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Investigation of chatter detection with sensor-integrated tool holders based on strain measurement

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Abstract

Machining chatter is one of the most critical issues that restrict the productivity in milling of thin wall workpieces. Sensor-integrated tool/tool holders, which provide data collection during cutting, can be employed for online chatter detection. Recently, there has been an increasing number of strain-measurement-based smart tool holders, which can measure bending moments and/or torque. Although accelerometer-integrated tool holders have been tested, sensor-integrated tool holders based on strain measurement have not been evaluated for the chatter detection in milling. This paper investigates the potential of chatter avoidance using a commercial sensor-integrated tool holder based on strain measurement.

Keywords: Monitoring; Chatter; Milling; Vibration

1. Introduction

Chatter is one of the most important issues that have to be avoided for high productivity in machining operations. The present of chatter can result in damage to the tool or surface integrity of the part. It is possible to avoid chatter by applying offline or online techniques. Offline techniques are mostly based on the stability prediction and setting parameter (e.g., spindle speed, depth of cut, helix angle) according to the stability prediction [1]. However, stability prediction requires system identification such as modal parameters obtained via impulse test [2]. This requires equipment and expert knowledge in this subject. Moreover, the material removal and/or moving parts of the machine can affect the dynamic behaviour of the system leading to inaccuracy in chatter prediction.

Online chatter detection methods are mostly based on the onset chatter detection in real time. Once the chatter is detected, it can be avoided by applying chatter avoidance techniques [3–6]. Smith and Delio [4] adjusted spindle speed by matching the dominant frequency to the tooth passing frequency. Bediaga et al. [6] developed a spindle speed selection algorithm based on the detection chatter and the lobe number where the cutting is conducted. They experimentally proved the effectiveness of the proposed algorithm by using a built-in microphone for chatter detection. Accelerometers and dynamometers as well as microphones have been mostly used for chatter detection [7, 8]. Kuljanic et al. [9] investigated different sensors for chatter detection performance in milling operations. They indicated that a multisensor system consisting of an axial force sensor and accelerometer provided the best performance. The axial cutting force in their experiments was measured with a rotating dynamometer. Both rotating [10] and plate-type dynamometers [11] have been effectively employed for chatter detection.

Monitoring cutting forces for not only chatter but also other factors in machining operations such as tool wear condition and surface integrity has become very important to maximise productivity and work quality. Cutting forces can be used not only for process monitoring but also for decision-making regarding the machining performance. Therefore, there is an increasing number of studies focusing on the sensor-integrated tool and tool holders for measuring cutting forces. Xie et al. [12] incorporated six capacitive sensors into a standard tool holder to measure triaxial cutting forces and torque for milling and drilling operations. In a different study [13], the authors integrated a MEMS accelerometer as well as capacitive sensors to include the acceleration for tool condition monitoring. Luo et al. [14] developed an indexable tool embedded thin film sensors under each insert. This enabled the cutting forces in three directions to be measured for tool condition monitoring. In order to reduce manufacturing costs, low-cost strain gauges have been extensively utilised for force/torque measurement in tool hold-

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ers. Qin et al. [15] developed a tool holder using semiconductor strain gauges to measure axial cutting force and torque during milling operations. They suggested that the tool holder can potential be used for chatter detection and tool wear monitoring. Recently, Zhang et al. [16] utilised semiconductor strain gauges to develop a sensory tool holder for cutting forces and torque measurements. In addition to the use of strain gauges for cutting forces and torque measurement, Rizal et al. [17] integrated an accelerometer and a thermocouple into the tool holder and tool for real time condition monitoring in milling operations.

