Cutting force measurement from acceleration sensor in milling operation

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1. Introduction

In the manufacturing industry, productivity is a key factor besides quality, efficiency and sustainability. However, productivity cannot be increased arbitrarily due to undesired vibration that may arise during the cutting process [1]. The prediction and avoidance of these vibrations are still an active researched area.

In order to thoroughly discover and understand the dynamic behavior of machining processes, an accurate and reliable identification of the resultant cutting force is an important factor. In general, it can be measured accurately by means of dynamometer, although, these sensors are usually quite expensive measurement equipments. In addition, for sufficiently accurate measurement results, it may be necessary to take into account the dynamic characteristics of dynamometers which limits the reliable bandwidth of the measurement.

The purpose of this paper is to propose an alternative method that makes it possible to predict cutting force without using expensive dynamometer. First, the basic idea and the developed method of the alternative cutting force measurement is presented, in which the force is predicted based on measured acceleration signal treated with inverse Frequency Response Function (FRF). This section gives the mathematical background for the identification of the cutting force. Then, this measurement technique is applied on a case study, which is the main contribution of the paper (see Section 3). Finally, in order to validate the proposed method, the reconstructed result is compared with cutting force measurement with dynamometer.

2. Reconstruction of cutting force

In order to reconstruct the cutting force without dynamometer, the key idea is to capture the system's response and using the FRF, which describes the dynamic behavior of the system [2]. The FRF, also called transfer function, describes the ratio between the output (resultant vibration $x(t)$) and the input (cutting force $F(t)$) in frequency domain. It is usually determined by modal analysis, typically by means of impact test with modal hammer [2]. Once the FRF is known, then the resultant cutting force $F(t)$ can be reconstructed as follows:

$$F(t)=\mathcal{F}^{-1}\left\{H^{-1}(\omega)\mathcal{F}\left\{x(t)\right\}\right\}, \qquad (1)$$

where $H(\omega)$ is the measured FRF, while $\mathcal{F}\{\square\}$ and $\mathcal{F}^{-1}\{\square\}$ denote the Fourier and inverse Fourier transformation, respectively.

2.1 Sampled discrete case

In practice, the FRF and the response are measured as sampled discrete data, therefore, the proposed method can be applied in discrete form as the following steps shows:

$$x(t)\xrightarrow{\text{FFT}}\xi(\omega)\xrightarrow{H^{-1}(\omega)}\Phi(\omega)\xrightarrow{\text{IFFT}}F(t), \qquad (1)$$

where $\xi(\omega)$ and $\Phi(\omega)$ are the FFT of $x(t)$ and $F(t)$, respectively. The number of the measured discrete values during one tooth-passing period m_x and the number of the reconstructed cutting force values m_F can be given as:

$$m_x=\text{floor}(2f_sT),\ m_F=\text{floor}(2f_{\max}T), \qquad (1)$$

where f_s is the sampling frequency of the acceleration measurement, while $f_{\max}$ is the available bandwidth of the mechanical system's FRF. The time period T in seconds reads as:

$$T=60/(nN), \qquad (1)$$

where n is the spindle speed in rpm and N is the number of cutting teeth.

Note that the number of the measured points of the periodic vibration signal is usually larger than the number of the reconstructed cutting force points, since the bandwidth f_s is usually greater than the relevant bandwidth $f_{\max}$ of the measured FRF. Consequently, the reconstructed cutting force is more accurate in lower spindle speed domain, where sufficiently large number of reconstructed points are available.

3. Case study

The above described measurement technique is applied in a case study during a peripheral milling test along straight path with down-milling operation. In the experimental procedure, the workpiece (Aluminum 2024-T351) is clamped onto the top of a flexible structure, which was designed to mimic the dynamics of a single-degree-of-freedom system (SDoF) (see Fig. 1) [3]. The structure is flexible only along y direction and can be considered to be rigid in the other directions. The measured FRF can be seen in Fig. 2c.

The cutting tests was performed with spindle speed n = 4650 rpm, radial immersion a_e = 2 mm, feed per tooth f_z=0.05 mm/tooth and axial immersion a_p = 2 mm. The TIVOLY P615H endmill had diameter D = 16 mm, number of flutes N = 2, helix angle $\beta = 30^\circ$ and rake angle $\kappa = 90^\circ$.The response was acquired by NI cDAQ-9178 Chassis with NI 9234 Module at 51.2 kHz sampling rate and PCB 352C23 type acceleration sensor. One time period $x(t)$ and its FFT can be seen in Fig. 2a and 2b, respectively. Reconstructed cutting force is plotted in Fig. 2d together with direct force measurement with Kistler dynamometer (9129AA) repeated with the same technological parameters. Note that the difference is in the range of the typical error of force measurement with dynamometers.

4. Conclusions

In this paper, an alternative method is proposed which uses only accelerometer sensor and modal hammer. It is capable to measure the resultant cutting force during milling operations directly from vibration measurements without using expensive dynamometer. The method is based on the followings: the response of the system is captured by acceleration signal, from which the resultant cutting force can be reconstructed by means of the multiplication of the inverse FRF.

The efficiency and accuracy of the proposed methodology were validated experimentally in laboratory environment by means of direct cutting force measurement with dynamometer.

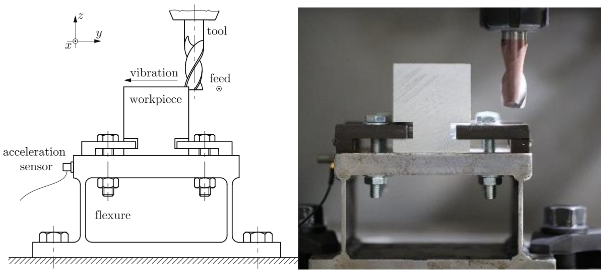

Fig. 1. Schematic figure and experimental setup for milling with single-degree-of-freedom experimental structure [3].

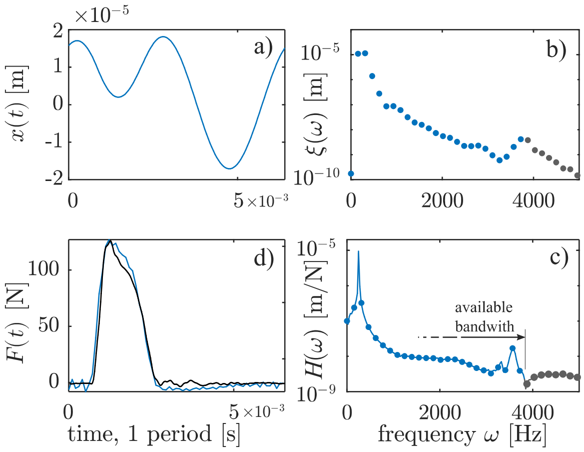

Fig. 2. a) Periodic response during one time period; b) FFT of the periodic response; c) measured FRF (curve) and interpolated values (dots); d) cutting force reconstructed by acceleration sensor (blue) and measured by means of dynamometer (black).

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