World Academy of Science, Engineering and Technology
International Journal of Mechanical and Mechatronics Engineering
Vol:7, No:6, 2013

Experimental Investigation of Chatter Vibrations in Facing and Turning Processes

M. Siddhpura and R. Paurobally

Abstract**—**This paper investigates the occurrence of regenerative chatter vibrations in facing and turning processes. Orthogonal turning (facing) and normal turning experiments are carried out under stable as well as in the presence of controlled chatter vibrations. The effects of chatter vibrations on various sensor signals are captured and analyzed using frequency domain methods, which successfully detected the chatter vibrations close to the dominant mode of the machine tool system.

Keywords**—**Chatter vibrations, facing, turning.

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I. INTRODUCTION

TURNING is the most common and very basic machining operation in the manufacturing industry. In a turning process, three different types of mechanical vibrations are present due to a lack of dynamic stiffness/rigidity of the machine tool system comprising of the tool, tool holder, workpiece, and machine tool itself [1]. These are free, forced, and self-excited vibrations. Free vibrations are induced by shock and forced vibrations are due to unbalance effects in machine tool assemblies like gears, bearings, spindles. Free and forced vibrations can be easily identified and eliminated. But self-excited chatter vibrations are still not fully understood due to its complex nature. They are the most harmful for any machining process including turning. Self-excited vibrations are generally classified into primary chatter and secondary chatter [2]. Primary chatter is caused by friction between the tool and workpiece, thermo-mechanical effects or by mode coupling. Secondary chatter is caused by the regeneration of a wavy surface on the workpiece. Regenerative vibration is the most destructive among all other vibrations.

Chatter was first identified as a limitation of machining productivity by [3], in which extensive studies were carried out on metal-cutting processes as early as in the 1800s. Numerous influences to which a tool is subjected to during cutting were examined analytically as well as experimentally for lathes and other machines. The mechanisms generating chatter were studied and the proposed cutting forces as a function of speed were explained [4]. It was shown that the most important characteristic property of chatter vibration is that it is not induced by external periodic forces, but rather that the forces which bring it into being and maintain it are generated in the vibratory process (dynamic cutting process) itself. Chatter is caused by instability in the cutting processes, which was first understood by [5] and [6] almost simultaneously but independently. It was observed that modulated chip thickness due to vibration affects cutting forces dynamically, which in turn, increases vibration amplitudes yielding a process known as regenerative chatter. It was also observed that the depth of cut was the key process parameter in the cutting process stability. A stability condition was presented in which stability limits can be calculated based upon the system dynamics for orthogonal cutting and it was analytically shown that for the depth of cuts higher than the stability limit, the magnitude of the dynamic forces and oscillations increases, yielding instability and thus chatter vibrations [6]. The solution has been approximated by resolving cutting forces and structural dynamics into one direction only, i.e. the chip thickness direction and thus can only be valid for a one dimensional process. The modeling of the dynamic response, structural aspects and stability limit aspects of regenerative chatter was studied in [7] and [8]. These studies are only applicable to orthogonal cutting, where the direction of the cutting force, system dynamics and chip thickness do not change with time. Most of the research has been carried out to avoid this regenerative chatter vibration by either predicting its occurrence earlier or detecting it as soon as it occurs.

Due to increasing demand of cutting down the production costs under market pressure, unattended machining is the key feature in most of the manufacturing industries. So, in unmanned turning operations, automatic detection of regenerative chatter is very important in order to avoid detrimental effects on surface integrity and damage to the workpiece or machine tools caused by catastrophic tool failure resulting from large amplitude vibrations. Experimental techniques are useful in predicting the stability condition in the off-line mode and detecting chatter onset in the online mode [9]. These experimental techniques have potential to establish an unmanned machining environment. The experimental investigation is imperative to know the stability limit of a specific process by identifying chatter onset in the cutting process. This identification is possible using tool condition monitoring (TCM) techniques. Chatter in orthogonal turning was experimentally investigated with time domain analysis in [10].