Although accelerometer-integrated tool holders have been evaluated to improve chatter performances [18, 19], investigation for the use of sensor-integrated tool holders based on strain measurement for chatter detection has received very limited attention. Suprock et al. [20] proposed using the torque data collected from a sensor-integrated tool holder instrumented by strain gauges for chatter frequency prediction. However, they only considered the torque data in their work. To the authors' knowledge, the evaluation of cutting forces measured by the strain gauges integrated into a tool holder for chatter detection has not been investigated. In this paper, a commercial sensory tool holder, SPIKE [21], which uses strain gauges to monitor bending moments, axial force, and torsion, will be evaluated for chatter detection. The bending moments measured by SPIKE provide the radial cutting forces scaled by a constant. Thus, the bending moments will be directly used for the representation of the radial cutting forces. The obtained signals from the sensory tool holders will be evaluated in the frequency domain for the chatter detection.

The rest of the paper is organised as follows. Section 2 introduces the theoretical model for prediction of stability in milling operations. The experimental setup and the procedure are explained in Section 3. Section 4 presents the results and discussion. Finally, a conclusion is drawn in Section 5.

2. Theory for milling stability prediction

Milling stability can be predicted applying different methods such as the zero-order approach [22], the temporal finite element analysis [23], semi-discretization method [24], and multi-frequency approach [25]. Among them, the zero-order approach is applied in this paper since it provides an accurate prediction for cuts with high immersion as in this study. The depth of cut for the stability limit is defined as [22]:

$$a_{lim} = -\frac{2\pi}{N_t K_t}\Lambda_{Re}\left(1+\left(\frac{sin\left(\omega_c\tau\right)}{1-cos\left(\omega_c\tau\right)}\right)^2\right) \quad (1)$$

where N_t, K_t, and τ are the number of flutes, the tangential milling force coefficient, and the tooth period, respectively. Λ_{Re} and ω_c are the real part of the eigenvalues and the chatter frequency which are the functions of the frequency response function of the milling system. The details for τ, Λ, and ω_c are given in ref [22]. Experimental results will be collected in Section 3 and stability prediction obtained by using Eq. 1 will be presented in Section 4 together with the experimental results.

3. Experimental setup and procedure

The milling setup consisting of an end mill cutter and Aluminium workpiece, as shown in Fig. 1, was used for the evaluation of the chatter detection performance. A 3 flutes solid carbide end mill with 12 mm diameter and overhang of 120 mm was employed so that the cutting tool was the most flexible part in the milling system. A SPIKE sensory tool holder capable of measuring tool bending moments at 2.5 kHz sampling rate was used. This represents common scenarios in machining of aerospace components using long and slender cutting tools. An Al6061-T6 aluminium alloy workpiece with the dimension of $100 \times 50 \times 30$ mm^3 was rigidly clamped to the worktable. Two accelerometers attached on the workpiece (Dytran 3263A2) and the spindle housing (Monitron MTN/1020), and a microphone were also utilised for the comparison of the chatter detection performance. The data from the accelerometers and the microphone were collected by NI 9775 data acquisition system with 20 kHz sampling rate, whereas the sampling rate for the sensory tool holder was 2.5 kHz. The chatter frequency due to the cutting tool system is generally higher than can be detected with this sampling unless a large tool overhang is used. However, chatter frequencies in this range is common for flexible workpiece milling. The setup with a long overhang reflects the same dynamics as one for a flexible workpiece, which is sometimes the case in the common machining scenario.

All experiments were performed on a XYZ machining center with a 13 kW spindle. An impulse hammer test was performed to the tool tip installed on the spindle. The first natural frequencies and the damping ratios in x and y directions were identified as 608 Hz and 613 Hz, and 0.011 and 0.016, respectively. Stability lobe diagram was created for Al6061-T6 aluminium alloy and the milling parameters in Table 1 by using Eq. 1 for the milling system as shown in Fig. 1. Following this, milling experiments were carried in dry cutting and a cut length of 100 mm by removing the material from the long side of the workpiece in each cut.

Table 1. Tool geometries and cutting parameters.

