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Dynamics and Surface Quality Analysis in Robotic Milling

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Industrial robots excel Computerized Numerical Control (CNC) machines in pose dexterity and working range, making them suitable for machining operations of large-format complex workpieces. Stability characteristics of robotic milling need to be studied for milling performances enhancement. In this research, modal analysis is applied to a robot-spindle-tool assembly in order to obtain modal frequency and damping ratio which are two essential parameters for milling stability prediction. The milling stability prediction at three different robot configurations based on regenerative chatter theory is generated using Zeroth Order Approach (ZOA). Validation milling experiments are conducted on 6061 Aluminium alloy at each robot configuration. Vibration signals during milling processes are collected using a three-axial accelerometer and analyzed in the frequency spectrum. Results verify the accuracy of stability prediction, similar to many other existing works. However, most prior work lacks systematic investigation on the milling surface quality. The main contribution of this work lies in the detailed analysis of the milling marks left on workpiece surfaces. A criterion based on the continuity of milling marks is proposed to differentiate chattered surfaces from chatter-free surfaces. If the milling marks are smooth and continuous, the process is chatter-free and the surface quality is acceptable, whereas if the milling marks are rough and broken, the process is chattered and the surface quality is not acceptable. Based on surface roughness measurement, it is observed that chattered surfaces have significantly higher roughness value than chatter-free surfaces which further validates the proposed criteria. Furthermore, this paper establishes a qualitative relationship between the vibration signals during milling process and the after-milling surface quality. It is found that occurrence of chattered milling surfaces is closely related to occurrence of high vibration frequencies above 3500 Hz. The average lengths of broken marks on chattered surfaces are measured in order to calculate the chattering frequencies which are found to be close to vibration frequencies collected by the accelerometer. In other words, quantitative evaluation of frequencies of chattered milling marks further validates the correlation.

1. Introduction

Industrial robots excel in machining flexibility as compared to Computerized Numerical Control (CNC) machines. However, their low structural stiffness leads to easier occurrence of chattering during machining [1]. To analyze the milling performance of robotic machining, the milling stability prediction theory traditionally developed from CNC machines has also been applied to robots in prior work [2]–[4]. As compared to CNC machines, industrial robots have much more complicated structural dynamics due to the multi-link, multi-joint structure. Thus, it is essential to verify the validity of stability prediction theory in robotic machining.

Regenerative chatter is the major type of self-excited vibration that has been extensively studied in CNC milling. The regenerative chatter in milling refers to the interference between the current cutting tooth and the wavy surface created from the previous teeth [5]. The regenerative chatter usually occurs at relatively high frequencies (10^2-10^3 Hz) and is highly affected by the dynamics model of the tool-workpiece system. This work focuses on capturing the regenerative chatter in robotic milling.

Stability lobe diagram (SLD) is an efficient tool to predict the stability of milling processes. In this work, zero-order approach (ZOA) is adopted to generate SLD. Frequency response function (FRF) and cutting force coefficients are two important parameters to obtain accurate SLD. FRF reflects dynamic characterizations of the milling system which can be obtained experimentally by conducting hammer impact tests at cutting tool tip.

In prior work, Mejri et al. [2] demonstrated varied milling stability prediction at different robot configurations. Hao et al. [6] assumed regenerative chatter as the dominant vibration mode in high speed milling. Slotting tests were conducted to validate the accuracy of stability prediction at spindle speeds 13700 rpm, 16700 rpm, and 19000 rpm. Similarly, this work first validates the regenerative chatter theory on robotic milling with experimental results.

In some other prior work, general comments were made to distinguish acceptable and non-acceptable milling surfaces [3], [7], [8]. However, there was no standardized criterion for evaluation of milling surfaces. Hence, besides verifying the theory on robotic milling, this work attempts to establish a criterion to differentiate chattered surfaces from chatter-free surfaces. Furthermore, this work presents a qualitative relationship between vibration in high frequency spectrum and milling surface quality.

The paper is structured in 4 sections. Section 2 includes the methodology of dynamics identification and milling stability prediction. Section 3 presents the results of stability prediction and corresponding validating milling tests with detailed investigation on milling surface quality. Section 4 concludes the work.

