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Effect of Different Tool Edge Conditions on Wear Detection by Vibration Spectrum Analysis in Turning Operation

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Abstract: The present study is an experimental study on the effects of sharp and worn tools on the vibration frequency of the tool in turning operation. For this purpose, two forms of cutting were used that is orthogonal (knife edge tools) and oblique cutting (Vee shaped tools) conditions with varying rake angles and tool overhang. Machining test cuts were conducted on a CNC lathe machine (Okuma LH35-N) without coolant for different depth of cut. In addition, the work piece material was mild steel and the cutting tool was made of high speed steel (HSS). Flank wear and vibration signals were measured by surface texture and accelerometer instruments, respectively. The experimental results show that, the majority of the sensitive portion of the spectrum to sharp and worn conditions is within the frequency range of 0 to 3.5 kHz such that worn tools may be detected by increasing the spectrum amplitude. Also it was found that the proposed detection method is robust against changing of the rake angle and tool overhang conditions within the specified range.

Key words: Tool wear, tool geometry, turning conditions, vibration spectrum, tool overhang

INTRODUCTION

Wear of cutting tools is a very complicated phenomenon and it is dependent on many variables (Bhattacharyya, 1998). Also, the production of wear tool data is an extremely lengthy process, which involves long periods of test under both practical and simulated conditions (Stephenson and Agapiou, 1997). The researches, done on the positive effects of in-time prediction of the cutting tool failure show that it is possible to reduce considerably the expenses and the time of machining (Castejon *et al*., 2007).

There are generally two methods, direct and indirect (Fan *et al*., 2008), for displaying the rate of wear and the prediction of the tool failure during the chip removal. In the direct method, the distance between the tool tip and the workpiece is measured by optical systems, radio active wear techniques and electrical resistance sensors (Choudhury and Srinivas, 2004). But in indirect method, the rate is determined by the parameters related to the tool wearing, such as cutting force/torque, tools vibration, surface finish, tool temperature and thermo electric effect measurement (Dimla and Lister, 2000; Ghasempoor *et al*., 1999; Leondes, 2000). In general, indirect methods make easier the tool wear measurement, since they do not require the machining process to stop. For this reason, they have been the most popular methods for years. However, precision is not as good as that achieved with direct methods, since the measurement is affected by noise signals; hence the insistence on implementing direct methods for wear measurement without machining interruption and tool extraction from the machine or tool-holder (Castejon *et al*., 2007). Among the indirect methods, those based on the tool vibration are more acceptably accurate (Dimla and Lister, 2000). Also along with the researches, related to the wear detection by vibration analysis, the cutting conditions effects on the cutting forces and vibrations signals are studied by some researchers, such as Dimla (2004) showed that the effects of cutting speed and feed rate are more complex compared to a liner increment in depth of cut change. Also, Clancy and Shin (2002) presented a three-dimensional mechanistic frequency domain chatter model for face turning processes, which can account for the effects of tool wear including process damping. In addition, Lee *et al*. (1999) developed the microplasticity model for predicting the effect of crystallographic orientation on vibration and its effects on surface quality in ultra-precision machining.

In all of the mentioned research, the effects of the tool edge (knife edge and Vee shaped tools) on the tool vibration parameters have not been studied so far. Additionally the sensitivity analysis based on tool overhang and clamping force variation, has not been considered. Therefore, this research intends to study the effect of mentioned condition on the tool vibration experimentally in the frequency domain. Also, a wear detection method based on the derived results, when

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applying the sharp and worn tools, will be proposed. Finally, the robustness of the proposed wear detection method against tool overhang and rake angle changes will be evaluated using sensitivity analysis.

MATERIALS AND METHODS

All the test work was carried out on a CNC lathe machine (Okuma LH35-N). The lathe had a wide range of speeds and feeds available. The test piece throughout all the tests consisted of a mild steel bar, also its initial dimensions measuring was 100 mm in diameter and 500 mm long. To maintain the tool loadings be realistic values, the feed rate was set at 0.084 mm rev^{-1} for the most part of the test. Additionally, the cutting tools, used for the test, were standard high speed steel tools with 20 mm^2 shank with orthogonal (knife edge tools) and oblique cutting conditions (Vee shaped tools). It should be mentioned that, all tests were carried out without the use of cutting fluid and the tool flank wear (VB_{max}) was selected to be 0.6 mm according to ISO (Boothroyd, 1975).

