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Experimental analysis of chatter in grooving with slender blades

Danaram Jakhar, Mohit Law *

Machine Tool Dynamics Laboratory, Department of Mechanical Engineering, Indian Institute of Technology Kanpur, Kanpur 208016, India

A R T I C L E I N F O

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A B S T R A C T

This paper reports on experiments that offer new insights on chatter in grooving with slender blades. Experiments reveal two distinct blade modes cause two types of chatter: diametrical chatter that is of the regenerative kind and snaking chatter on the side walls that is of the mode-coupling type. We find that diametrical chatter can be avoided by using damped blades designed for the purpose. However, since no such blades are available to damp snaking chatter, we show that by cutting in the low-speed process damping region snaking chatter too can be avoided.

1. Introduction

Machining deep grooves on cylindrical parts requires the use of slender blades. These blades vibrate under the action of cutting forces. Since grooves are made to house seals and O-rings, vibration marks imprinted on the diameter and on the walls are not acceptable. Understanding and mitigating vibrations in grooving is hence important. However, unlike studies characterizing the stability of turning and milling, grooving has received less attention. This paper reports results aimed at partially remedying that gap by presenting experiments that offer new insights on the process stability of grooving.

As the vibrating slender blade is fed into the rotating workpiece, vibration waves on the diameter from the previous rotation are machined away and new vibration waves are generated on a fresh surface. A phase difference between these waves can cause forces and the response to modulate with large amplitudes to result in regenerative chatter on the diameter. Since these blades are stiffer along their length (l) than their height (h) and/or width (w), the feed directional cutting process induced excitation does not contribute to regeneration on the diameter. Instead, the chip thickness modulation along the feed direction that causes diametrical chatter is thought to be due to the tangential and feed forces causing in-plane bending of the blade [1,2]. This is shown schematically in Fig. 1.

Grooving is a fixed width of cut operation. As such, the traditional stability diagrams find little use in guiding the selection of combination of widths of cut and spindle speeds at which the process could be stable. Since grooving insert geometry is usually selected only for better chip control [3] and not from the perspective of avoiding vibrations, previous related work had hence approximated grooving as a 1D process and had developed damped blades to arrest bending in the xy plane [1] such as to avoid diametrical chatter.

Grooving is however a 3D process. Though forces along the z direction are generally negligible [1–3], since the blade is significantly more flexible in this direction, we hypothesize that any perturbance of the blade along this direction may result in chatter on the walls. We call this snaking chatter – shown schematically in Fig. 1. Since the blade cuts a new surface on the side walls as it advances in the feed direction, there is no regeneration action on the side walls. We hence postulate that snaking chatter is not of the regenerative kind, but of the mode-coupling type that occurs due to coupling of modes in different directions [4–6].

To test our hypothesis about snaking chatter being real and it potentially being distinct from diametrical chatter, we cut aluminium with two blades. One regular and the other damped. The experimental setup and plan are discussed in Section 2. Section 3 discusses the measured dynamics of the blades. Sections 4 discuss our experimental observations from cutting. Main conclusions follow.

* Corresponding author.
E-mail address: mlaw@iitk.ac.in (M. Law).