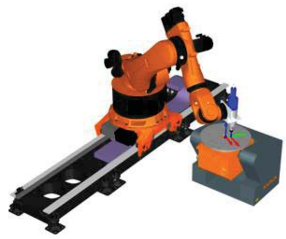
2. Methodology

2.1 Robot-spindle-tool assembly structural dynamics identification

The experimental setup follows a robot-spindle-tool assembly, the robot being 6-axis robot arm KUKA KR500, the spindle being high-speed spindle Jaeger F150-H930.01 K1VW2, the cutting tool being M.A. Ford® TuffCut® GP 2 Flute End Mill 16 mm × 30 mm × 89 mm with a helix angle of 30°. Hammer impact test is conducted at the cutting tool tip in both *X* and *Y* directions w.r.t. the tool frame (Fig. 1). The tool frame follows the end-effector and is parallel to the positioner frame. In this work, the impact force is exerted by a hammer (Dytran, Model:5800B2) at the tool tip. The response is measured by a triaxial accelerometer (Kistler, Model:8763B). The two measurements must be captured with coherent time stamps.

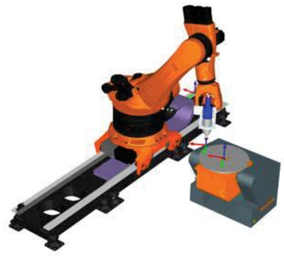
Fig. 1 Hammer impact test setup

The workpiece is mounted onto a dynamometer which is clamped to a rotary positioner next to the robot. Three robot configurations are chosen by rotating the positioning stage about the *Z* axis (Fig. 2).



(a)

(b)



(c)

Fig. 2 Robot configurations (a) C0, (b) C60, (c) C-60.

Modal parameters identified, i.e., modal frequency and damping ratio, are used to reconstruct the receptance FRF, assuming a Single Degree of Freedom (SDoF) system with viscous damping (Eq. (1)).

$$\alpha(\omega) = \frac{X(\omega)}{F(\omega)} = \frac{1}{k - \omega^2 m + j\theta_r\omega_r} = \frac{\omega_r{}^2/k}{\omega_r{}^2 - \omega^2 + j2\theta_r\omega_r\omega} \tag{1}$$

where ω_r is modal frequency and θ_r is damping ratio.

2.2 Stability prediction method

The ZOA was first proposed by Altintas. Y [10]. The key concept is transforming the time-varying dynamic coefficients to time invariant coefficients by using the average component of their Fourier expansion. To achieve critical stability system vibrating at chatter frequency, the second order characteristic equation (Eq. (2)) of the dynamic system is solved to obtain two eigen values as solutions

$$\det|[I] + \Lambda\Phi_0(i\omega_c)| = 0 \tag{2}$$

where $\Phi_0(i\omega_c)$ is the oriented FRF matrix, ω_c is the chatter frequency.

The corresponding critical DOC ($b_{\lim}$) and phase shift of eigenvalues (ψ) are calculated using Eq. (3) and Eq. (4) respectively.

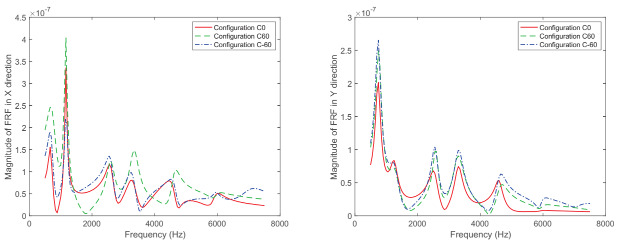
$$b_{lim} = -\frac{2\pi\Lambda_R}{NK_t}\left(1 + \left(\frac{\Lambda_I}{\Lambda_R}\right)^2\right) \tag{3}$$

$$\frac{\Lambda_I}{\Lambda_R} = \tan\psi = \frac{\cos(\omega_c\frac{T}{2})}{\sin(\omega_c\frac{T}{2})} = \tan[\frac{\pi}{2} - (\omega_c\frac{T}{2})] \tag{4}$$

3. Results

3.1 Hammer impact test

Magnitude of the FRF against frequency is plotted in Fig. 3 to identify the dominant modes. The dominant modes in *X* direction occurs around 1100 Hz, whereas the dominant mode in *Y* direction occurs around 750 Hz.



(a) (b)

Fig. 3 Magnitude of identified FRF against frequency at three robot configurations in (a) *X* direction and (b) *Y* direction.

3.2 Cutting force coefficients identification

Peripheral milling test (Table 1) is conducted on 6061 Aluminum alloy (Rockwell HRB=56). A 3-axial dynamometer (Kistler, Type 9129AA) measures milling forces in the feed and radial directions.

Table 1. Peripheral milling cutting parameters

Number of teeth on the cutter, N_t	Radial cut depth, a_e (mm)	Radial immersion (%)	Axial cut depth, a_p (mm)	Linear feed rate (mm/sec)	Start angle $Ø_s$ (°)	Exit angle $Ø_e$ (°)	Spindle speed (rpm)
2	0.8	5	3	10	0	25.84	8450

Specific cutting force is calculated to be K_s = 2863 N/mm^2, cutting force angle is calculated to be β = 64.9°.

