HSM 2019
15th International Conference on High Speed Machining
October 8-9, 2019, Prague, Czech Republic
www.hsm2019.cz

HSM2019-00000

INVESTIGATION OF PROCESS DAMPING IN ROBOTIC MILLING

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Abstract

In robotic milling, at the presence of the low frequency modes, introduced by the robot structure, the process damping effect may not be observed as in CNC milling. So that, high speed machining may be favorable compared to low speed machining for increased chatter-free removal.In this study, the process damping effect is investigated in robotic milling through experimental results. Stability diagrams are compared to the experimental results to highlight the conditions where the flexible dynamics of the robot may hinder process-damped regions. Favourable high-speed machining regions are shown, and conclusions are derived for future research.

Keywords:
Robotic Milling; Process Damping; Milling Dynamics

1 INTRODUCTION

Process damping is observed at relatively low cutting speeds, leading to increased stability limits. In the literature, there are several studies demonstrating the effect of process damping on milling stability in CNC machining, where the machine tool structure is significantly more rigid than the tool holder and tool structure. In such cases, low cutting speed may be favourable than high cutting speeds for increased chatter-free material removal. However, at the presence of significant low frequency modes, the process damping effect may be hindered.

Robotic milling is proposed as an alternative machining method to perform especially roughing operations for large scale metal or composite parts in heavy industries. Up to date, relevant research shows that the low frequency dynamic flexibility of industrial robots introduces high amplitude vibration modes [Verl, 2019], which become dominant especially at low spindle speeds, where process damping arises due to low cutting speeds [Tunc, 2018]. This leads to a contradictory and interesting case for machining strategy and parameter selection for robotic milling applications.

In machining, material removal rate and hence productivity is usually limited to chatter vibrations, leading to poor surface quality, decreased tool and equipment life as emphasized by Tlusty (1983). Thus, accurate prediction of chatter stability limits is of great importance for increased productivity as highlighted by Budak (2006). This stands as even more critical for machining of materials with low machinability such as nickel and titanium alloys, where the cutting speed is inherently bounded. In machining of such materials, axial cutting depth should be increased as much as possible to compensate the reduction of material removal rate (MRR) as summarized in a recent CIRP Keynote paper by Munoa (2016).

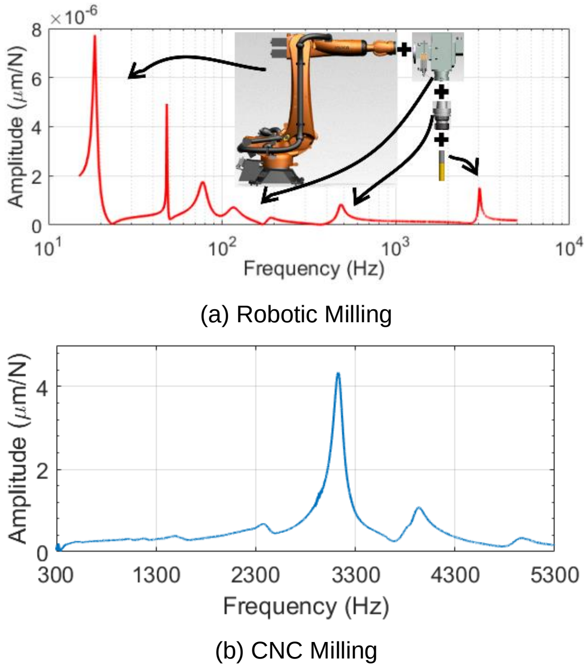
Although the primary source of damping is the loss factor due to the machine tool – spindle – tool holder and tool assembly, the cutting process may be source of significant process damping at low speeds. Sisson and Kegg (1969) were the first pioneers to explain the chatter behavior at low speeds, which was consistent with published experimental observations. They dealt with the forces acting on the cutting edge flank face and concluded that process damping force is function of hone radius and clearance angle in addition to the cutting speed. Tlusty and Ismail (1983) showed that the stability limit increases with decreasing cutting speed due to the cyclic physical contact between the tool flank face and the vibration wave left on the workpice surface. Process damping effect was properly related to the tool indentation to the workpiece, by Wu (1989), where the process damping effect was expressed in terms of the indentation forces arising due to the tool-workpiece indentation. After almost 20 years, this idea was verified by Altintas et al. (2008), by use of a oscillating the tool at a known vibration amplitude, controlled by a piezo actuator. In this way, they calculated the indentation volume for a known vibration amplitude and frequency to relate the vibration information to the amount of process damping through dynamic cutting force coefficients.

