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Dynamic characterization of the cutting conditions in dry turning

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Abstract. Machining instability in the form of violent vibrations or chatter is a physical process characterized by extreme cutting force at the cutting point. The process has very negative impact on machine integrity, tool life, surface quality and dimensional accuracy. Thus it could significantly compromise productivity and manufacturing quality. In the present paper, the importance of characterization and identification of dynamic instability in dry turning operation are shown. The stability behaviour of machine vibration or chatter has been examined and the various relevant parameters are studied and discuted. For chatter detection and identification of the transition between stable and unstable states, different methods are used. Results obtained proof the accuracy of these methods.

1. Introduction

Turning is one of the most commonly used machining processes in manufacturing industry. In an attempt to achieve high material removal rates in production, aggressive cutting conditions are often employed. Use of such aggressive cutting conditions leads to chatter, wherein intense vibrations and excessive cutting forces occur at the cutting point. Vibrations and chatter is highly undesirable because it adversely affects the surface quality, limits the dimensional accuracy of a workpiece, leads to higher tool wear rates, creates high levels of noise and could result in damage to the machine tool itself or to the spindle [1].

In order to achieve chatter free machining, conservative cutting conditions are usually chosen resulting in lower metal removal rates and a loss of productivity. For this reason, it is essential to identify chatter free cutting conditions. Knowledge of the stability limits would be necessary to maximize the metal removal rate while maintaining the product quality. The motivation for this work is to identify bounds of dynamic stability and instability in turning process and finally to predict the stability lobes which in turn can be used to determine chatter limits for different cutting conditions [2].

In most cases of pratical interest, the chatter observed in a turning operation is due to the regenerative effect : as the tool cuts a surface, the undulations generated in the previous revolution sustain the tool-workpiece vibrations which are closely coupled to the cutting forces. Chatter prediction models have a long history that began with work by Tobias [3] and

Tlusty [4, 5]. These early efforts concluded that the regenerative effect is the main cause of instability, which leads to the development of chatter. Tlusty and Polacek [6] developed a stability condition in which stability limits can be calculated based upon the system dynamics for orthogonal machining. In the work by Tobias and Fishwick [7] the dynamics of the cutting process were modeled and effects such as process damping were included into the stability model. Early stability lobe diagrams were created by Merrit [8] based upon feedback control theory to model regenerative chatter.

This paper presents a comprehensive dynamic instability model for chatter prediction in a dry turning operation. The first section presents an analysis of chatter during turning operation. The next two sections present the experimental set-up and the procedure used in chatter verification experiments. They are followed by a presentation and discussion of experimental results. The last section outlines the conclusions and recommendations for future work.

2. Analysis of chatter in turning operation

Figure 1 shows the control block diagram of chatter during turning lathe work. In this figure, the uncut chip thickness $h(s)$ is composed of the mean uncut chip thickness $h_0(s)$, the inner modulated cut surface $y(s)$, and the outer modulated workpiece surface $y(s)e^{-\tau s}$, where τ is the time delay between the inner and outer modulated surface (spindle period). The uncut chip thickness $h(s)$ is fed into the cutting process to produce the cutting force $F(s)$ acting on the cutting tool. The transfer function of the cutting process can be expressed as : $K_c\, b$ where K_c is the specific cutting force and b the cut width.

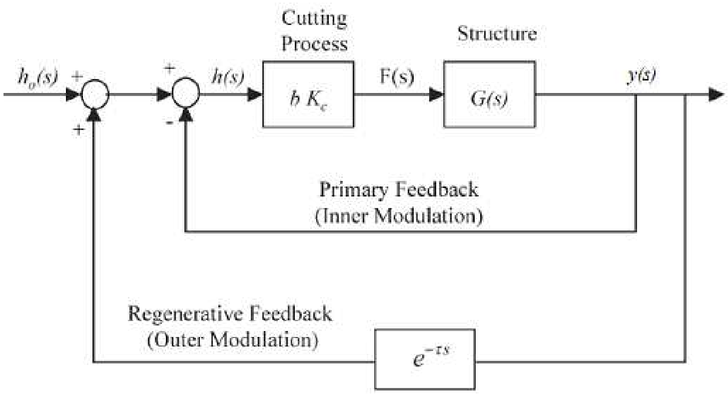

Figure 1. Control block diagram for chatter in turning.