3.3 Stability prediction and validating milling tests

Experimentally obtained FRFs and cutting force coefficients are used to predict the milling stability boundary (Fig. 4). The critical DOC is the lowest point of the boundary. Any cutting parameter pair (spindle speed, axial DOC) above the boundary is predicted as unstable, and vice versa. Configuration C-60 is predicted to be the most stable because it has the highest critical DOC than configurations C0 and C60.

A short and straight milling path along Y direction is chosen to minimize the change in robot configuration. The validating milling tests are conducted with 50% radial immersion in an up-milling mode on 6061 Aluminium alloy. The spindle speed is selected to be 7900 rpm so that the transition from a stable milling to an unstable milling can be observed as the axial DOC increases from 3 mm to 7mm. The same set of milling experiments are repeated at three robot configurations. Detailed process parameters can be found in Table 2.

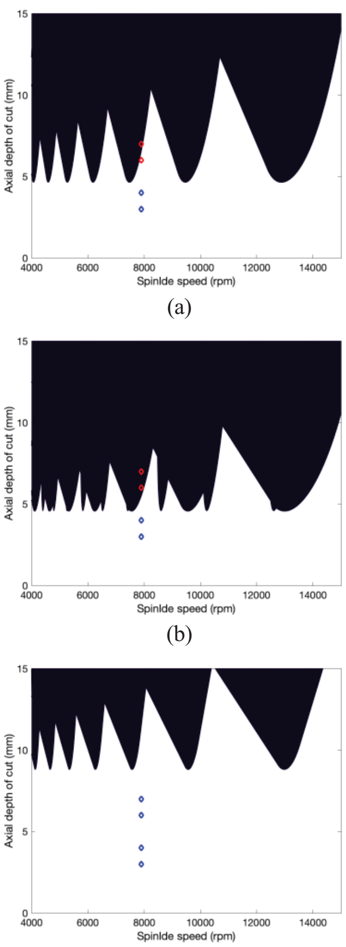


Fig. 4 Stability prediction at spindle speed 7900 rpm at three configurations (a) C0, (b) C60, and (c) C-60.

Table 2. Process parameters in the validating milling tests

Number of teeth on the cutter, N_t	Radial depth, a_e (mm)	Radial immersion (%)	Axial depth, a_p (mm)	Linear feed rate (mm/sec)	Start angle $Ø_s$ (°)	Exit angle $Ø_e$ (°)	Spindle speed (rpm)
2	8	50	3, 4, 6, 7	10	0	90	7900

An accelerometer is mounted on spindle to capture the vibration signal at a sampling frequency of 50 kHz. A milling process is considered unstable if there is dominant chatter frequency around either 750 Hz or 1100 Hz, and vice versa. At configuration C0 and C60, milling process is stable at DOC of 3 mm and 4 mm. When the DOC is 6 mm and 7 mm, chatter frequency around 1008 Hz became observable which indicates that the boundary of the stability has been reached (Fig. 5). In contrast, at configuration C-60, chatter frequency remains non-observable throughout the DOC from 3 mm to 7 mm just as predicted by SLD. Experimental results are marked in Fig. 4. Blue dots indicate stable milling process where chatter frequency is almost unobservable. Red dots indicate unstable milling process where chatter frequency becomes observable. Good agreement between predicted stability and experiments is validated.

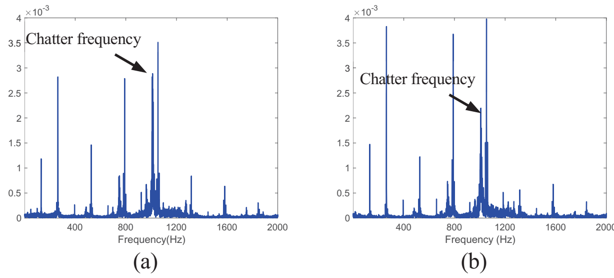


Fig. 5 Vibration data at DOC of 7 mm at robot configuration (a) C0, (b) C60, spindle speed at 7900 rpm, 0 ~ 2000 Hz.

3.4 Milling surface quality analysis

Microscopic images of milling surfaces are taken using Keyence VHX-2000 Digital Microscope coupled with 100X lens. To differentiate chattered surfaces from chatter-free surfaces, a criterion is proposed in this work: If the milling marks are smooth and continuous, the surface is considered chatter-free, whereas if the milling marks are rough and broken, the surface is considered chattered and undesirable.

