Calibrating measured milling force during long-duration monitoring

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Abstract. Piezoelectric force sensor is used to measure cutting force in most milling process to get important manufacturing information. However, the measured milling force may be not accurate due to the charge leak in piezoelectric sensor during long-duration monitoring, which will cause a zero-drift problem in measuring milling force. Measuring milling force with zero-drift problem, the measured average cutting force should be calibrated in order to get correct force information. In this study, the measured first harmonic force components are used to calibrate average cutting force components based on cutting force model. There are two steps in this method for calibrating average force components. The first step uses the measured first harmonic force components to extract the specific cutting constants from the ratio of the measured first harmonic force components in X and Y directions, and the second step utilizes the identified cutting constants to calibrate the average force components. The limitations of presented method are also discussed in this paper. The validity of the proposed method is confirmed through milling experiments.

1. Introduction

The current trend of “Intelligent manufacturing” requires that manufacturing technology is improved by the introduction of methods including self-optimization, self-configuration, self-diagnosis and the other intelligent supports in the milling process. Undoubtedly, the cutting force signal can be fundamental and important manufacturing information for the required intelligent milling technology. In the past research, many manufacturing technologies based on cutting force signal such as detecting cutter offset [1-3], sensing cutting tool breakage and tool wear [4-5], as well as the prediction of surface error and stability in the milling process [6-7] have been developed. For the purpose of self-diagnosis of cutting tool condition, the cutting force needs to be identified at any time in milling process. Once the threshold value of cutting force is detected, the cutting tool can be replaced automatically. Piezoelectric force sensor is used to measure cutting force in most milling process due to the faster responsibility compared to the other force sensors. However, charge leakage in piezoelectric sensor often causes the average forces to drift with time [8]. Due to this, the measured milling force is not suitable for applications wherein continuous monitoring of milling process is desirable during long duration. To overcome the zero drift problems due to the charge leakage in piezoelectric dynamometer, it is necessary to calibrate average force measured by piezoelectric dynamometer. But so far, there is no proper method to be presented in the literature to calibrate the
average milling force measured by piezoelectric dynamometer during long-duration monitoring, which forms the objective of the present research study. Section 2 of this paper first presents a method to extract the specific cutting constants from the measured first harmonic force components based on analytical cutting force model. Then, the identified cutting constants can be used to calibrate the measured average force components. Experimental verifications are presented in Section 3 followed by conclusions and discussions.

2. Calibration of measured forces

From the work presented by Wang et al. [9], the milling forces \( f \) can be expressed as a function of cutter angular displacement \( \phi \) in a vector form as

\[
f(\phi) = \left[ f_x(\phi), f_y(\phi) \right] = \sum_{n=-\infty}^{\infty} A[nk]e^{in\theta}
\]

where

\[
A[nk] = \frac{A_1[nk]}{A_1[nk]}
\]

\[
= \frac{Nk_t}{2\pi} \left[ CP_1(Nk) + k_r CP_1(Nk) - k_t CP_2(Nk) \right]
\]

are the coefficients of the Fourier series expansion of total milling forces in X and Y directions. It is shown that the spectra magnitude of total milling forces at normalized harmonic frequencies \( Nk \) can be expressed explicitly as the algebraic functions of cutting parameters, \( k_r \) and \( k_t \) denote as specific cutting constants in tangential and radial directions. They can be shown from Eq. (2) that

\[
\begin{bmatrix}
k_r \\
k_t
\end{bmatrix} = \begin{bmatrix}
CP_1(Nk) & CP_2(Nk) \\
CP_2(Nk) & -CP_1(Nk)
\end{bmatrix} \begin{bmatrix}
A_1[Nk] \\
A_1[Nk]
\end{bmatrix} \frac{2\pi}{N_t}
\]

where \( N \) and \( t_r \) denote as flute number of cutter and feed per tooth. Cutting parameter functions \( CP_1(Nk) \) and \( CP_2(Nk) \) are expressed in terms of flute number of cutter \( N \), helix angle \( \alpha \), radius of cutter \( R \), axial depth of cut \( d_a \), entry cutting angle \( \theta_e \) and exit cutting angle \( \theta_i \) by

\[
\begin{bmatrix}
CP_1(Nk) \\
CP_2(Nk)
\end{bmatrix} = CWD(Nk) \begin{bmatrix}
P_1(Nk) \\
P_2(Nk)
\end{bmatrix}
\]

with

\[
CWD(Nk) = \frac{2R \sin \frac{Nk}{N} \pi}{N \tan \alpha} \left[ 1 + \frac{Nd_a \tan \alpha}{2\pi R} \right]
\]

\[
\begin{bmatrix}
P_1(Nk) \\
P_2(Nk)
\end{bmatrix} = \left[ e^{-i\theta_0} \left( \frac{jNk \sin 2\theta + 2 \cos 2\theta}{2[4 - (Nk)^2]} \right) \right]^{-\theta_0}
\]