Identification of process damping effect has been another challenge throughout the literature. Towards this aim Budak and Tunc (2010) were the first researchers to propose an inverse stability method to identify the average process damping coefficient from experimental stability limits.

Following such an identification approach, Wan et al. (2017) used inverse Fourier transformation to extract the process damping ratio, leading to tangential and radial ploughing force coefficients based on energy balance principle. Although, the proposed model and approach is suitable for extension towards multiple-mode dynamics, in the experimental and simulation study, they considered the effect of process damping on single dominant dynamic mode cases. In the literature, almost all the studies on process damping focused on single dominant mode case, which is usually the cutting tool mode at relatively high frequencies. This assumption may be considered as valid in CNC machining, where the structural modes of the machining system is much more rigid than the cutting tool. However, there may be cases where multi-mode vibration may be observed and process damping effect may be hindered. Towards this direction Tunc et al. (2018) were the first to demonstrate that when there are relatively low frequency modes, process damping effect may be cut down by the low frequency mode. This is basically because the process damping does not only depend on cutting speed but also the vibration frequency. It was shown that although the tool mode is suppressed with the effect of process damping at low cutting speeds, the lower frequency mode is excited as cutting depth is increased. This leads to a point where the stability limit does not further increase.

Robotic milling is a typical case for machining dynamics, where low frequency modes demonstrate vibration amplitudes even higher than the high frequency modes. Therefore, as the process damping effect is concerned, the contribution of every significant mode should be considered. Such a discussion is useful especially in selection of machining strategy and parameters in for robotic milling technology.

Structural dynamics contributed by industrial robots to machining dynamics was first experimentally demonstrated by Pan et al. (2006) through comparison of robotic milling and CNC milling. The excessive vibrations due to the robot modes were emphasized. Later, Zaghbani et al. (2013) studied the vibration response of robotic machining systems based on vibration and cutting forces as the stability criterion. The significance of low frequency modes on stability of robotic milling was emphasized by Tunc and Shaw (2016). It was shown that the low frequency modes may significantly affect the range and shape of the high frequency modes contributed by the tool body. As a result, the asymmetrical tool tip dynamics and hence feed direction effect was discussed. Building on top of these research on robotic milling, it is seen that robotic milling is a case where low and high frequency modes interact almost at the same amplitudes. In this study, the effects of such low frequency modes on process-damped stability is discussed through experimental results. Process damping effect is a function of the wavelength of the vibration, i.e. the ratio of the cutting speed and the chatter frequency. In this regard, even at the same cutting speed if the chatter frequency is low, process damping effect may not be observed due to almost not interaction between the cutting tool and the undulations left on the workpiece. Supporting this idea, the experimental results show that although the tool modes are process-damped at low cutting speeds the robot modes start to be excited as the cutting speed is decreased, which cannot be suppressed to the lack of process damping at such frequency range. Henceforth the manuscript is organized as follows; Section 2 describes stability analysis, this is followed by dynamics of robotic milling to clearly express the multi-mode interaction. The experimental results are given and shown in Section 4 and conclusions are derived.



(a) Robotic Milling

(b) CNC Milling

Fig. 1: Comparison of Robotic milling and CNC milling

2 DYNAMICS OF ROBOTIC MILLING

The dynamic response at the tool tip is coupled function of the robot structure, spindle, tool holder and the tool body as shown in Fig. 1a. In this coupling, there two important points with regards to robotic milling (i) the amplitude of low frequency modes, (ii) the varying dynamic response of the robot, which are discussed through in this section.

2.1 Modal contributions in robotic milling

As the modal contributions at the tool tip dynamics are concerned, the robot structure introduces highly flexible low frequency modes as shown in Fig. 1. In this example, the amplitude of the modes (around 15Hz and 40 Hz) due to the robot are significantly higher than that of the tool (around 3000 Hz). Another important issue in robotic milling is the variation of dynamic response with the robot position and configuration. Thus, even if the dynamics of spindle, tool holder and tool stay the same as the lower frequency modes are changing, under some cases, the tool tip FRF is affected both at the low and high frequency ranges.