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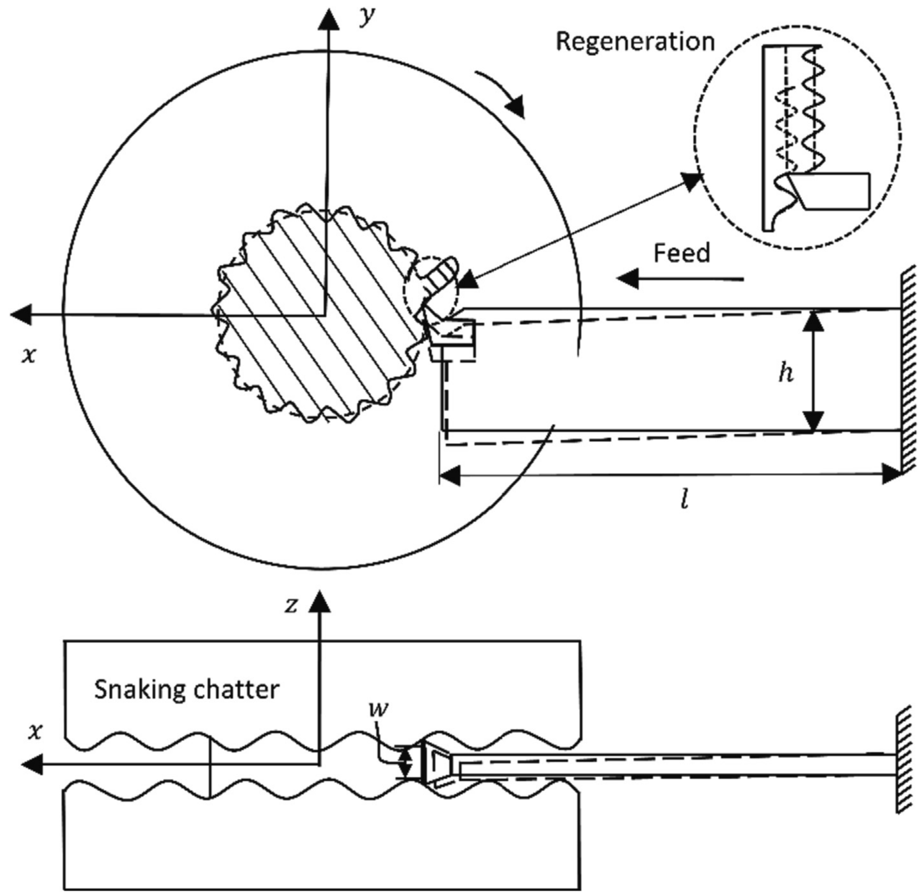

Fig. 1. Schematic of deep grooving showing diametrical and snaking chatter.

2. Experimental setups and plan

The setups to cut and measure dynamics are shown in Fig. 2. Experiments were done on a CNC turning machine with an ISCAR-make CGHN 53-P8 regular blade and its damped equivalent [7]. We used a GIMY 808 insert with a 0.8 mm radius and 8 mm width. Blade overhang was 130 mm. We used a tri-axial accelerometer and a microphone for process monitoring. Experiments were repeated twice and were with a constant feed of 0.2 mm/rev. Cutting speeds were varied in the range of 50–300 m/min.

To measure dynamics of both blades, we used a modal hammer and a single axis accelerometer. We measured h_{xy} – the cross-frequency response function (FRF) by exciting in the y direction and measuring in x direction. We also measured h_{zz} – the direct FRF in the thickness direction. The damped blade has a tunable vibration absorber placed strategically within it to damp the xy bending vibrations. Since development of the damped blade assumed the critical stable width of cut to be inversely proportional to h_{xy} [1], the damped blade is not expected to significantly modify the blade's behavior in the z direction.

3. Measured dynamics

Measured FRFs are shown in Fig. 3. As is evident in Fig. 3(a), there is just one very flexible low-frequency mode along the z direction. Interestingly, this low-frequency mode is also visible in the xy direction, wherein there is also another higher-frequency mode – making the xy direction have two distinct modes – see Fig. 3(b). Since the low-frequency mode is three orders of magnitude more flexible in the z direction than it is in the xy direction, it can be considered to primarily be a bending mode of the blade in the z direction with some coupling to the xy direction. It is also evident that h_{zz} for the damped blade is dynamically stiffer than the regular blade, and that there is no high frequency mode in the xy direction for the damped blade.

4. Cutting behavior

Representative experimental results for cutting with a regular blade are shown in Fig. 4(a) and for cutting with a damped blade in Fig. 4(b).