The cutting force $F(s)$ then excites the cutting tool to generate the vibration $y(s)$ between the cutting tool and workpiece. The oriented transfer function of the cutting tool $G(s)$ can be expressed as :

$$G(s) \;=\; \sum_{i=1}^{n} u_i\, G_i(s) \tag{1}$$

where n is the number of modes, u_i the directional factor for mode i, and $G_i(s)$ the direct transfer function for mode i, which can also be expressed as :

$$G_i(s) \;=\; \frac{1}{m_i\, s^2 \,+\, c_i\, s \,+\, k_i} \tag{2}$$

where m_i, c_i, and k_i are the mass, damping, and stiffness parameters respectively.

According to the Nyquist stability criterion [9], the control system for turning lathe work is at the stability limit when the gain of the open loop transfer function has the critical value of

-1. The cut width b at the stability limit is called "critical cut width" b_{lim} [10] and can be expressed as :

$$b_{lim} = \frac{-1}{2\,K_c\,\Re\,(G(j\,\omega))_{neg}} \tag{3}$$

where $\Re\,(G(j\,\omega))_{neg}$ is the negative real part of the frequency response function of the cutting tool and ω the chatter frequency in rad/s.

For the sake of simplicity, the cutting tool is taken as a single-degree-of-freedom vibration system. The parameters of the vibration system for the cutting tool are selected as mass, $m = 1kg$, damping ratio, $\zeta = 0.03$ and natural frequency, $f_n = 100\ Hz$. The specific cutting force is equal to $K_c = 1000\ N/mm^2$. Figure 2 shows the real part and magnitude of the frequency response function of the cutting tool. Based on (3), the chatter frequency and the critical cut width b_{lim} can be calculated [10].

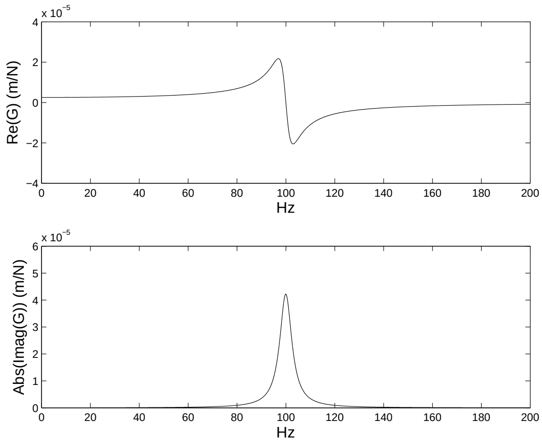

Figure 2. Frequency response function of the simplified cutting tool.

Figure 3 shows the chatter frequency and the critical cut width b_{lim} as a function of spindle speed. Chatter will occur when the cut width b is greater than b_{lim}. However, the critical cut width b_{lim} can be increased if the magnitude of the negative real part of the frequency response function of the cutting tool is reduced (3).

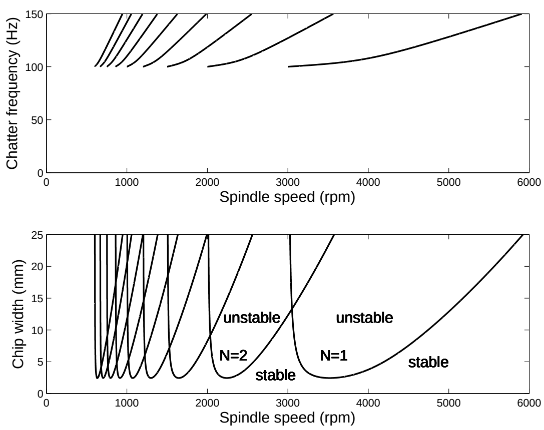

Figure 3. Simulated stability chart.

3. Experimental setup and procedure

Cutting experiments were performed on a CNC lathe Realmeca Conventional plus T400 (Figure 4). The speed of spindle rotation is from 100 to 4000 rpm and the feed rate is from 0.1 to 8 m/min.