Almost all of the process damping analysis is performed for CNC milling, where the modal contributions at low frequencies are significantly much less than that of the tool modes as shown in Fig. 1b, where only one clear dominant mode is seen around 3000 Hz.

As both cases are compared, the low frequency modes in robotic milling would interfere with the process-damped stability limits and hinder the potential benefits to be achieved by process damping. Having discussed the modal contributions in robotic milling, the next section discusses the stability prediction in multi-mode systems with the effect of process damping.

3 STABILITY OF MULTI-MODE SYSTEMS

This section briefly presents the stability of multi-mode milling systems under the effect of process damping. Stability analysis are performed in frequency domain, where the process damping coefficients are accounted by updating the frequency response function (FRF) through modal parameters.

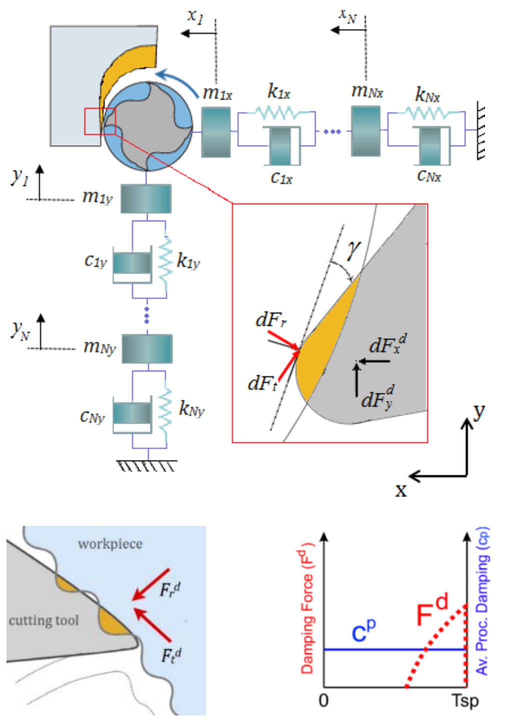


Fig. 2: Process damping effect in milling (a) Multi-mode milling (b) tool – workpiece interaction (c) Damping energy balance [Tunc et al. 2018].

The total damping term is introduced as summation of the structural damping and process damping [Budak and Tunc, 2010]. Energy balance analysis is followed to predict the average process damping coefficients as explained in Section 2.1. This is then used in the frequency domain stability analysis to update the effective FRF at the tool tip. So that, process damping is considered in construction of the stability diagrams as discussed in Section 2.2.

3.1 Average process damping coefficient

In dynamic cutting process, the cutting edge vibrates sinusoidally as the tool rotates, leaving undulations on the generated workpiece surface. If the wavelength is short enough to create a steep wave, the tool flank face starts to indent against the wavy surface as it travels down the wave, i.e. positive chip thickness direction, as shown in Fig. 2a. This creates a counter force against the vibration direction, creating a damping effect, namely process damping. The friction coefficient, μ, causes tangential indentation force.

The amount of the indentation forces is expressed in terms of the indentation constant Kd, and the indentation volume, U(t), [Budak and Tunc, 2010] as follows:

$$F_r^d(t) = K^d\, U(t)$$
$$F_t^d(t) = \mu F_r^d(t) \tag{1}$$

The effect of damping forces in Equation (1) is added to the dynamic milling equations of motion by defining the average process damping coefficients, cp, through energy balance analysis. The amount of dissipated energy by the indentation forces over one tool rotation period, Tsp, and by the average process damping coefficients are equated to each other, as illustrated in Fig. 2b.