As is evident from the representative spectra of the measured sound for a chatter case for cutting with a regular blade (Fig. 4 (a)), there are peaks around ~1150 Hz that correspond to the mode in the xy plane and that is responsible for diametrical chatter. Visual inspection confirms that there was chatter on the diameter.

For cutting at high speeds with a damped blade (Fig. 4(b)), visual inspection shows severe undulations on the side walls and no chatter marks on the diameter, suggesting this to be a case of snaking chatter. Since the damped blade was specifically designed to damp the xy mode responsible for diametrical chatter, not observing chatter on the diameter is not unsurprising. And, though the measured sound in this case is like that for the case of diametrical chatter for cutting with the regular blade, the spectra does not show any peak corresponding to the z directional mode. Though there appear to be clusters of peaks around 1–1.5 kHz, since the damped blade has no modes in this frequency range, inferring chatter from the spectra of measured sound is not possible. Spectra of measured accelerations (not shown herein) also did not exhibit

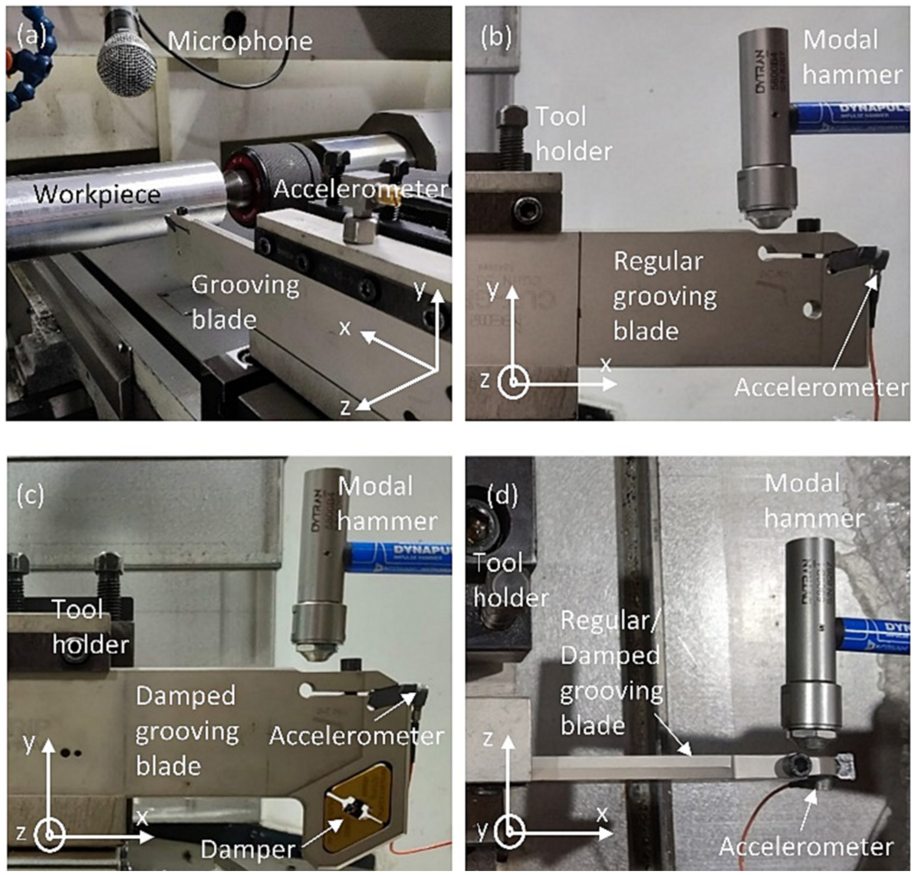

Fig. 2. Setups for (a) cutting, (b) measuring the *xy* dynamics of the regular blade, (c) measuring the *xy* dynamics of the damped blade, and (d) measuring the *z* directional dynamics of both blades.

