actual physical response of the machining processes. To show the advantage of the proposed method, both the improved inverse filter and traditional Kalman filter are utilized to correct the cutting forces measured from three tests. Thorough comparison implies that both methods can give good and consistent corrected results in most cases, while Kalman filter will lose correction accuracy if the transfer function cannot be fitted so well to be sufficiently close to the measured result. Especially, calculation procedure turns out that the improved inverse filter is better in efficiency than Kalman filter.

1. Introduction

Machining process has been playing a dominant role in the industry all the time. It is widely used for producing a variety of workpieces such as molds, blades and aircraft thin-walled parts. Since the goals of machining process are to achieve high productivity and better surface quality, processing problems like chatter vibrations, overload and tool wear need to be monitored and solved. All studies on these problems are closely related to cutting forces [1,2]. Therefore, it is very important to obtain accurate cutting forces.

One of the most common and effective methods to obtain cutting forces is directly measured by using table dynamometer, which can adapt to severe plant environment and provide stable cutting force measurements for a long time. Typical table dynamometer is made up of piezoelectric sensors which are assembled between two plates [3]. However, because of dynamic characteristics of cutting force measuring system, sometimes cutting force measured from table dynamometer will be distorted and cannot accurately reflect the actual physical property of machining process [4]. Therefore, some means must be taken to correct the distorted measured cutting forces.

Tlusty et al. [5] and Lapujoulade [6] used hardware, i.e. accelerometer, to correct the measured cutting forces through compensating for the inertia and structural damping of the dynamometer. However, this kind of method revealed some accuracy problems [7]. To overcome this drawback, two kinds of methods with more accuracies, i.e. inverse filter and Kalman filter methods, were proposed by researchers to improve the correction reliability. Inverse filter method is generally carried out by multiplying the spectrum of the measured cutting forces with the inverse of the frequency response function of the measuring system to remove unwanted dynamic effects [7–10].

Castro et al. [7] carried out this by using discrete frequency response functions without coupling effects between different directions. Girardin et al. [8] improved Castro's method by introducing the coupling effects. It should be mentioned that both methods did not consider the one-to-one corresponding relationship between the frequency points of cutting forces and those of the measured Transfer Function (TF). To achieve the one-to-one correspondence of both frequencies, Magnevall et al. [9] and Zhu et al. [10] adopted fitting method to approximate the measured discrete TF as a continuous function.

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The second method utilized for reconstructing the measured cutting forces is the famous Kalman filter technique [11–19]. Park [11–13] made important contributions to the application of Kalman filter on correcting distorted measured cutting forces. Park and Altintas [11] integrated Kalman filter into a spindle integrated force sensor system to decrease the unwanted dynamic effects. Albrecht et al. [12] used capacitance displacement sensors to indirectly measure cutting forces, and adopted Kalman filter technique to extend the bandwidth of measuring frequency to 1000 Hz. Chae and Park [13] extended the Kalman filter approach to the field of micro-milling. Scippa et al. [14] focused on developing numerical methods for fitting the measured TF required in Kalman filter.

In summary, the state of the art has the following characteristics:

- Since there exists non-correspondence between the frequencies of the measured cutting forces and TF, inverse filter method with discrete TF may result in relatively large correction errors, as discussed in detail in Section 3.
- Continuous frequency response function, either used in inverse or Kalman filters, is generally obtained by using a relatively complex curve fitting procedure. This will take a relatively long computation time, and also may lead to some accuracies loss, as discussed in detail in Sections 3 and 4.2.2.
- Designing a Kalman filter itself is a relatively complex procedure and requires long time to process data, as discussed in detail in Section 4.2.

Hence, this paper proposes an improved inverse filter by using interpolation technique to achieve the correspondence between the frequencies of the measured cutting forces and TF with relatively low accuracy loss and computation time. First, the reasons why sometimes cutting forces measured by table dynamometer cannot reflect the actual cutting forces accurately will be discussed in Section 2. Second, the main limitation of conventional methods is discussed in Section 3, and numerical scheme for achieving the improvements of both computation accuracy and efficiency of TF is established. Finally, experimental validation is carried out to check the applicability of the proposed method in Section 4. Cutting forces measured from the same depth of cuts and feed but different spindle speed are analyzed in time domain and in frequency domain, and the criterion for whether the measured forces can reflect the actual case is also given according to the distributions of the transfer function. Kalman filter technique is also adopted for comparison study. The results of correcting measured cutting forces with the improved inverse filter and Kalman filter agree with each other well in most cases, while the improved inverse filter has higher efficiency and reliability than Kalman filter.