3.2 Stability diagrams for multi-mode milling systems

The equations of motion for a system with N_m number of modes is written as follows:

$$m_{x,q}\ddot{x} + c_{x,q}^t\dot{x} + k_{x,q}x = F_x;\ c_{x,q}^t = c_{x,q}^s + c_{x,q}^p;$$
$$m_{y,q}\ddot{y} + c_{y,q}^t\dot{y} + k_{y,q}y = F_y;\ c_{y,q}^t = c_{y,q}^s + c_{y,q}^p; \tag{2}$$
$$q = 1,\dots,N_m$$

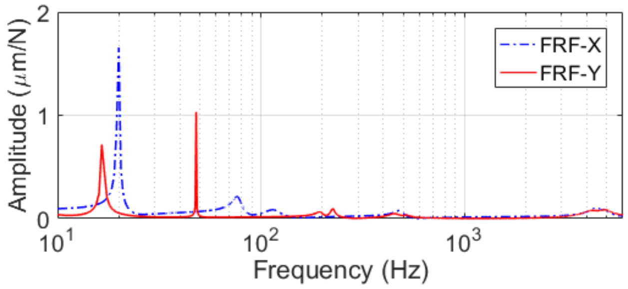


Fig. 3: FRF in X and Y directions measured at the tool tip.

where *m*, *k*, c^s and c^p are the modal mass, stiffness, structural damping and process damping coefficients of the system, respectively.

Stability diagrams for the multi-mode milling system is predicted by constructing stability diagram corresponding to each individual mode in frequency domain [Altintas and Budak, 1999] using the modal parameters given in Equation **Error! Reference source not found.**). The average process damping coefficient, $c_{i,q}^p$, corresponding to each vibration mode, at the corresponding chatter frequency, is simulated and added on top of the relevant structural damping ratio, $c_{i,q}^s$ along direction *i*. Then, the lowest envelope as superposition of individual stability diagrams is taken as the overall stability diagram for the multi-mode milling system.

3.3 Simulation of stability diagrams in robotic milling

The stability diagram for a representative robotic milling case is simulated to provide an understanding about the multi-mode stability analysis with the effect of process damping. The studied case is half immersion, down milling of AL7075 with cutting force coefficients K_{tc}=1600 MPa and K_{rc}=600 MPa at a feed-rate of 0.05 mm/rev per tooth. The tool is a 12-mm diameter end mill with two flutes. The measured FRFs in X and Y directions are given in Fig. 3. The system has two significant low frequency modes at 16 Hz and 48 Hz. Whereas, the amplitude of the mode attributed to the cutting tool is almost 20 times smaller than that of the robot modes. So, if the absolute stability limits are concerned, a factor of 20 would be expected.

3.3.1 Modal analysis

The modal parameters extracted from the measured FRFs are given in Tab. 1. In order to investigate the interaction between the robot modes and the tool modes, Mode 1, Mode 2 and Mode 6 along X direction, Mode 1, Mode 2 and mode 4 along Y direction are taken into consideration in stability diagram simulations.

Tab. 1 : Modal parameters for the case study.

	Mode	fn (Hz)	ζ (%)	k (Mn/m)	m (kg)
X	1*	19.88	0.81	3.65	234.25
	2*	77.17	5.15	5.00	21.28
	3	115.86	8.78	7.12	13.44
	4	482.53	4.06	12.91	1.40
	5*	4850	3.15	4.46	0.048
Y	1*	17.8	1.76	2.31	183.95
	2*	47.3	0.74	33.60	380.25
	3	225	2.24	24.50	12.29
	4*	4170	0.72	2.85	0.01

*modes considered in stability diagram simulations.

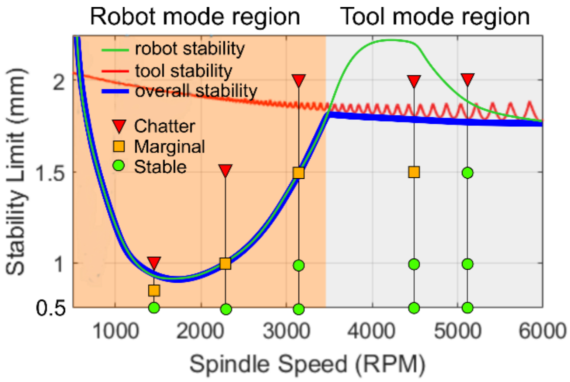


Fig. 4: Stability diagram for the robotic milling system.