Table 1: Experimental conditions and variables

Conditions and variables	Description
Workpiece material	BS 970
Workpiece hardness	Brinell 170
Workpiece composition	0.35% C, 0.05% Si, 0.6% Mg
Tool type	HSS (AISI M10)
Tool material	0.85% C, 4% Cr, 8% Mo, 2% V
Spindle speed (rpm)	150
Feed rate (mm rev^{-1})	0.084 constant
Depth of cut (mm)	1, 1.5, 2
Cutting fluid	None
Tool overhang (mm)	20, 30, 50
Rack angles	7, 10, 14
Side clearance angle of knife edge	7 deg
Side clearance angle of vee shaped	7 deg
Approach angle of knife edge	90 deg
Approach angle of vee shaped	45 deg

The details of the experimental and tool conditions are presented in Table 1. Also, Table 2 shows the procedures of the designed experiments.

The vibration signal was measured using to B and K accelerometers (type 4331). The accelerometers were positioned on the lathe tool such that they would record both the vertical and axial vibration of the lathe tool. The extracted signal of the accelerometer was amplified by B and K amplifier (type 2626) and fed to two channels of the Solatron (Schlumberger 1200) analyzer (Fig. 1).

Clamp and the tool overhang were adjusted such that tool overhangs of 20, 30 and 50 mm occurred. The saddle and cross slide was adjusted to place the lathe tool at a central position along the workpiece and the cutting tool was adjusted to a no-contact position, which corresponded to a lathe tool/workpiece separation distance of 20 mm. This position was used as the reference position for determination of the vibrational response of the machine tool, under the no cut conditions (Fig. 2).

In general, depth of cuts was set between 1 to 2 mm, which could be classified as intermediate finishing cuts in mentioned lathe machine. It should be mentioned that selection of the maximum depth of cut was largely based on trial tests, which were carried out without the use of cutting fluid. The use of cutting fluid was found to cause problems with the accelerometers, but without its use the cutting tool tended to heat up considerably, causing the high speed steel cutting tools to burn out. But if cutting fluid was used in experiment, it is predicted that the vibration characteristics would not change noticeably. Because it is obvious that temperature variation has very little effect on vibration of structures. Therefore the results, achieved in this study, are valid while cutting fluid is applied.

Table 2: The procedures of designed experiments (feed rate f = 0.084 mm rev^{-1}; cutting time = 20 sec; tool material and workpiece material were HSS and BS 970, respectively)

No.	Tool shaped	Tool edge condition	Spindle speed (rpm)	Depth of cut (mm)	Tool overhang (mm)	Rake angle (deg)
1	Knife	Sharp	150	1.0	30	14
2	Knife	Worn†	150	1.0	30	14
3	Knife	Sharp	150	1.5	30	14
4	Knife	Worn	150	1.5	30	14
5	Knife	Sharp	150	2.0	30	14
6	Knife	Worn	150	2.0	30	14
7	Vee	Sharp	150	1.0	30	14
8	Vee	Worn	150	1.0	30	14
9	Vee	Sharp	150	1.5	30	14
10	Vee	Worn	150	1.5	30	14
11	Vee	Sharp	150	2.0	30	14
12	Vee	Worn	150	2.0	30	14
13	Knife	Sharp	150	1.5	30	7
14	Knife	Sharp	150	1.5	30	10
15	Knife	Sharp	150	1.5	30	14
16	Knife	Sharp	150	1.5	20	14
17	Knife	Sharp	150	1.5	30	14
18	Knife	Sharp	150	1.5	50	14