Milling parameters	
Tool diameter	12 mm
Tool overhang	120 mm
Tool helix angle	30°
Feed per tooth	0.05 mm
Flute number	3
Milling type	Down milling
Radial depth of cut	6 mm (Half immersion)

The sensory tool holder provides the bending moments (BMs) in both $x-$ and $y-$directions, which can be turned into cutting forces by considering the lever arm length (distance from the strain gauges on the tool holder and the tip of the tool) as well as the torsion and the axial force. Therefore, four different signals collected from the sensory tool holder. In addition the accelerometers and microphone signals were evaluated for chatter detection. Experiments were conducted for four differ-

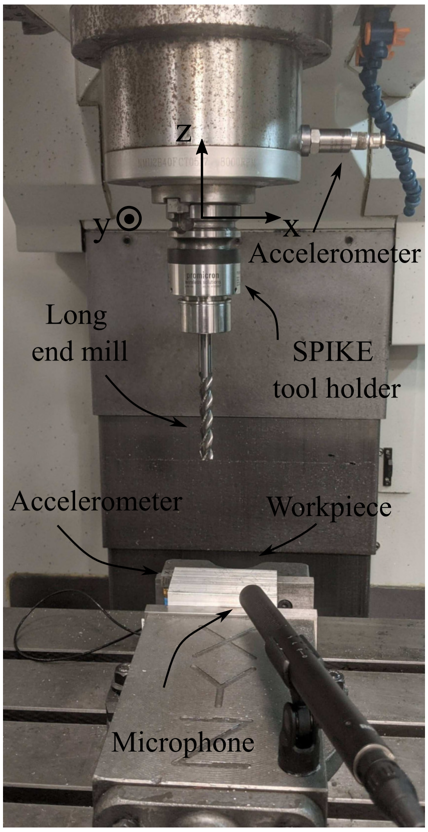

Fig. 1. Experimental setup consisting of a long end mill, an Aluminium workpiece, a sensory tool holder, two accelerometers, and a microphone.

ent spindle speeds and increasing axial depth of cut until chatter onset was detected from one of the sensors (the sensory tool holder, accelerometers, or microphone). Following this procedure, the sets of experiments in this study are presented in Table 2.

Table 2. Experimental sets

Spindle speed (N)	Axial depth of cut (a_p)
2400 (rpm)	0.05, 0.1, 0.2, 0.3, 0.4, 0.6, 1 (mm)
3250 (rpm)	0.05, 0.1, 0.2, 0.3, 0.4, 0.6 (mm)
4400 (rpm)	0.05, 0.1, 0.5 (mm)
5500 (rpm)	0.05, 0.1, 0.2, 0.3, 0.5 (mm)

It is well known that in the case of chatter, the chatter frequency dominates the frequency spectrum. Chatter detection was realised by observing the frequency spectrum after each cut was completed. The frequency spectrum was obtained by applying the Fast Fourier Transform (FFT). Chatter was observed by checking the peaks in the frequency spectrum whether they are different from the spindle and tooth passing frequency, and/or their harmonics.

4. Results and Discussion

Experimental results with the predicted stability limits are given in Fig. 2. Each cut conducted was marked as stable, marginal, or chatter by analysing the data collected from the accelerometers and the microphone. For chatter cases, the data collected by sensory tool holder were evaluated for the use in chatter detection.