3.3.2 Stability diagrams

In the representative case study, the feed direction is selected along Y-axis of the cartesian coordinates. The stability simulated stability diagram is given in Fig. 4. There are three curves representing stability limits, tool mode, robot mode and the common stability, where the stability diagram is divided into two in terms of the active mode. The tool mode tends to be suppressed with the effect of process damping after a spindle speed range of 3500 rpm. However, the robot modes become active and hinder the process damped stability region. It is observed that the region from 1000 rpm to 3000 rpm demonstrates significantly low stability. The stability limit gap between the process damped tool stability and robot mode stability is more than 100%. Consequently, it can be said that compromising stability at low cutting speeds is not possible in robotic milling as opposed to the case in CNC milling.

4 EXPERIMENTAL RESULTS

The theoretical simulations given in Section 3 are verified by experimental results as discussed in this section. Although aluminium is known to be its good machinability at high speeds, the tests are performed on AL7075 material as being easy to obtain in terms of costs.

4.1 Experimental setup and test conditions

The cutting tests were conducted on a robotic milling system composed of KUKA KR270 R2900 industrial robot (see Fig. 5) having a 15 kW spindle, which can run at 22000 rpm max. The vibration was measured by an accelerometer and LEICA AT960 laser tracker, where a spherical measurement reflector (SMR) was attached on the spindle.

The cutting tests were performed to verify the high cutting speed stability, where process damping effect is negligible. Then, the cutting speed was gradually decreased until 1660 rpm to demonstrate the transition from the tool mode dominant region to the robot mode dominant region. In the tests, 12 mm diameter end mill with 2 flutes were used at a feed rate of 0.05 mm/rev per tooth at slot milling condition. The feed direction was selected as the Y axis of the cartesian workpiece coordinates system (see Fig. 5). The cutting tests are marked on Fig. 4 and given in Tab. 2.

Tab. 2 : Cutting test conditions

Spindle speed (rpm)	Cutting Depth (mm)	Dominant Mode	Process Damping Effect
1660	[0.25, 0.5, 0.75, 1]	Robot	3.65
2300	[0.25, 0.5, 1, 1.5]	Robot	5.00
3210	[0.5, 1, 1.5, 2]	Tool	33.60
4490	[0.5, 1, 1.5, 2]	Tool	24.50
5300	[0.5, 1, 1.5, 2]	Tool	2.85

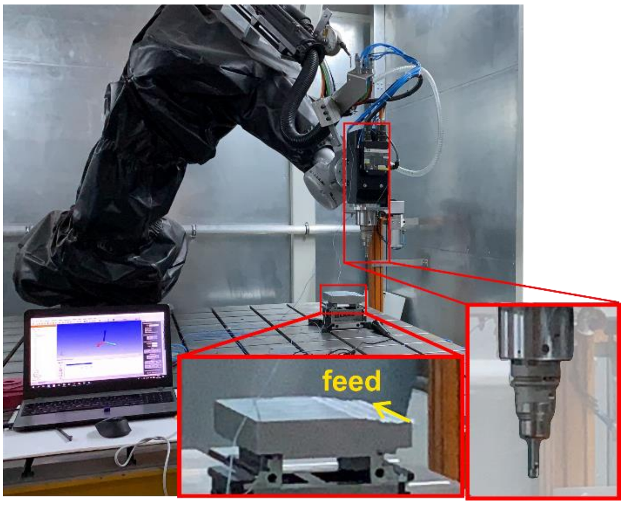


Fig. 5: Experimental setup.

4.2 Results and discussion

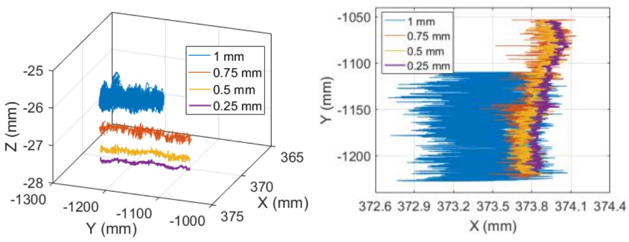
In this section, the experimental results are presented and discussed based on the vibration measurements, i.e. accelerometer and laser tracker. The results are discussed based on the below points

- The accuracy of the stability predictions at both regions, i.e. robot dominant and tool dominant.
- The transition of the active vibration frequencies as the spindle speed is decreased.
- The variation of vibration amplitude as the active mode varies from the tool to the robot.

