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Sustainable Cutting Process for Milling Operation using Disturbance Observer

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Abstract

This paper focuses on design of disturbance force observer for sustainable machining process in milling application. In milling process, cutting force acts directly on work surfaces thus producing external impact on the drives system of the positioning table. This effect must be compensated in order to preserve accuracy and quality of the final product, thus creating a sustainable machining process. Disturbance force observer (DFO) is a type of estimator that estimates precisely the disturbance force with prior knowledge of the cutting force harmonics frequencies. This paper presents both numerical and experimental results of DFO performed on an XYZ positioning milling table using measured cutting force. Four control configurations were considered; PID, cascade P/PI, PID with inverse model based disturbance observer, and PID with DFO. The FFT tracking error analysis showed that a near complete compensation of the disturbance force at identified harmonics frequencies was achieved.

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Keywords: controller; observer; milling process; disturbance compensation; sustainable manufacturing

1. Introduction

Milling process is a common classical removal process used on production of parts in many metal based industries such as automobile, aerospace, and else. The performance of the milling process is affected by the cutting force and the rigidity of the cutting process. Cutting force exists during cutting process in any machine tool application [1]. Cutting forces influence the tools life and quality of the cut. Therefore, there is a need to monitor and compensate for the cutting forces. A study by [2] designated a repetitive controller which is ideal for periodic reference command signal and disturbance input. Another study of [3] attempted on explicit estimation of the cutting force based on the balance of force acting on the system using relative acceleration sensor measurement. A conventional method to obtain the velocity signal is by differentiating position encoder signal. An improvement by [4] had utilized a relative acceleration sensor recognized as Ferraris sensor. The benefit of using this sensor is that the noise amplification observed initially can be excluded. However, the implementation of this sensor is costly. Recently, intelligent control approach such as neural network and fuzzy logic have gain large interest. [5] had implemented the control of cutting force based on artificial neural network for system evolved through learning using controller and identifier. Other researchers had applied fuzzy logic to control and compensate cutting force as shown in [6]. This study developed adaptive fuzzy logic control (AFLC) to control the peak of cutting force. It was reported that the controller was able to maintain the cutting force within the optimal range by controlling the table speed based on predicted cutting force and measured cutting force.

Cutting parameters such as feed rate, depth of cut and cutting speeds are the variables that influence the cutting force characteristics. The characteristic of this cutting force is observed using Fast-Fourier-Transform (FFT) analysis. The analysis of these FFT data allows for the identification of all force components existed on the cutting force. There were also unwanted forces that contribute to positioning inaccuracy due to several causes. One of the causes is current measurement error due to current sensor offset or gain deviation as explained in [7] and [8]. From the analysis, the frequencies

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that contribute to ineffective positioning are determined. Disturbance observer could estimates this unmodeled dynamics including internal and external disturbance to the controlled system. An observer algorithm is often embedded into the system to estimate and compensate the cutting force into desired results.

Inverse model based observer designed by [9] was able to be applied with any types of input disturbance. In order to improve the disturbance rejection, the observer excites a high gain loop to existing control configuration. However, the accuracy of the system model plays importance role toward the bandwidth of the observer and thus affects the performance and stability of the controlled system. Another type of the observer that has been used to estimate external disturbance forces is disturbance force observer (DFO). [6] had introduced this type of observer for estimation of disturbance force such as cutting force in order to improve tracking performance of a system. Disturbance force observer considers sinusoidal disturbance force input and their first and second derivative. This type of observer shows greater potential to remove almost all errors. Others such as [10] had made study on haptic controller for measurement of human hand force. Meanwhile, [11] showed the superiority of the observer in compensating internal and external disturbance force in medical tele-analyzer. [12] had demonstrated the effectiveness of inverse model based observer in compensating cutting force to improve the tracking performance. The literature reviews showed that observer based approach is a reliable method for compensating disturbance such as cutting force especially in tracking application.

The objective of this research is to compensate cutting force in order to improve cutting performance in term of improved tracking accuracy. The organization of this paper is as follows. The following section introduces the experimental setup and described the system identification performed. This section is followed by introduction to the methodology used for cutting force characterization and analysis. Section 3 and 4 explained the design of classical proportional-integral-derivative (PID) controller and the observer (namely DFO and IMBDO). Results and discussion are shown in section 5 meanwhile section 6 concluded the finding of this paper.

1.1. System identification

The equipment used in this research is a Googol XYZ milling table (see Figure 1). This stage consist of three axes and driven by Panasonic MSMD 022G1U A.C. servo motors respectively. An incremental encoder with resolution of 0.0005mm/pulse located at each near end of both axes. Fig 1(b) shows the schematic diagram of overall system. The XYZ milling table is linked to DS1104 DSP board then connected to computer with MATLAB Simulink software for applying control design and data collection. The DSP board is a data acquisition unit for capturing signal exited by the system for analysis purposes.

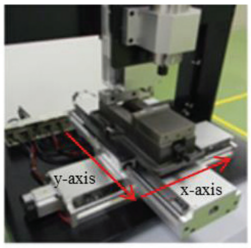

Fig. 1. XYZ ballscrew driven milling table.

The dynamic behaviour of the system was captured using data acquisition equipment (DS1104 DSP). From the single-input single-output (SISO) signal, the Bode diagram of frequency domain format (FRF) is estimated using H1 estimator [13]. A mathematical model is obtained by fitting the parametric model onto the FRF of the system using fdident toolbox in MATLAB Simulink software. Estimated second order model transfer function for the *x*-axis of the XYZ milling table is given in equation (1) and the system parameters are tabulated in Table 1.

$$G(s) = \frac{Z(s)}{U(s)} = \frac{A}{s^2 + Bs + C} e^{-sT_d} \quad (1)$$

Table 1. System parameter of *x*-axis.

Axes	A (mm/Vs^2))	B (s^{-1})	C (s^{-2})	T_d(s)
x-axis	67940	155.1	53.81	0.00129

1.2. Characterization of cutting forces

A straight line milling cutting process was performed on a block of aluminium (Fig 2(a)) with high-speed steel (HSS) cutter of 10mm in diameter. The cutter has four edges with rotational speed of 1000rpm. The cutting parameters are 0.5mm depth of cut and 502mm/min feed rate. The cutting force harmonic components (see Fig 2(b)) explain the characteristic of cutting force during machining. The data of cutting force was extracted using Kistler Dynamometer and frequency harmonic components were obtained using Fast-Fourier-Transform (FFT) analysis.

The analysis showed three distinct peaks that significantly affects tracking accuracy. The identified frequencies were 2.833Hz, 17.33Hz and 35.17Hz. These frequencies contribute to the tracking error. In order to improve tracking accuracy, cutting force at these frequencies need to be compensated. A controller for positioning control is needed for better tracking control meanwhile an observer is required for estimation of cutting data to improve tracking performance of the system.