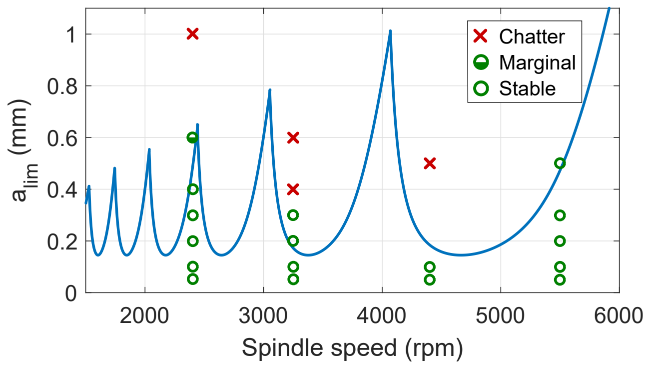

Fig. 2. Predicted stability lobe diagram (blue line) and experimental cuts

The lowest axial depth of cut (a_p) for four spindle speeds in Table 2 resulted in a stable cutting condition. The axial depth of cuts were increased until chatter occurred. In order to eliminate the noise streaming from the sensory tool holder, air cutting was conducted for each spindle speed. Fig. 3 shows the frequency spectrum of the air cutting at 2400 rpm. The spindle frequency and its harmonics in the figure are indicated with a dash line. It was found that the sensory tool holder has noises at frequencies of 357.1 Hz and 714.2 Hz (as demonstrated with diamond in the figure) for all four channels. Other air cutting tests showed that these noises were independent of the spindle speed. They were constant for each spindle speed tested. Rotation of the tool holder can be seen from the peak close to the first spindle frequency.

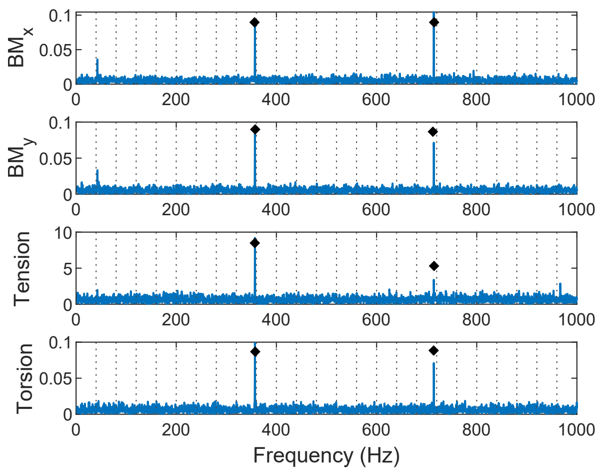

Fig. 3. Frequency spectrum for the bending moments (x and y), tension, and torsion for air cut at 2400 rpm, where the diamond marks indicate the noise frequencies.