In this paper, occurrence of chatter vibrations was detected by continuous monitoring of the facing and turning processes using force, acceleration and acoustic signals and the effects

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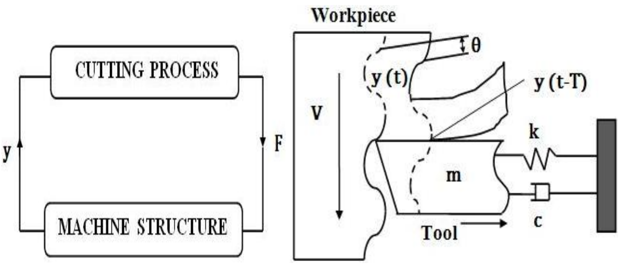
of chatter on these signals are analyzed using frequency domain methods.

II. MECHANISM OF CHATTER IN TURNING

Regenerative chatter vibration arises due to the interaction between the metal cutting process and the machine tool structure as shown in Fig. 1 (a) and it is a major obstacle in achieving maximum material removal rate (MRR).



(a) (b)

Fig. 1 (a) Machine tool, cutting process interaction (b) Mechanism of regenerative chatter

Regenerative chatter occurs at the frequency of the most dominant mode of the machine tool structure. Excitation of this mode causes a relative motion between the machine tool and the workpiece due to the tool cutting over a previously machined undulated or wavy surface. Fig. 1 (b) displays the relative motion between the tool and the workpiece in turning. The tool parameters *m, k* and *c* are the mass, stiffness and damping coefficient respectively and *V* is the cutting velocity of the workpiece. Here, y*(t)* is the wave generated during the current revolution and *y(t-T)* is the wave generated during the previous revolution of the workpiece. The phase delay/shift (θ) between the waves in the previous revolution *y(t-T)* and in the current revolution y*(t)* is the key factor governing the occurrence of chatter in the turning process. If the two waves are in phase ($\theta=0$), the undulations on the workpiece will not grow and the process will remain stable because the chip thickness variation is negligible resulting in a relatively constant force on the tool. From the point of view of energy transfer in the turning system, the onset of chatter can be regarded as the stability threshold of the system in which the energy supplied to the system is equal to the energy dissipated by the system. So, when there is no phase delay/shift ($\theta=0$), there is no surplus energy in the system resulting in a stable cutting process. However, when the waves are not in phase ($\theta\neq0$), the undulations on the workpiece grow due to energy being supplied to the cutting tool and the dissipated energy is less than the supplied energy. This finally results in an unstable cutting process. Under these vibrations, the chip thickness varies continuously which in turn creates dynamic cutting forces at a frequency close to one of the natural modes, and further excites the system.

III. EXPERIMENTAL SET-UP

The chatter experiments were carried out on a 7.5 hp Macson lathe. Fresh coated carbide tool inserts (ISCAR IC8150) were used for orthogonal turning (facing) of unsupported steel (AISI 1045) and aluminum (6061) workpieces of 60mm diameter and 250mm length. Fresh coated carbide tool inserts (ISCAR IC9250) were used for turning tailstock-supported steel workpieces (AISI 1045) of 70mm diameter and length of 250mm.