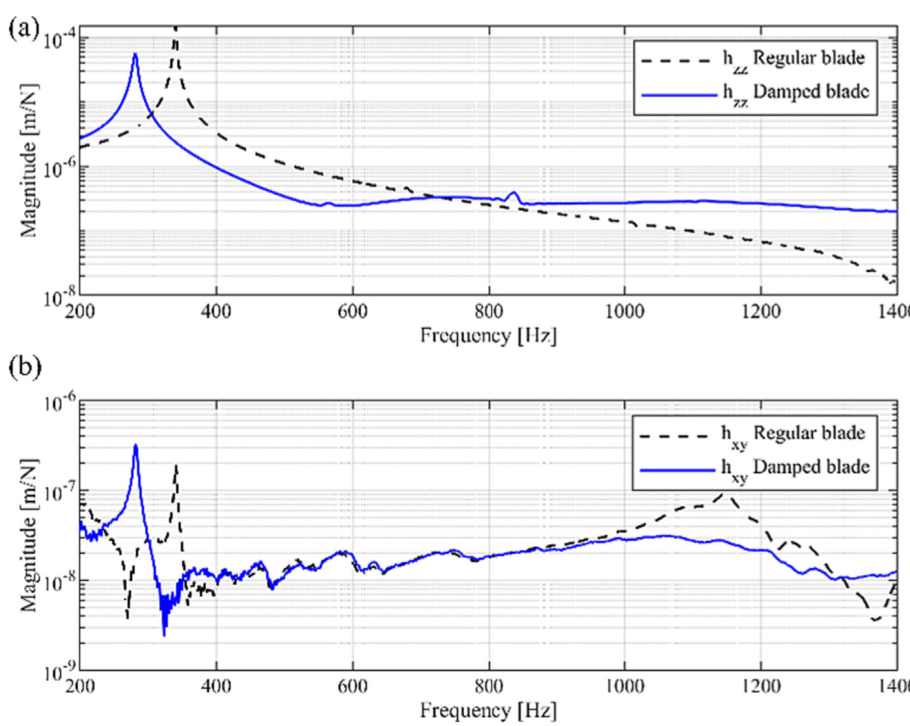

Fig. 3. Measured FRFs of the blade in the (a) *z* direction, and (b) *xy* direction.