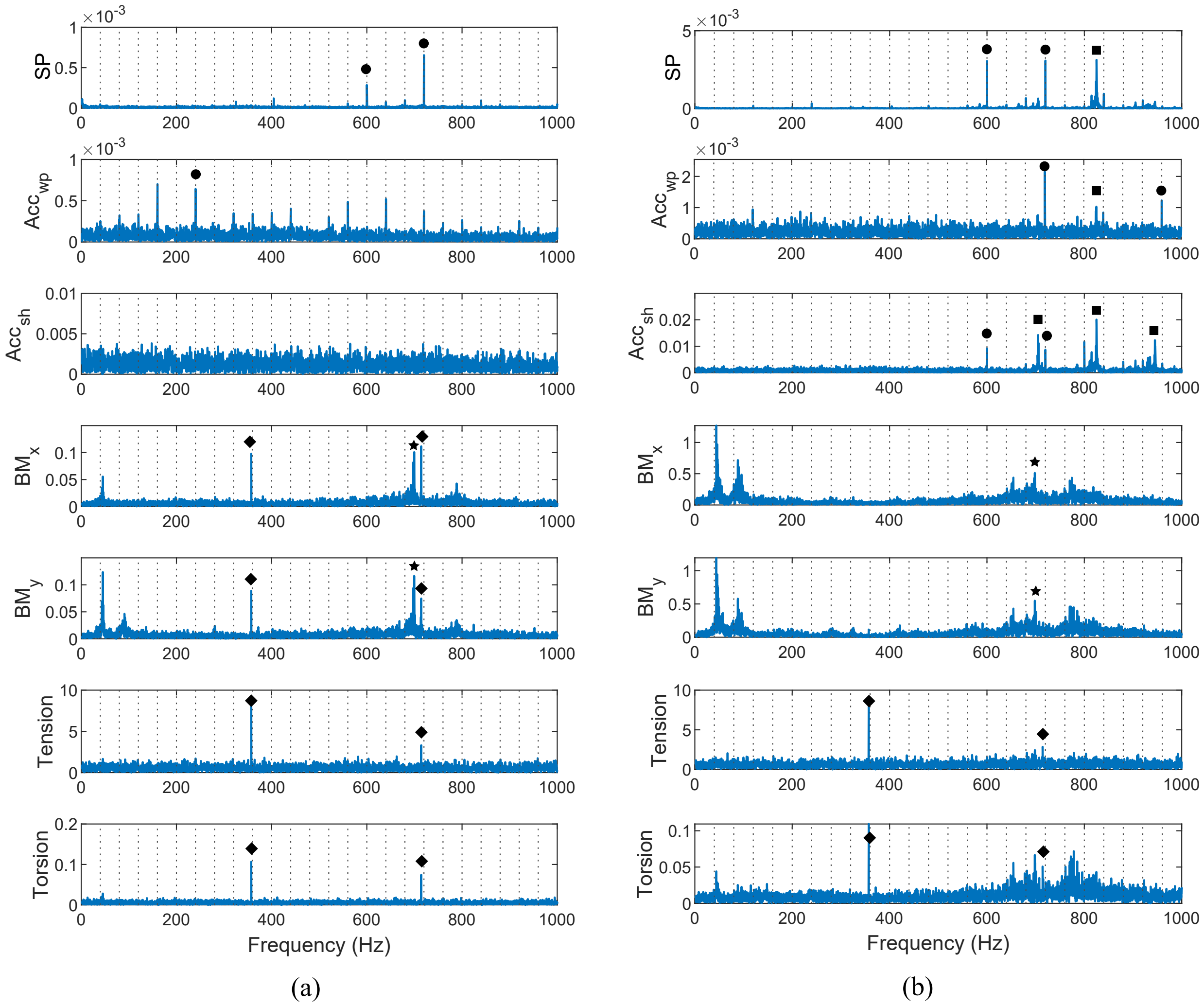

Fig. 4. Frequency spectrum for the sound pressure (Mic), acceleration signals from the workpiece (Acc_{wp}) and the spindle housing (Acc_{sh}), the bending moments, tension, and torsion for (a) a stable cut (N = 2400 rpm and a_p = 0.05 mm) and chatter (N = 2400 rpm and a_p = 1 mm). The dash lines indicate the spindle frequency and its harmonics. The circle, square, diamond,and star signs shows the tooth passing frequency or its harmonics, chatter frequencies, noises existing in the air cutting, and noises occurring in the cut, respectively.

Starting from 0.05 mm, the axial depth of cut was increased to 1 mm. The frequency spectrums for the sound pressure (SP), the accelerations by the accelerometers on the workpiece (Acc_{wp}) and on spindle housing (Acc_{sh}), the bending moments (BM_x and BM_y), tension, and torsion are presented in Fig. 4(a) and (b) for both stable cut (N = 2400 rpm, a_p = 0.05 mm) and chatter (N = 2400 rpm, a_p = 1 mm), respectively. In stable cut, the sound pressure is dominated by the tooth passing frequencies (as indicated by a circle in the figure) while the acceleration signal obtained from the accelerometer on the workpiece shows frequency contents related to the spindle frequency, the tooth passing frequency and their harmonics. The accelerometer on the spindle housing presents no peak in the frequency domain as the axial depth of cut was very small to generate enough acceleration on the rigid spindle housing. For the signals monitored via the small tool holder, another peak differently from ones seen in the air cut (as marked with a star sign in the figure) is observed at 699.5 Hz. Although the frequency is not exactly the same, similar peaks with smaller amplitudes in a frequency range between 700 Hz and 760 Hz were detected for stable cuts at spindle speeds of 3250 rpm, 4400 rpm, and 5500 rpm. It is also worth noting that the first harmonics in the bending moments' frequency spectrum do not exactly match with the spindle frequency. The reason for this could be that the output signals from the sensory tool holder are filtered and post processed as it is a commercial product. Another reason could be the missing data points due to the wireless transmission during the cut. One of these could lead to the frequencies shifted. The peak seen at 699.5 Hz could be the harmonic of that shifted spindle frequency or tooth passing frequency.