4.2.1 Displacement measurement by laser tracker.

The laser tracker measurements provide the direct dynamic displacement of the spindle attached on the robotic arm. In Fig. 4, it is seen that the predicted stability limits are governed by a large stability pocket, which is attributed to the robot vibration mode, until 3000 rpm. Then, as the excitation frequency passes by the robot modes, the tool mode tends to govern stability as evident from that the stability lobes become narrower.

The measurements taken from the laser tracker are evaluated based on the vibration amplitude in order to judge stability of the test. A representative laser tracker measurement is shown in Fig. 6, where four cutting tests at 1660 rpm are plotted and cutting depth values of 0.25mm, 0.5mm, 0.75mm and 1mm. In Fig. 6a, the 3D view of the displacement is given. It is clearly seen that vibration amplitudes are almost at the same level for cutting depth values of 0.25mm, 0.5mm and 0.75mm. However, as the cutting depth is increased to 1mm, i.e. the onset of stability (see Fig. 4) the vibration amplitude significantly shifts up. The 2D plot in In Fig. 6b, gives a clear comparison among these cutting depth values. So, it can be concluded that the stability predictions agree well with the experimental results. The comparison of vibration amplitude for all the other spindle speeds is shown in Fig. 7.



(a) 3D plot (b) 2D plot

Fig. 6: Laser tracker measurement at 1660 rpm.

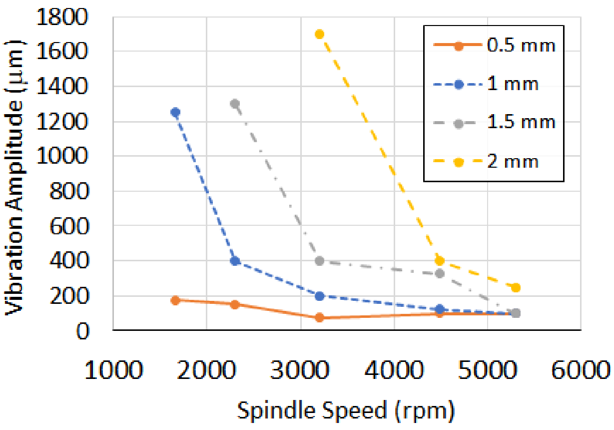
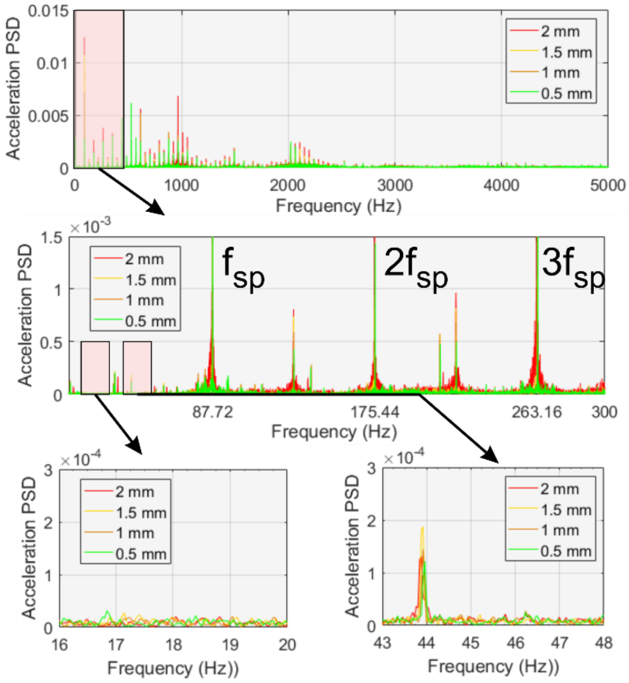