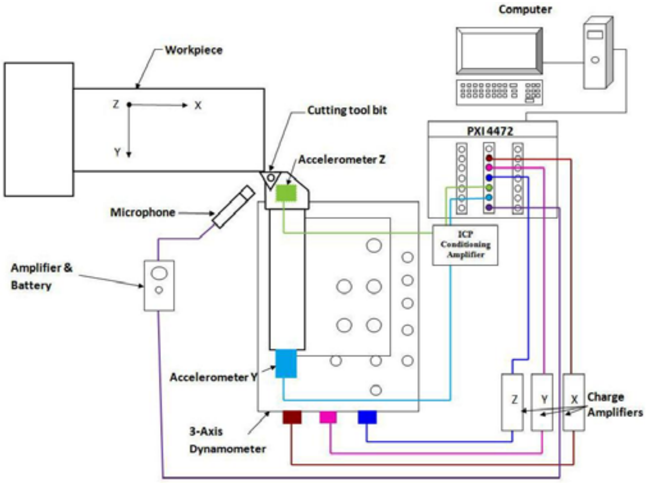


Fig. 2 Schematic of experimental set-up for facing

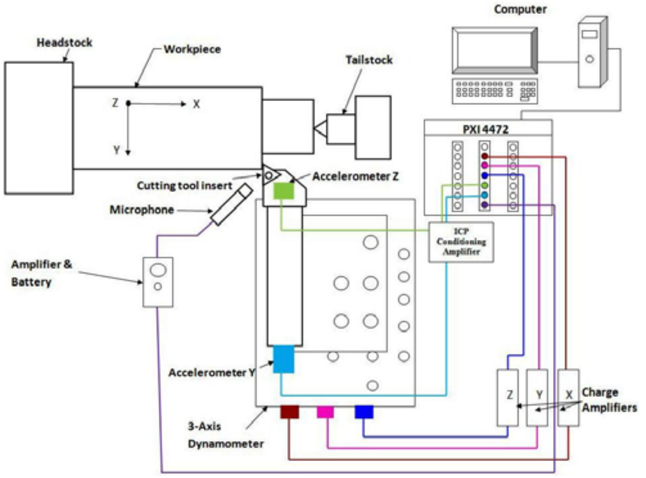


Fig. 3 Schematic of experimental set-up for turning

Facing and turning experiments were carried out for various speeds by keeping the feed constant and by progressively increasing width of cuts for each speed-feed combination. The cutting forces were measured with a Kistler 9257A three-component piezoelectric dynamometer along with PCB 462A charge amplifiers for each force channel. Two PCB 333B piezoelectric accelerometers were used along with an in-house built ICP conditioning amplifier to measure the vibration amplitudes in Y and Z directions. A Realistic® electret microphone was used with an in-house built amplifier to measure the acoustic signals from the cutting process. All 6 signals measured by 3 sensors and amplified by their amplifiers were sent to the NI PCI/PXI 4472. Each signal was then filtered and analysed on the computer using NI LabVIEW

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software. Figs. 2 and 3 show the schematic of the complete experimental setup for facing and turning respectively.

IV. ORTHOGONAL TURNING (FACING) TESTS

The orthogonal turning tests were carried out and experimental stable and unstable states were found by progressively increasing the width of cuts. A constant feed of 0.15mm/rev and the cutting speeds of 470rpm and 870rpm were selected during all these tests. The width of cut of 0.8mm was found to be stable during all the cutting tests and the stable cutting data were obtained at this width of cut. The width of cut was increased from 0.8mm until chatter occurred above 2mm of widths of cut during turning. The cutting forces, accelerations and acoustic signals were acquired for a few seconds for stable cutting and acquired continuously for chatter cutting.

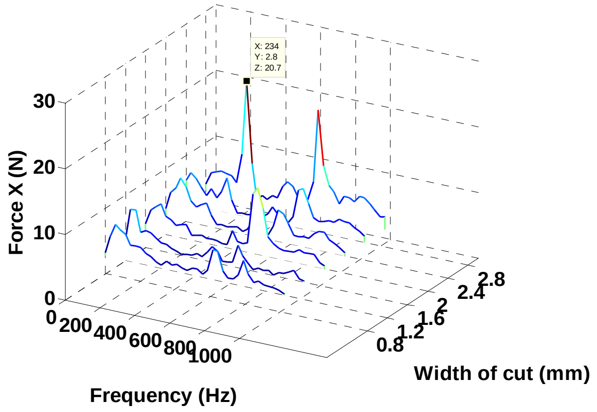
V. TURNING TESTS

Turning experiments were carried out and the experimental stability states were found by progressively increasing the width of cuts. A constant feed of 0.3mm/rev and the cutting speeds of 470rpm and 870rpm were selected during all these tests. Fig. 3 shows the complete schematic of the experimental setup of the turning experiments, which is similar to the orthogonal turning set-up except that in this set-up a tailstock support is provided and the feed direction is parallel to the workpiece axis (x).