Equation (3) shows that cutting constants can be determined from the measured milling force data at different harmonic frequencies in a single cutting test. When the normalized harmonic frequency \( Nk=0 \) is selected, it means that measured average forces are used to estimate the cutting constants, which have been presented in [9]. However, the measured average cutting force is not corrected due to the zero-drift problem, and the method presented in [9] can’t apply for identification of cutting constants with zero-drift problem during long-duration milling. When it is desirous to extract cutting constants without the knowledge of average forces, measuring dynamic force data at harmonic frequencies would aid the user to identify cutting constants based on Eq. (3). It is noted that the measured harmonic forces will not be affected by the zero-drift problem. Therefore, the identified cutting constants from the measured harmonic forces can be used to calibrate the measured average
cutting through Eq. (2) by letting $Nk=0$. For the acquisition of highest signal to noise ratio, the measured first harmonic force components ($N$ or $-N$) seems to be more suitable to use in extracting cutting constants rather than other harmonic force components. Comparing with usefulness of measured average forces, it is worth noticing that Eq. (3) may not be applied directly for extracting cutting constants by using the measured first harmonic force component due to the lack of knowledge of starting angular position of the measurement with respect to the force model coordinate system. This means that in order to use $k$th ($k \neq 0$) harmonic force component to identify cutting constants via Eq. (3), the Fourier coefficients in Eq. (3) have to be transformed from the measured harmonic force components by the following transformation

$$
A[Nk] = A[P]Nk e^{-jNk\Delta \phi}
$$

(7)

where $\Delta \phi$ denote as the phase angle difference between the starting angular position of the force measurement and the origin of cutting position defined by the force model as shown in Fig. 1.

By setting $k=1$ in Eq. (7), the ratio of first harmonic forces can be expressed as

$$
\frac{A_x[N]}{A_y[N]} = \frac{A_x[N] e^{-jN\Delta \phi}}{A_y[N] e^{-jN\Delta \phi}} = \frac{A_x[N]}{A_y[N]} = b + jc
$$

(8)

Equation (8) shows that the phase angle difference between the first harmonic force components in $X$ and $Y$ directions remain the same regardless of the starting angular position of the force measurement, and the values of $b$ and $c$ can be obtained from the force measurement. According to the expression of Eq. (2), left hand side of Eq. (8) can be written as

$$
\frac{A_x[N]}{A_y[N]} = \frac{P_x(N) + k_x P_y(N)}{-k_x P_y(N) + P_x(N)}
$$

(9)

Equating right hand sides of Eq. (8) and Eq. (9) results in the following equation:

$$
\frac{P_x(N) + k_x P_y(N)}{-k_x P_y(N) + P_x(N)} = \frac{b + jc}{b + jc}
$$

(10)

where $P_x, P_y, I_x, I_y$ are the real and imaginary parts of $P_x(N)$ and $P_y(N)$ respectively. Based on the assumption in which cutting constants are real numbers and splitting both sides of Eq. (10) into their real and imaginary parts, two possible values of $k$ can be solved with

$$
k_1 = \frac{b_{1x} + c_{1y} - P_{1x}}{b_{1x} - c_{1y} + P_{2x}}, \quad k_2 = \frac{b_{2x} + c_{2y} - P_{1x}}{b_{2x} + c_{2y} + P_{2x}}
$$

(11)
Substituting $k_1$ into Eq. (2) and using the magnitude of first harmonic forces in X and Y directions, two possible values of $k_t$ can be determined by the following formula:

$$k_t = \frac{2\pi A[N]}{N_1 \left[ CP(N) + k_r CP(N) \right]}$$

Similarly, Substituting $k_2$ into Eq. (2) and using the magnitude of first harmonic forces in X and Y directions, there also exist two possible values of $k_t$, in that case, they become:

$$k_t = \frac{2\pi A[N]}{N_1 \left[ CP(N) + k_r CP(N) \right]}$$

According to the above analysis, four sets of possible cutting constants can be obtained from the first harmonic forces. They are $(k_{1x}, k_{1y}), (k_{2x}, k_{2y}), (k_{3x}, k_{3y})$ and $(k_{4x}, k_{4y})$. Based on cutting force model in [9], the measured first harmonic forces do not include ploughing components. Therefore, it can be found that $(k_{1x}, k_{1y}) = (k_{2x}, k_{2y}) = (k_{3x}, k_{3y}) = (k_{4x}, k_{4y})$. However, in most cutting conditions, shearing and ploughing forces are all associated with the first harmonic forces. Thus, the four sets of possible solutions are different in practical milling operations. In this study, the best set of the possible cutting constants $(k_{ix}, k_{iy})$ can be determined by finding the set of cutting constants with minimum error of predicting forces from the four sets of possible cutting constants. Then, letting $Nk=0$, the cutting constants $(k_{ix}, k_{iy})$ can be used to calibrate the average force components through Eq. (2).