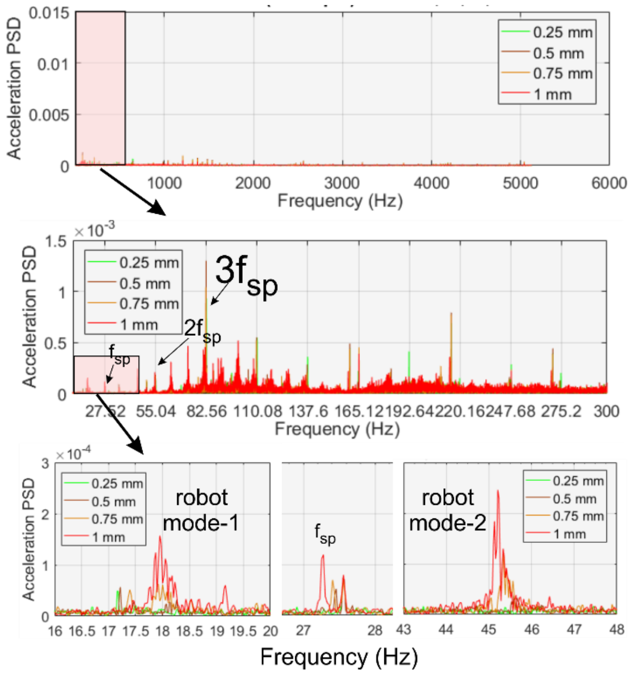
Fig. 7: Variation of vibration x-y amplitude.

As the vibration amplitude at other spindle speeds are reviewed, it is clearly evident that the vibration amplitude at the same level of cutting depths are increasing as the spindle speed is decreasing, which is most probably due to the active mode shifting from the tool mode to the robot mode. For instance, at 1.5mm of cut depth, vibration amplitude of 300 microns and 100 microns were observed at spindle speeds of 4490 rpm and 5300 rpm, respectively. However, 1.5mm of cutting depth leads to 400 and 1300 microns of vibration amplitude at 3210 rpm and 2300 rpm, respectively.

The shift of the active mode can be clearly identified as the frequency content of the vibration is investigated as given for 5300 rpm and 1660 rpm in Fig. 8a and Fig. 8b, respectively. At 5300 rpm, the spindle rotational frequency is around 87.72 Hz. Although the higher frequency (beyond 3000 Hz) content could not be caught by the low frequency accelerometer, the FFT plot in Fig. 8a shows relatively significant high frequency content in the measured acceleration. As the lower frequency ranges are focused, the vibration signal does not have any peaks around 17 Hz, which is the first mode of the robot. However, there is almost the same amplitude content around 44 Hz, which is the second mode of the robot. Nonetheless, the contribution from the 44 Hz mode is much less than the spindle rotational frequency at 87.72 Hz. Thus, this may be classified as a forced vibration.



(a) 5300 rpm



(b) 1660 rpm

Fig. 8: Frequency plot of acceleration in feed (Y) direction.

As the accelerometer's frequency content at 1660 rpm is investigated, at first it can be observed that the high frequency content is significantly suppressed at all cutting depth values. As the lower frequency range is focused both mode 1 and mode 2 of the robots contributes a significant content when the cutting depth is increased toward 0.75 and 1 mm. It is noteworthy to state that the amplitude of the robot mode contribution is higher than the spindle rotational frequency, which can be considered as chatter vibration.

5 SUMMARY

In this study, the effect of robot modes on the process damped stable regions in end milling processes was investigated through simulations and experimental results. The simulations showed that although the robot modes are relatively damped at low cutting speeds, the contribution of the robot modes leads to decreased expected stability limit. Then, the simulations are verified by controlled cutting experiments, where spindle speeds on the stability diagram are selected to demonstrate the effect of robot modes. Considering both the laser tracker and accelerometer measurements, it can be said that the end milling process demonstrates relatively higher stability at higher spindle speeds, which would be expected to increase at lower spindle speeds with the effect of process damping. However, as high flexibility modes of the robot are introduced, the process damped regions are hindered, leading to low stability.

This study contributes to understanding of chatter mechanism in robotic milling, as well. It was shown that, regenerative chatter theory still works well even at low frequency modes in robotic milling.

Another important conclusions of this study would support the high rotational speed applications of robotic milling rather than low rotational speeds in order not the excite the robot modes, for increased milling stability.

6 ACKNOWLEDGMENTS

The authors gratefully acknowledge the support of TUBITAK under grand number 217M078.

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