2. Problem statement

As shown in Fig. 1, a measurement system with a workpiece being clamped on a table dynamometer is usually adopted to capture the cutting forces. By using this system, the input signal, i.e. actual cutting forces F_a, is finally measured as the output signal, i.e. the measured

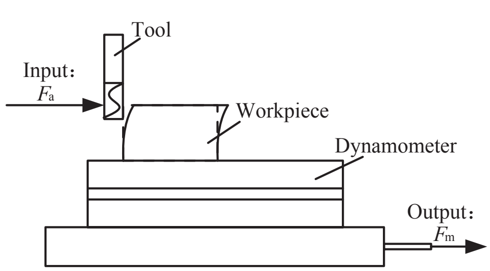

Fig. 1. Illustrative diagram of distorted measured cutting forces reflecting actual cutting forces inaccurately.

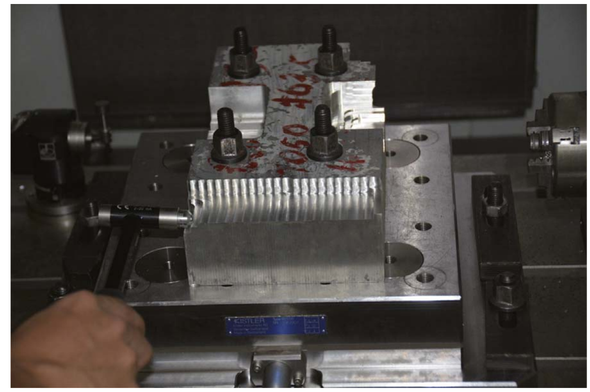

Fig. 2. Experimental impact test set-up.

cutting force F_m. The transfer function between F_m and F_a can be identified as the following expression in frequency domain:

$$\phi(s) = \frac{F_m(s)}{F_a(s)} \tag{1}$$

Usually, $\phi(s)$ can be measured by using standard impact method to stimulate the workpiece installed on the dynamometer, as shown in Fig. 2. An illustrative profile of $\phi(s)$ is plotted in Fig. 3. In an ideal case, the magnitude of $\phi(s)$ should be close to unity in full frequency range if there are no dynamic influences. However, in some certain bands of frequency, e.g. the frequency band A_2 shown in Fig. 3, actual magnitude of $\phi(s)$ will deviate from the ideal value (i.e. one) due to the comprehensive effects of multiple factors such as the mass and dynamic deformation of the workpiece, and the distance between the actual cutting position and the positions of force transducers in dynamometer. As a result, if the tooth passing frequency, especially its first three order harmonic, is in the vicinity of these frequency bands, the measured cutting force F_m will deviate from the actual cutting force F_a, and cannot reflect the real physical properties of machining process. In this case, the measured cutting forces need to be corrected to be as close to the actual values as possible. In the following section, an improved inverse filter method will be described to carry out this.

3. Improved inverse filter method

From Eq. (1) it can be seen that if the transfer function matrix $\boldsymbol{\phi}(\omega)$ in frequency domain is obtained, the three-direction measured cutting force $\mathbf{F}_m(\omega)$ at each frequency point can be corrected as $\mathbf{F}_{mc}(\omega)$ by the following equation:

$$\mathbf{F}_{mc}(\omega) = \mathbf{F}_m(\omega)\boldsymbol{\phi}^{-1}(\omega) \tag{2}$$

with

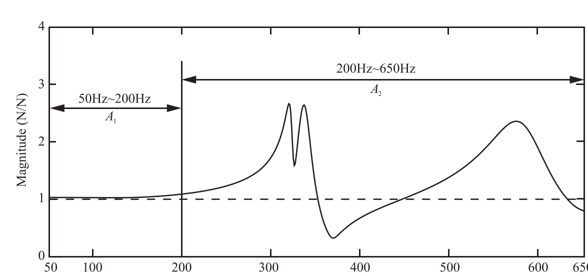

Fig. 3. Typical transfer function of cutting force measuring system.