Machining tests were carried out by cutting a 42CD4 steel workpieces with a cutting tool SNMG TP200 using diamond shaped CVD coated carbide inserts (120408-MF2) which a nose radius of 0.8 mm, side and end cutting angles of $-6°$ and a rake angle of $93°$. The unmachined round bar of diameter 40 mm and length 500 mm, used in all experiments for dynamic charactrization, was rigidly mounted in the chuck of the lathe with tailstock.

Figure 4. CNC Realmeca T400 turning lathe.

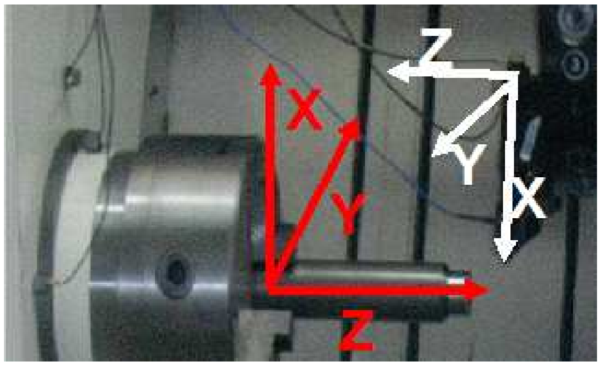

Figure 5. Directions of accelerometers on the workpiece and cutting tool.

The first step in evaluating vibration was to determine the appropriate mounting location for the sensor. Previous work has shown that mounting the sensor on a stationary tool is best. During the validation of the dynamic instability identification, the direct response of the spindle and the cutting tool were instrumented with six B&K unidirectional piezoelectric accelerometers type 4507 with the following characteristics : weight 4.8 g and size 10 mm^3 as shown in Figure 5 with sensitivities given in Table 1 to obtain acceleration signals during machining. The sensors had an upper frequency range of 6 kHz.

Using six accelerometers has allowed us to record as much as possible vibration data from the cutting process. This will generate a large number of features which may be helpful to acquire maximum information about the dynamic of the process and the state of the tool.

	Spindle			Cutting tool		
Direction	X	Y	Z	X	Y	Z
Serial number	2195615	2110703	2195617	2195616	2110695	2195618
Sensitivities (mV/ms^{-2})	10.10	9.86	9.90	10.06	10.14	10.05

Table 1. Sensitivities of accelerometers.

The impulse and displacement responses were recorded on a hard disk PC in a digital form using a B&K Multi-analyser system type 3560 and a B&K Pulse LabShop software. Signal processing was performed with Matlab environment.

The sensor signals were acquired for more than 12 s duration of observation and transmitted through six channels, sampled at 16384 Hz.

For the frequency response of the cutting tool, the impulse was given with a Brüel&Kjaer (B&K) impact hammer (model 8202) equiped with a plastic tip coupled with a piezo-electric force sensor type 2646 of sensitivity 1 mV/g.

The frequency response functions in the axial, radial and feed directions of the cutting tool which were used during validation are given on Figure 6. A first mode at 1900 Hz in the X and Z direction and at 3100 Hz in the Y direction can be clearly seen. A curve fitting technique was used to extract the modal parameters from the transfer function plot.