3. Experimental verification

The cutter/work pair is used: a three-fluted end mill of 10mm diameter with Al2024-T4. The cutting forces were measured with the Kistler 9255B dynamometer. Firstly, the force measurements are operated in short duration. The best set of cutting constants from first harmonic forces, $(k_{ix}, k_{iy})$, and the cutting constants identified from the measured average forces, $(k_{0x}, k_{0y})$, are used to predict the cutting forces by using milling force model presented by Kline et al. [10]. As shown in Fig. 2, the predicted forces from $(k_{ix}, k_{iy})$ and $(k_{0x}, k_{0y})$ in the angle and frequency domain were both in agreement the measured forces.
Figure 2. Comparison of predicted forces and measured forces during short milling duration, (a): in angle domain and (b): in frequency domain. Solid line: measured forces. O: predicted forces using cutting constants identified from \((k_{ri}, k_{tj})\). \(\Delta\): predicted forces using cutting constants identified from \((k_{si}, k_{sj})\). Axial depth of cut = 2.5 mm, radial depth of cut = 2 mm, up milling

The best set of cutting constants \((k_{si}, k_{sj})\) identified from measured first harmonic forces and \((k_{ri}, k_{tj})\) identified from measured average cutting forces were shown as in Table 1.

Table 1. Cutting constants identified from measured average cutting forces and first harmonic forces during short milling duration

| Tangential cutting constants (N/mm²) | Radial cutting constants |
|--------------------------------------|-------------------------|
| \(k_{si}, k_{tj}\)                  | \(k_{ri}, k_{tj}\)      |
| 1006,1004                           | 0.398,0.422             |

Comparing the identified cutting constants for milling Al2024-T4 as reported in [11], the values of cutting constants in Table 1 are reliable.

For further verification of the calibration method presented in this study, the force measurement is operated during long milling duration. The identified cutting constants are listed in Table 2.

Table 2. Cutting constants identified from measured average cutting forces and first harmonic forces during long milling duration

| Tangential cutting constants (N/mm²) | Radial cutting constants |
|--------------------------------------|-------------------------|
| \(k_{si}, k_{tj}\)                  | \(k_{ri}, k_{tj}\)      |
| 1074,259                             | 0.386,0.545             |
Figure 3. Comparison of predicted forces and measured forces during long milling duration, (a): in angle domain and (b): in frequency domain. Solid line: measured forces. O: predicted forces using cutting constants identified from \((k_{r0}, k_{t0})\). Δ: predicted forces using cutting constants identified from \((k_n, k_r)\). Axial depth of cut = 3 mm, radial depth of cut = 2 mm, down milling

The predicted forces from \((k_n, k_r)\) and \((k_{r0}, k_{t0})\) in the angle and frequency domain were compared with the measured forces as shown in Fig. 3. Obviously, comparing with the cutting constants in Table 1, the cutting constants identified from measured average forces in Table 2 are not reasonable, which results in that the predicted forces from \((k_{r0}, k_{t0})\) in Table 2 fail to predict the measured harmonic cutting forces. On the other hand, the predicted forces from \((k_n, k_r)\) succeed in predicting the milling forces at all nominal cutting frequencies, except for the average forces components. It is also noted that the identified cutting constants are very close to the cutting constants identified in Table 1. It is shown that the measuring milling forces in the Fig. 3 suffer a obvious zero-drift problem during long-duration monitoring and the predicted average forces from \((k_n, k_r)\) are reliable. Through above experimental results, the presented calibration method of measured milling forces with zero-drift problem by using cutting constants identified from measured first harmonic force components has been validated.

4. Conclusions and discussions

In this paper, a calibration method of measured milling forces with zero-drift problem during long-duration monitoring is presented. By using the ratio of measured first harmonic forces, four sets of possible cutting constants were found based on the assumption that cutting constants are real numbers. Subsequently, the best set of cutting constants is selected from the four sets of possible cutting constants by fitting the measured first harmonic force data in the least square sense. The main conclusions extracted from present work are given as follows:

- During short milling duration, the cutting constants identified from both average forces and first harmonic forces are nearly identical. It is noted that the cutting constants identified from average
forces are independent of those identified from first harmonic forces, since every term of Fourier series is independent of each other as shown in Eq. (1).

- During short milling duration, in contrast with the measured cutting forces, the cutting constants as identified from both average forces and first harmonic forces have good prediction accuracy.
- During long milling duration, the cutting constants identified from average forces will fail to predict the milling forces due to the zero-drift problem. On the other hand, the cutting constants identified from first harmonic forces still succeed in predicting the milling forces at all nominal cutting frequencies, except for the average forces components.
- Through the application of the presented method, a continuous monitoring of milling process is made possible where the piezoelectric dynamometer suffers a zero-drift problem.
- In theory, the four sets of possible cutting constants identified from measured first harmonic forces are found to be identical. However, the four sets of possible cutting constants are different in practical milling operations due to the existence of ploughing forces.

It is noted that for an end mill with flute number \( N = 4, 6, 8 \ldots \), Eq. (6) shows that only average force components exist in slot milling. In other words, in slot milling, first harmonic forces will vanish for an end mill with 4, 6, 8… cutting flutes and thus should be avoided to use the calibration method presented in this paper.

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