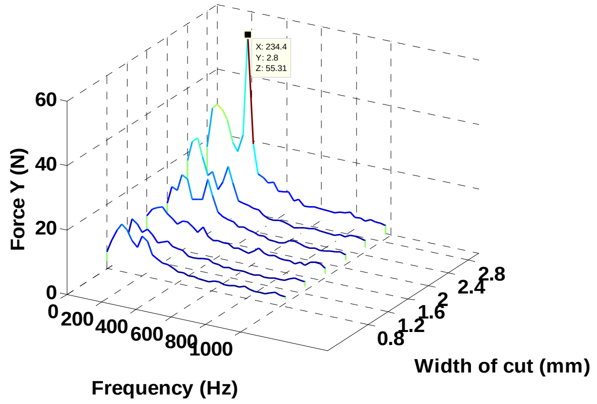
VI. EXPERIMENTAL RESULTS AND DISCUSSIONS

A. Orthogonal Turning (Facing) Tests

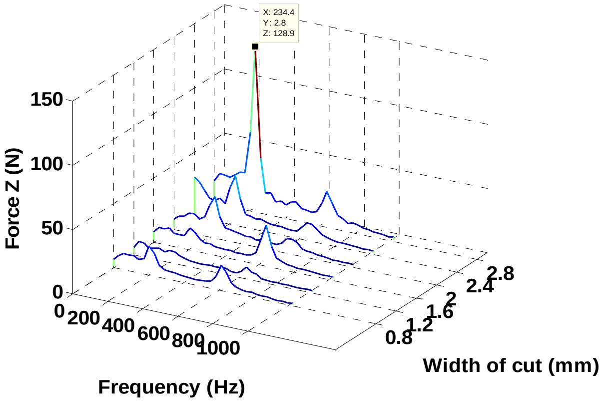
During orthogonal turning, the width of cut of 0.8mm was found to be stable during all the cutting and material conditions. Therefore, all the stable cutting data were obtained at this width of cut in the tests. The width of cut was increased from 0.8mm until chatter occurred above 2mm widths of cut during all the chatter turning tests. During all the chatter turning tests the tool inserts worn very fast and there were two different scenarios observed. First, the tool was broken instantly in the first few cuts due to excessive vibrations when chatter occurred around 3mm width of cut. Second, the tool inserts worn very fast up to 3mm of tool wear length without breaking and after that the tool wear rate became very slow, due to positive damping, as observed in the rest of the chatter tests.



(a) Waterfall plot of Force-X



(b) Waterfall plot of Force-Y



(c) Waterfall plot of Force-Z

Fig. 4 Waterfall plots of (a) Force-X, (b) Force-Y and (c) Force-Z displaying the onset of chatter at 2.8mm width of cut in facing

Fig. 4 displays the waterfall plots of the cutting force signals in X, Y and Z directions for stable and chatter cutting states by plotting the cutting force versus frequency versus width of cut parameters on the plots. The large increase in force amplitudes in the spectrum at 234Hz in all 3 force directions indicates the 2.8mm width of cut at which the process becomes unstable. The force amplitudes in Y and Z directions were much higher compared to the X direction