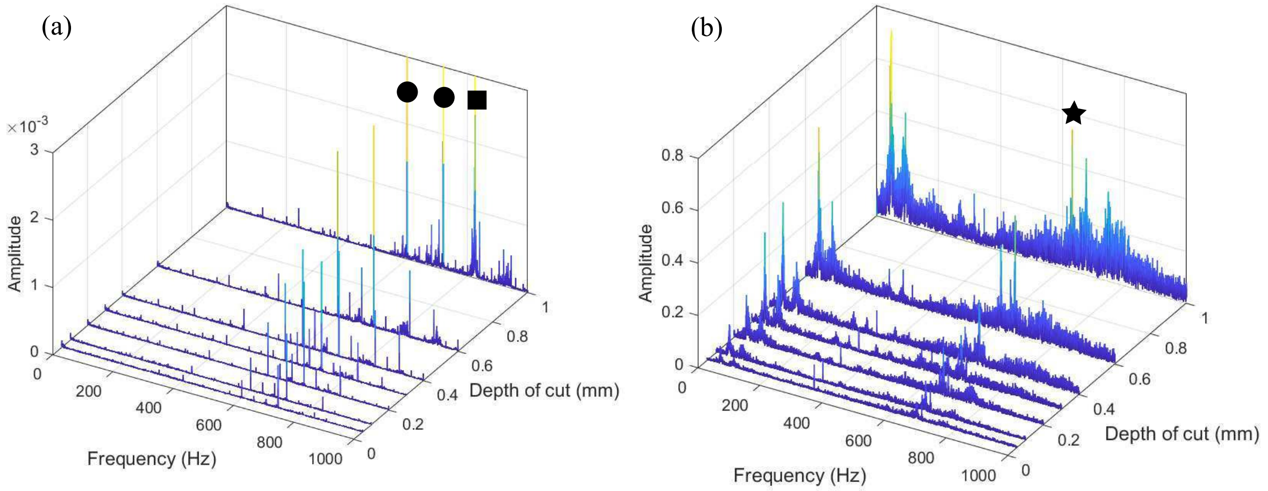

Fig. 5. Frequency spectrum given for all depth of cuts tested at 2400 rpm: (a) the sound pressure and (b) the bending moment in *y*− direction. The circle, square, and star signs demonstrate the tooth passing frequency or its harmonics, chatter frequencies, and noises occurring in the cut, respectively.