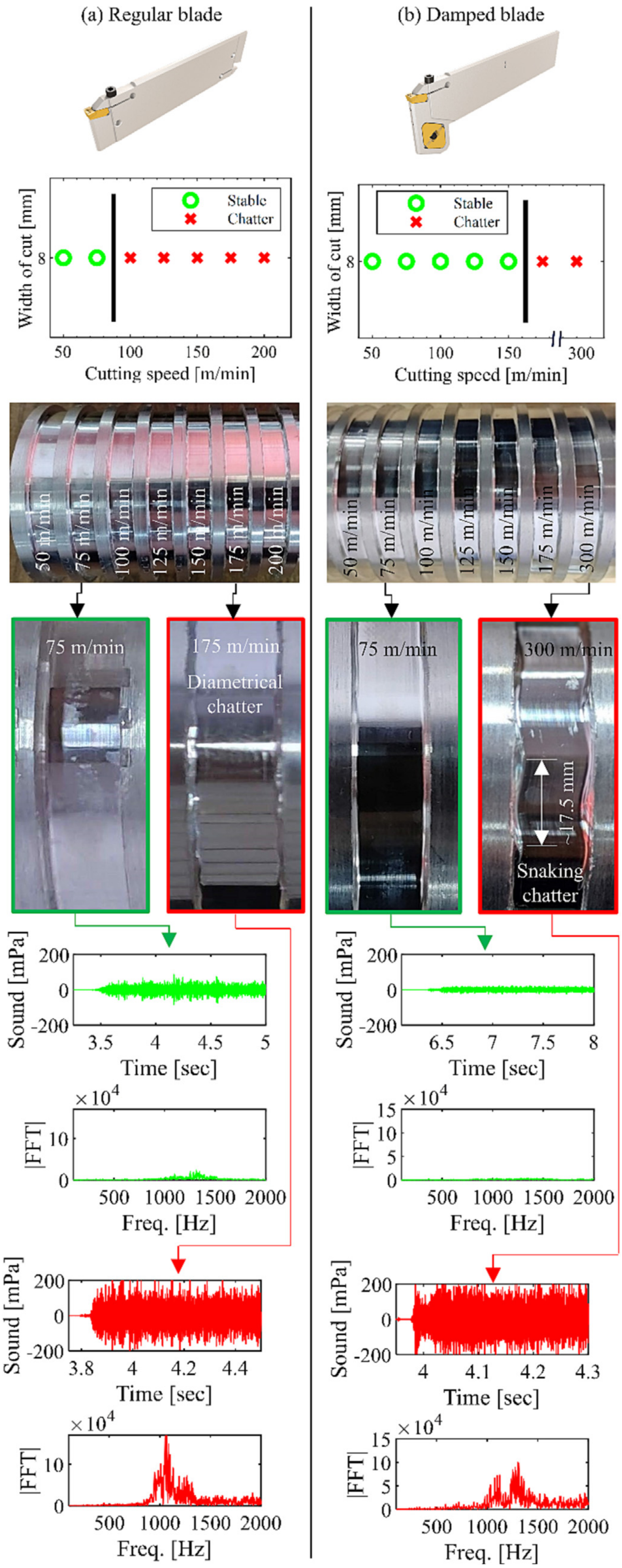

Fig. 4. Summary of experiments for grooving with a (a) regular blade, and a (b) damped blade.

any dominant peaks, perhaps due to the sensor being placed on the holder and not on the blade. Since spectra is inconclusive, we instead measure the wavelength, λ of the vibration marks left on the side walls of the machined surface and infer the snaking chatter frequency, f_{cs} from the wavelength and the cutting speed, v. Since $v = f_{cs}\lambda$, for cutting at 300 m/min, and λ measuring ~ 17.5 mm, f_{cs} is 286 Hz. This is just higher than the z directional mode at ~280 Hz, confirming that this is indeed a case of snaking chatter.

All cuts below speeds of 100 m/min with the regular blade and below 175/min with the damped blade were observed to be stable. For such cuts, the response did not exhibit a growing tendency and nor did the spectra show peaks near any of the natural frequencies. Visual inspection of the machined surfaces confirmed no chatter. Since nothing other than the speed was changed, the only plausible explanation for stability at low speeds is process damping. Since process damping is known to occur when the spindle frequency is lower than the chatter frequency [8], as it is in our case, we attribute stability at low speeds to process damping. Since grooving process stability models accounting for speed influencing regeneration in the presence of process damping for when the blade is flexible in the xy and z directions do not exist, our results can inform the development of such models.

Results reported herein were limited to cutting aluminium with a thick blade at a single feed. We also cut at other feeds, and separately with a regular thin blade with a width of 4 mm. Findings for other feeds and with the thin blade were consistent with our observations for cutting with the thick regular blade, i.e., cutting at high speeds results in chatter on the diameter and undulations on the side walls and cutting at lower speeds is stable due to the likely occurrence of process damping. We also cut steel with thick and thin blades and did not observe any chatter. That is likely due to steels being cut at the low-speed process damping regimes.

5. Conclusions and outlook

Experimental analysis of grooving with slender regular blades suggests that there are two distinct vibration modes of the blade responsible for two types of chatter: diametrical chatter that is of the regenerative kind and snaking chatter on the side walls that is of the mode-coupling type. For cutting with damped blades that are designed to suppress the bending mode responsible for diametrical chatter, only snaking chatter was observed to persist. Cutting at low speeds with both blades was always stable, suggesting that the low-speed process damping mechanism is at play. Observations reported herein could inform the development of expanded analytical stability models for grooving that could help in the design of stable and productive blade designs and processes.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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