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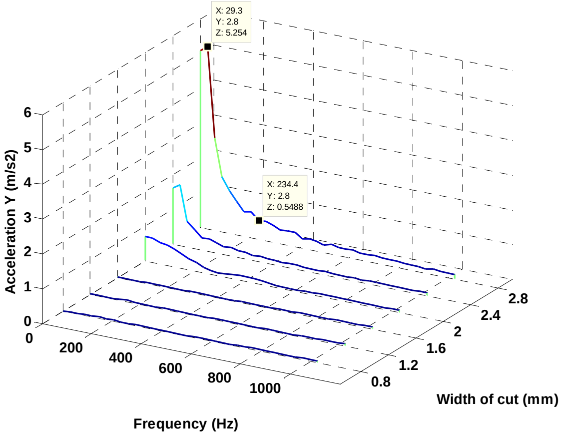
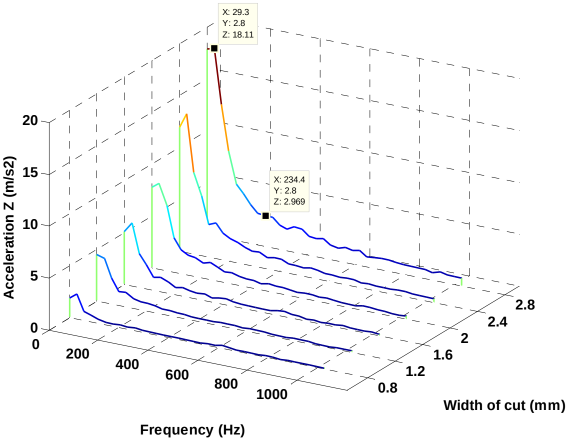
which is quite obvious for facing. The frequency of 234Hz corresponds to the flexural natural frequency during cutting. This frequency is higher than the natural frequency which could be measured by static impact testing due to the contact stiffness between the tool and the workpiece. The point where the spectrum dramatically increases is taken to be the transition from stable to unstable or the stability limit. For this facing test, the stability limit is at the width of cut of 2.8mm.



(a) Waterfall plot of Acceleration-Y



(b) Waterfall plot of Acceleration-Z

Fig. 5 Waterfall plots of (a) Acceleration-Y and (b) Acceleration-Z displaying the onset of chatter at 2.8mm width of cut in facing

Figs. 5 (a) and (b) show the waterfall plots of the acceleration signals in two directions (Y, Z) for stable and chatter cutting states respectively by plotting the acceleration versus frequency versus width of cut parameters on the plots. Some large acceleration peaks were observed around 29Hz which looks like second harmonics of the spindle speed of 870rpm (14.5Hz). The second large increase in acceleration amplitudes in the spectrum at 234Hz in both the directions confirms the natural frequency from the cutting force waterfall plots. It also indicates the 2.8mm width of cut at which the process becomes unstable.

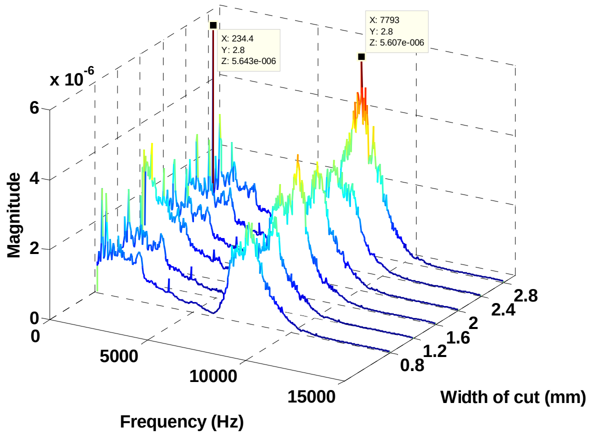
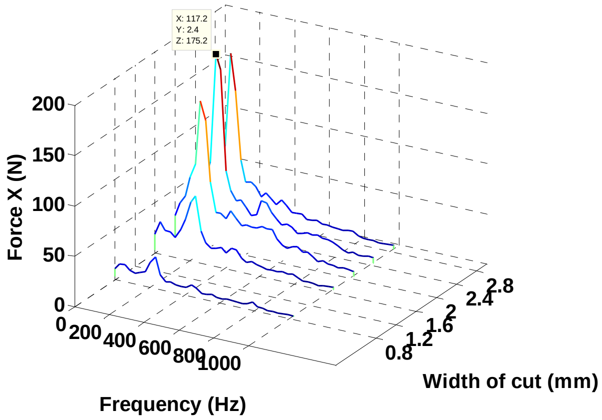