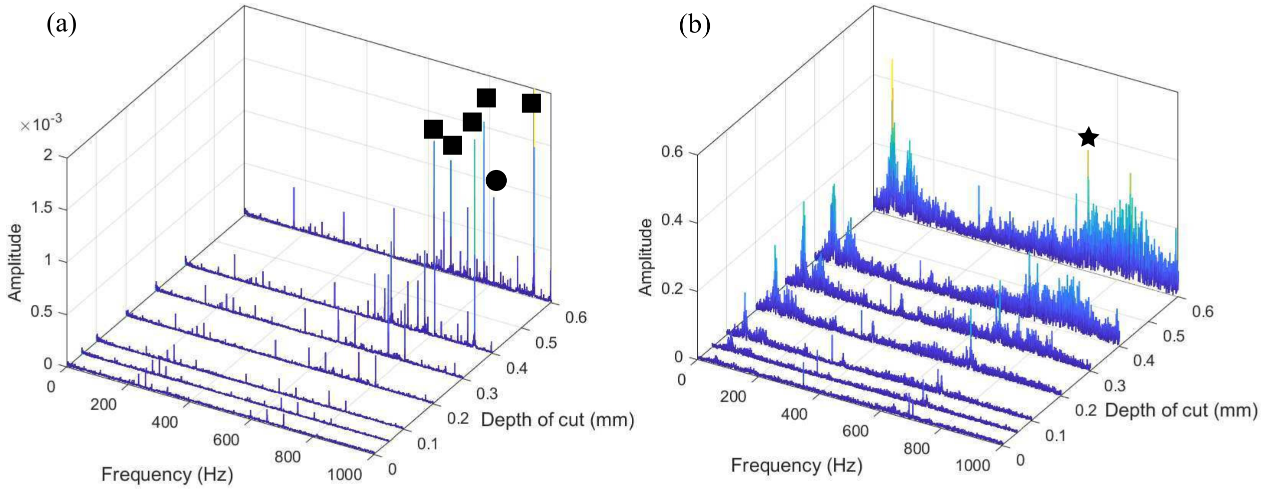

Fig. 6. Frequency spectrum given for all depth of cuts tested at 3250 rpm: (a) the sound pressure and (b) the bending moment in *y*− direction. The circle, square, and star signs demonstrate the tooth passing frequency or its harmonics, chatter frequencies, and noises occurring in the cut, respectively.

In the case of chatter, acceleration signals and sound pressure are dominated by the chatter frequencies (as indicated with a square mark) in the frequency domain as shown in Fig. 4(b). This can be clearly seen from accelerometer on the spindle housing and the microphone. However, none of the signals from the sensory tool holder dominates the frequency spectrum. For the bending moment signals, even though there is an increase in the amplitudes at higher harmonics, the most dominant peaks are still the ones close to the first and second harmonics of the spindle frequency. There is almost no change in the tension signal (which indicates the axial force). Similar to the bending moments, there is an increase in the amplitudes at higher frequencies around 800 Hz for the torsion. However, it does not show a clear chatter peak as in the sound pressure and the acceleration signals.

Frequency responses for all depth of cuts considered in this study for 2400 rpm and 3250 rpm are presented in Fig. 5 and Fig. 6. Fig. 5(a) and Fig. 6(a) indicate the frequency spectrum of the sound pressure signal and Fig. 5(b) and Fig. 6(b) presents the frequency spectrum of the bending moment signal in *y*− direction. Similar to results in Fig. 4, the onset chatter can be detected via discrete chatter frequencies dominating the response in the case of sound pressure signal. However, bending moment signal shows only an increase in the amplitude in higher frequencies and the most dominant frequency still occurs around the spindle frequency.

Having evaluated the results presented above, it seems that chatter detection using a sensor-integrated tool holder based on strain measurement is possible by monitoring the amplitudes at higher harmonics. However, chatter detection is not as straightforward as it is with a microphone or an accelerometer where distinct chatter frequencies are observed. Considering other parameters such as progressive tool wear, which leads to an increase in the amplitude at higher harmonics, the chatter detection process becomes more complicated. Furthermore, detection of chatter using the distinct chatter frequencies allows utilising easy-to-implement chatter avoidance techniques where the spindle speed is set to the chatter frequency detected [3, 4]. A sensor-integrated tool with the capability of detecting chatter frequency as well as the tool bending moment would allow chatter avoidance in real time taking into account the changing cutting geometry and workpiece rigidity as well as detecting the forces acting on the tool and detecting tool wear [26].

5. Conclusion

The presence of chatter can have detrimental effects on tool life and part quality in machining operation. In this paper, the use of strain gauge based sensory tool holder for chatter detection has been proposed and investigated. The analysis showed that there was an increase in the amplitude at higher harmonics in the bending moment and torsion signals. However, no discrete chatter frequency could be detected from the bending moment and torsion signals. This is despite the evidence of discrete frequencies in acceleration and sound pressure signals indicating chatter. Therefore, easy-to-apply real time chatter avoidance methods where the spindle speed is set according to the chatter frequency could not be applied. The most distinctive frequency peak obtained from the sensory tool holder was around the spindle frequency. However, there is a deviation between the measured and the real frequencies. This can potentially be due to the signal filtering, pre and post processing within the hardware and software. This necessitate further investigations which will be considered in the future work.

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