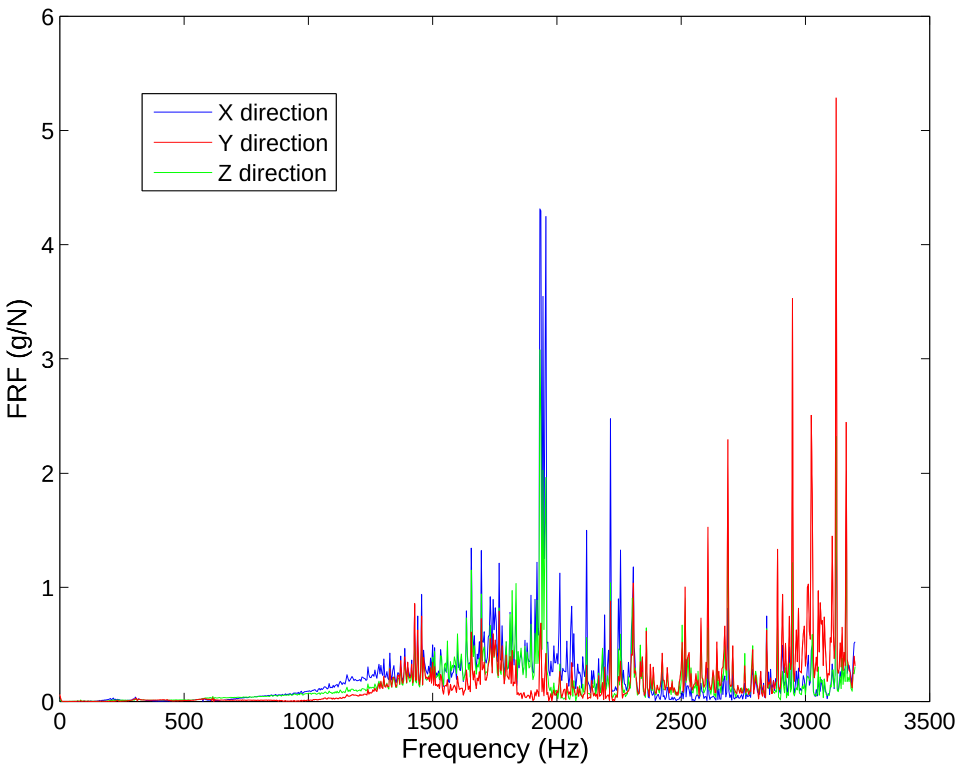

Figure 6. Frequency response function of the cutting tool in the X, Y and Z directions.

This section describes the procedure adopted in conducting experiments for verifying the limits for the unstable-stable turning lathe work. For the sake of clarity, the cutting conditions presented are : a variable depth of cut, a variable spindle speed, a constant feed speed of 0.2 mm/rev and under dry conditions. Once the conditions parameters of turning were determined, several experiments were performed to determine the depth of cut at which machining becomes unstable. Table 2 shows the list of all tests performed.

	Spindle speed (rpm)				
	1500	2000	2500	3000	3500
Depth of cut (mm)	1.4	0.8	0.8	0.8	0.8
	1.8	1.0	1.0	0.9	1.0
	2.3	1.2	1.2	1.0	1.1
	2.5	1.5	1.4	1.2	1.2
	2.9			1.3	

Table 2. List of tests performed.

4. Results and discussion

Figure 7 a) shows the accelerometer signal of the cutting tool in these conditions and without chatter. The signal becomes unstable and Figure 7 b) shows the results with a depth of cut of 1.5 mm.

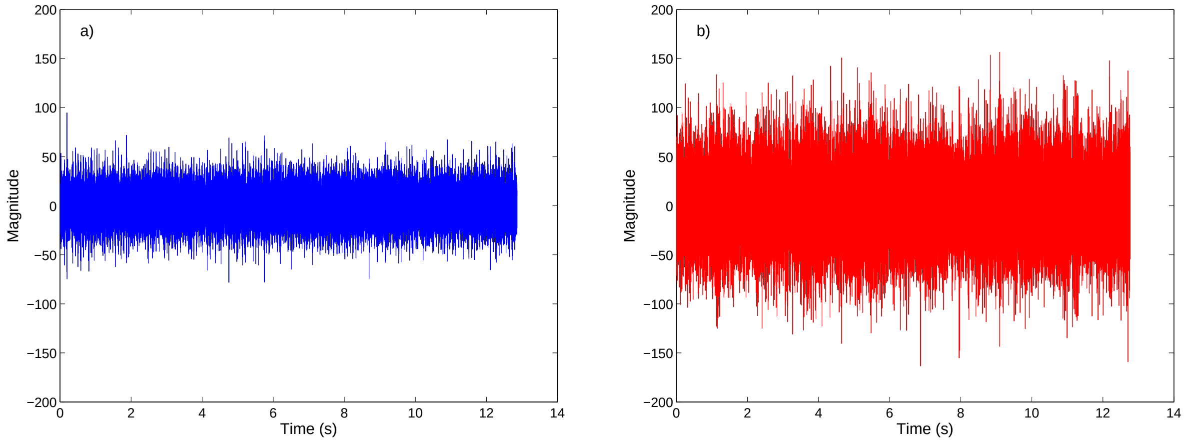

Figure 7. Representative spectra of acceleration signals in Z direction without chatter (a) and with chatter (b).