Fig. 6 Waterfall plots of acoustic signal from microphone displaying the onset of chatter at 2.8mm width of cut in orthogonal turning

Fig. 6 displays the waterfall plots of the acoustic signals for stable and chatter cutting states by plotting the acoustic signal magnitude versus frequency versus width of cut parameters on the plots. The large increase in magnitude of the spectrum at 234Hz confirms the width of cut of 2.8mm at which the process becomes unstable. The magnitude is also increased significantly at a higher frequency of around 7793Hz when chatter occurred at a 2.8mm width of cut which can be seen from the waterfall plot. This is mostly due to the increased vibration of the tool and workpiece in the presence of chatter, but there are chances that these high frequency acoustic signals could be a result of acoustic resonances in the room. The microphone picked up these high frequency vibrations which were not captured by the dynamometer or the accelerometers.

B. Turning Tests

During turning of a tailstock supported workpiece, the widths of cut were increased from 0.8mm until chatter appeared at 2.4mm.



(a) Waterfall plot of Force-X

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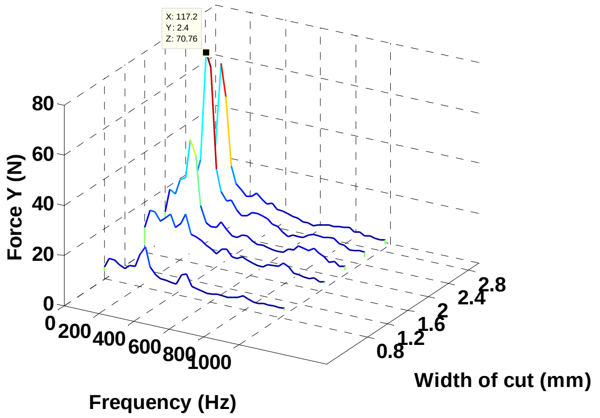
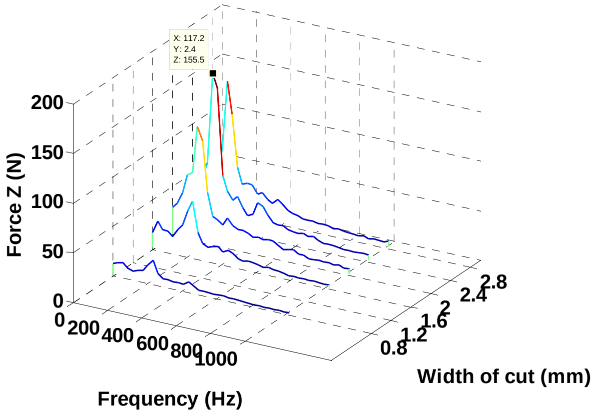