Based on the proposed criterion, configurations C0 and C60 have chatter-free surfaces at DOC of 3 mm and 4 mm and chattered surface at DOC of 6 mm and 7 mm. Configuration C-60 has chatter-free milling surface only at DOC of 3 mm and chattered surface at DOC of 4 mm, 6 mm and 7 mm (Fig. 6).

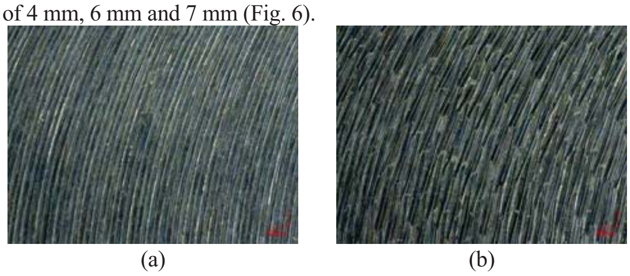


Fig. 6 Milling surface (100X) at configuration C-60, DOC of (a) 3 mm, chatter-free, (b) 4 mm, chattered.

Contradiction against theory arises when regenerative chatter theory predicts configuration C-60 the most stable while milling surface shows the opposite. The contradiction is further supported by surface roughness measurement results (Fig. 7). Surface roughness (Rz) is measured using a stylus profilometer (Taylor Hobson FORM TALYSURF®) along the feed direction of the milling process. A significant increase in surface roughness is observed as the surface quality transits from chatter-free to chattered. At configurations C0 and C60, the transition occurs between axial DOC of 4 mm and 6 mm which confirms the theoretical prediction. However, at configuration C-60, the transition occurs between axial DOC of 3 mm and 4 mm which is much lower than the predicted stability boundary.

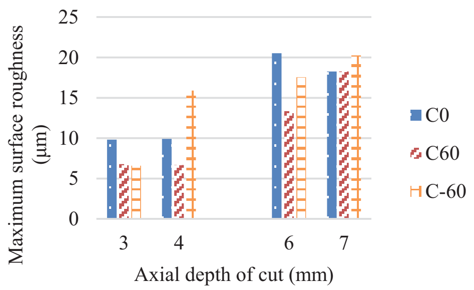


Fig. 7 Surface roughness (Rz) at three robot configurations.

To explain the contradiction, vibration data analysis is expanded to a wider frequency spectrum, i.e., 500 ~ 6000 Hz. Occurrence of dominant frequencies above 3500 Hz are spotted in all milling tests with chattered surface (Fig. 8). These high frequencies are not found in any chatter-free milling processes. Thus, the milling surface quality is believed to be more accurately related to the occurrence of dominant high frequencies above 3500 Hz than the expected chatter frequency around 1008 Hz.

Furthermore, by measuring the lengths of milling marks left on surface (Fig. 9), the frequency of milling marks left by spinning cutter flutes is calculated to lie between 3550 Hz and 4700 Hz. Therefore, it is supported that chattered surfaces can be related to high vibration frequencies above 3500 Hz instead of modal frequencies.

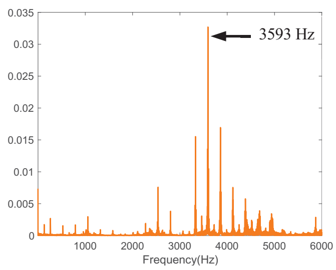


Fig. 8 Vibration data at DOC of (a) 3mm, (b) 7 mm, spindle speed at 7900 rpm, robot configuration C-60, 0 ~ 6000 Hz.

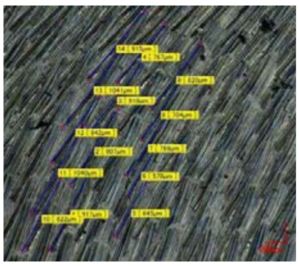


Fig. 9 Milling mark measurement at DOC of 7 mm, configuration C-60.

4. Conclusion

The stability and surface quality of robotic milling were investigated in this research. Half-immersion milling tests were conducted to validate the regenerative chatter theory at various axial DOC. A key contribution of this work is the establishment of a clear criteria in the robotic milling to distinguish chattered milling surfaces from chatter-free ones. The milling surface could categorized as "chattered" or "chatter-free", depending on whether the milling marks on surface were continuous or broken. And a qualitative relationship between occurrence of high vibration frequencies (above 3500 Hz) and milling surface quality. Future research focuses on finding the cause of high-frequency vibration, as well as robot pose and milling parameter optimization for surface quality enhancement.

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