A representative frequency spectrum is illustred Figure 8 where the evolution of the first mode at 1900 Hz is clearly significant. The time and frequency parameters are very influent regarding the dynamic stability of the process. For clarity, only the feed (or Z) direction of accelerometer mounted on the cutting tool is shown here.

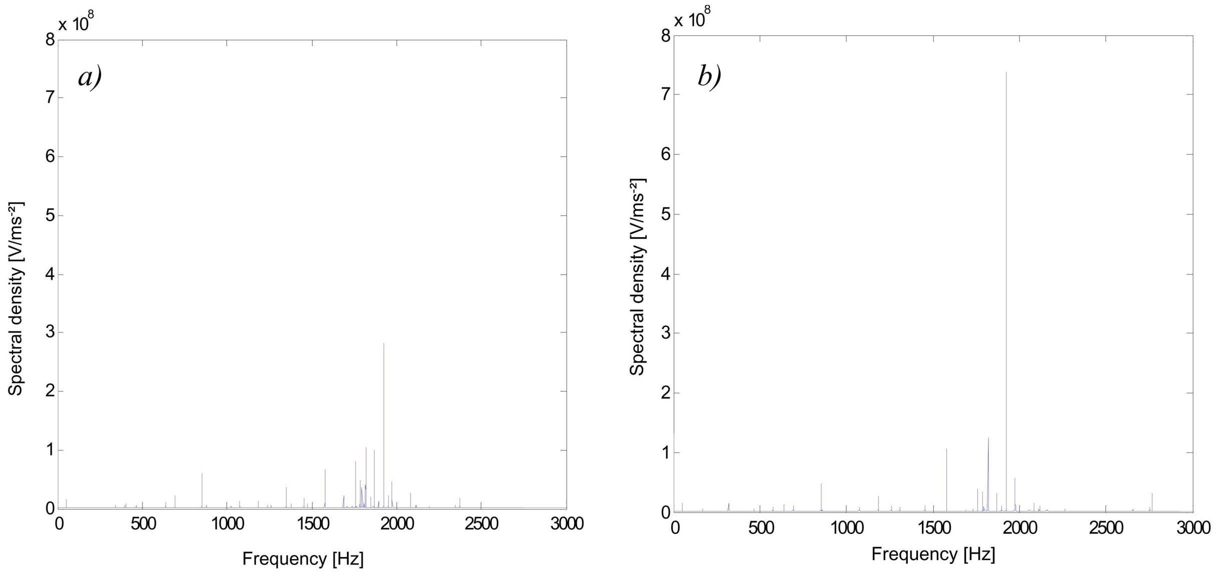

Figure 8. Representative spectrum density of acceleration signals without chatter (a) and with chatter (b).

In Figure 9, it can be seen that the magnitude of the frequency response function is greatly reduced whithout chatter when compared to those with chatter. It is consequently a good indicator of chatter.