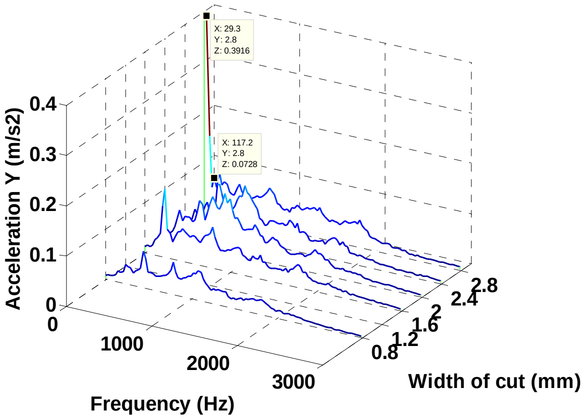
(b) Waterfall plot of Force-Y



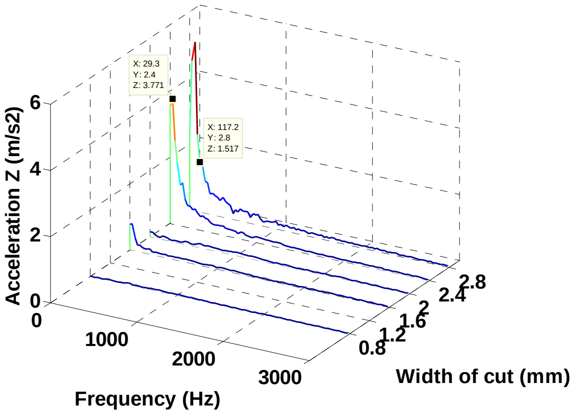
(c) Waterfall plot of Force-Z

Fig. 7 Waterfall plots of (a) Force-X, (b) Force-Y and (c) Force-Z displaying the onset of chatter at 2.4 mm width of cut in turning

Fig. 7 displays the waterfall plots of the cutting force signals in the X, Y and Z directions for stable and chatter cutting states while turning by plotting the cutting force versus frequency versus width of cut parameters on the plots. The large increase in force amplitude in the spectrum at 117.2Hz in all 3 force directions indicates the 2.4mm width of cut at which the process becomes unstable. The force amplitudes in the X and Z directions were much higher compared to the Y direction. The frequency of 117.2Hz corresponds to the flexural natural frequency during cutting. The point where the spectrum dramatically increases is taken to be the transition from stable to unstable or the stability limit. For this turning test, the excessive chatter vibrations appeared at a width of cut of 2.4mm.



(a) Waterfall plot of Acceleration-Y



(b) Waterfall plot of Acceleration-Z

Fig. 8 Waterfall plots of (a) Acceleration-Y and (b) Acceleration-Z displaying the onset of chatter at 2.4mm width of cut in turning

Figs. 8 (a) and (b) display the waterfall plots of the acceleration signals in two directions (Y, Z) for stable and chatter cutting states by plotting the acceleration versus frequency versus width of cut parameters on the plots. One large acceleration peak was observed in each of the acceleration directions Y and Z around 29Hz which looks like the second harmonic of the spindle speed of 870rpm. The second large increase in acceleration amplitudes in the spectrum at 117.2Hz in the Y and Z directions confirm the natural frequency from the cutting force waterfall plots of Fig. 7. It also indicates the 2.4mm width of cut at which the process becomes unstable. The waterfall plots confirm that the acceleration in the Z-direction is significantly affected when chatter occurs compared to the radial (Y) direction.

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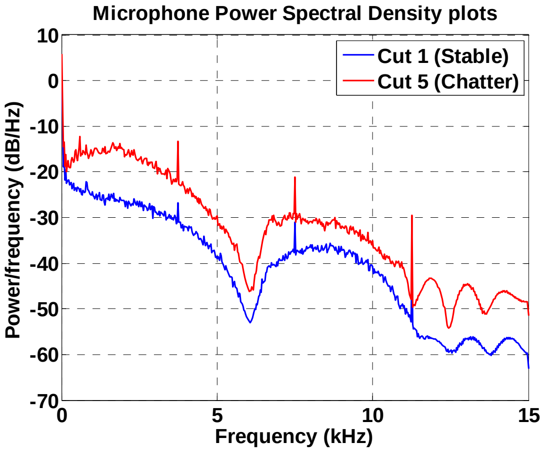

Fig. 9 Experimentally obtained PSD plots of acoustic signals from microphone in stable and chatter states

Fig. 9 shows the PSD plots of the acoustic signals for stable and chatter cutting states. The PSD level was higher in the whole frequency range when chatter appeared in the cutting process compared to stable cutting as shown in Fig. 9. This is because the tool failed during the 5th cut when severe chatter appeared which in turn produced excessive vibration and noise.

VII. CONCLUSION

All of the force, acceleration and acoustic signals could successfully detect chatter vibrations close to the dominant mode (natural frequency) of the machine tool system. The results clearly show the severity of chatter vibrations on these sensor signals as the amplitudes of these signals increased substantially during chatter compared to the stable process. Therefore, chatter vibrations can be avoided by online monitoring of the turning process using combined force, acceleration and acoustic signals.

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