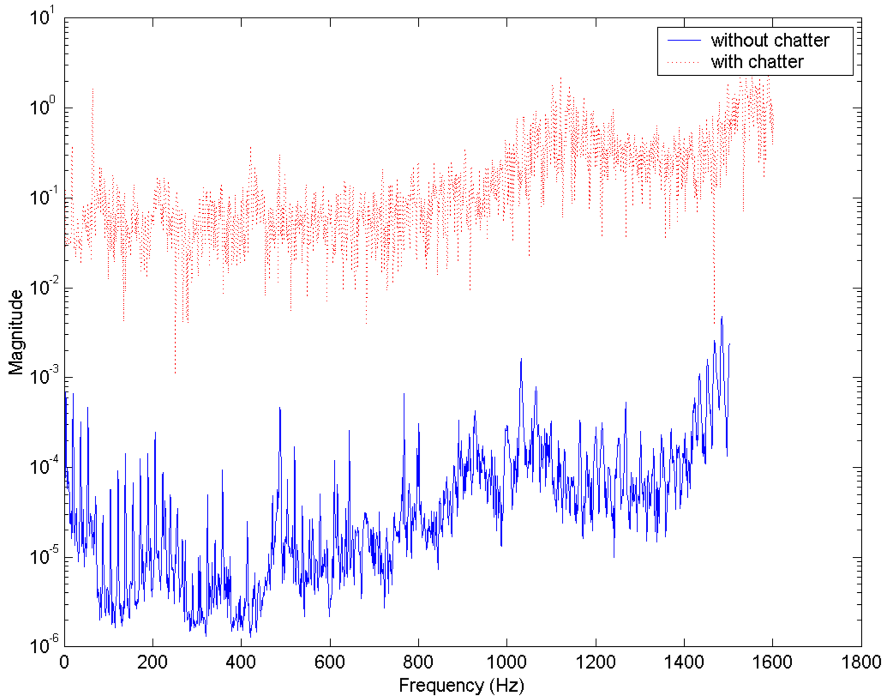

Figure 9. Representative magnitude of acceleration signals with chatter (top) and without chatter (bottom).

The experimental stability chart was created with all machining (see list in Table 2). The resulting diagram is given in Figure 10. In this diagram, stable cutting conditions are represented by a $\circ$ while unstable cutting conditions are shown by an $*$.

5. Conclusions

In this paper, the most relevant parameters of dynamic instability have been explored. Detection of unstable - stable limits from accelerometer signals is improved. Experimental results show that chatter in turning can be almost suppressed and cutting stability increased by an optimization of cutting parameters. Also, as chatter occurs the tool vibrates violently and thus creates an undulated pattern on the workpiece. It creates a rougher surface than in stable cutting, and hence surface roughness is also a good indication of chatter occurence. A future work will try to correlate the limits of instability with the surface roughness data, the tool life, the cutting force and the tool wear.

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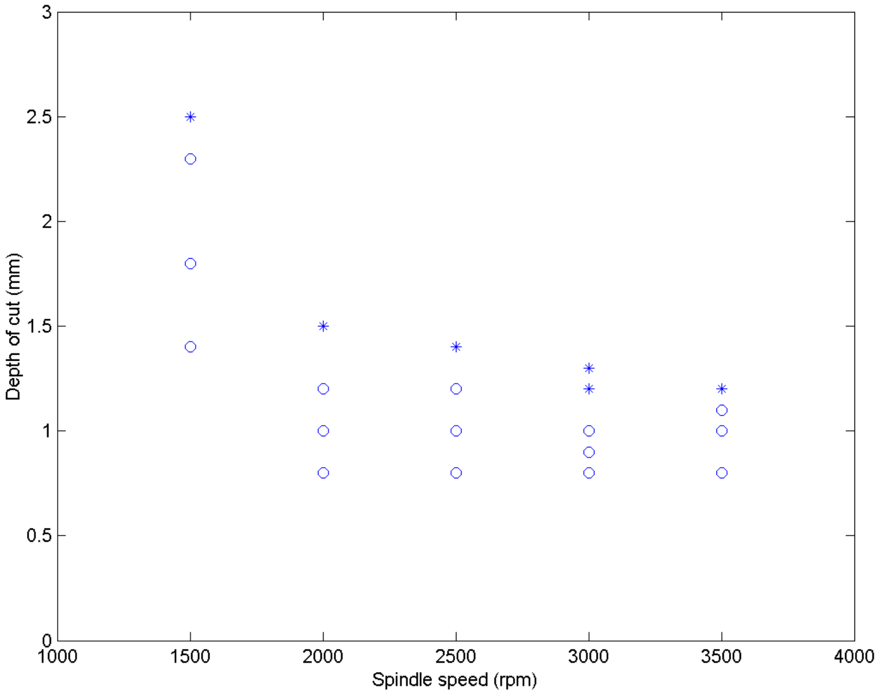

Figure 10. Experimental stability chart (○ - stable, ∗ - unstable).

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