$^{\dagger}VB_{max}$ = 0.6 mm

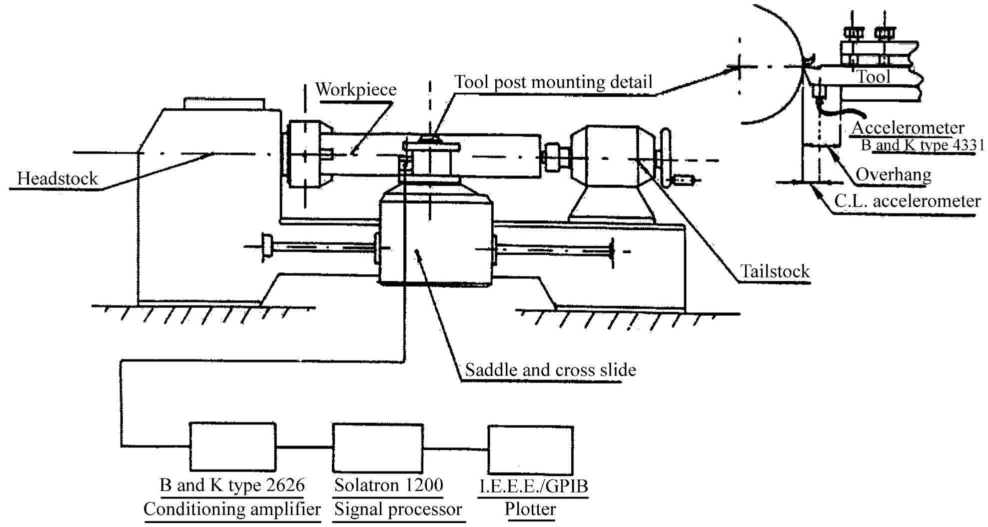

Fig. 1: Schematic layout of machine tool for vibration analysis test

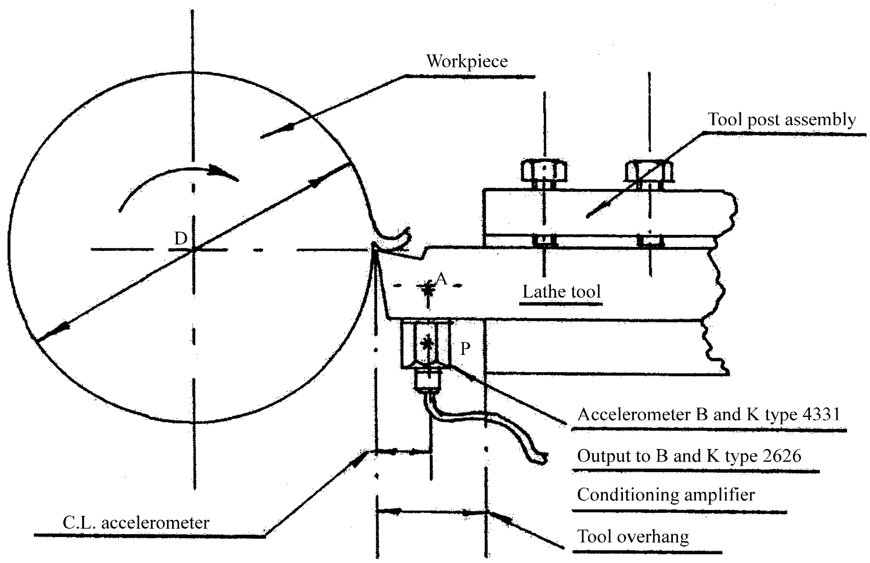

Fig. 2: Details of tool overhang and accelerometer position (axial mounting A, vertical mounting P)

RESULTS AND DISCUSSION

Here the spectrum of vibration signals are extracted by the FFT method (Steven, 1988) for different test conditions. Then, based on the mentioned spectrums, the effect of the cutting and tool edge conditions on the vibration phenomenon will be identified and studied.

Sharp and worn tool profiles condition in knife edge and vee shaped tools: For sharp and worn tool condition, the tests were carried out in knife edge and Vee shaped tools separately in different depth of cut. The relevant spectrum of the vibration signals for knife edge tools in specified conditions (spindle speed 150 rpm; feed rate 0.084 mm rev^{-1}; rake angle 14 deg; tool overhang 30 mm) were extracted for 1, 1.5 and 2 mm depth of cut as they are shown in Fig. 3, 4 and 5, respectively.

Also, the relevant spectrum of the vibration signals for Vee shaped tools in specified conditions (spindle speed 150 rpm; feed rate 0.084 mm rev^{-1}; rake angle 14 deg; tool overhang 30 mm) were extracted for 1, 1.5 and 2 mm depth of cut as they are illustrated in Fig. 6, 7 and 8, respectively.

As it is clear from data, the spectrums associated with worn tool contain more energy than sharp tool within 0 to 3.5 kHz. In other words, for detecting the worn tool by spectrum of extracted vibration signal, it is sufficient to

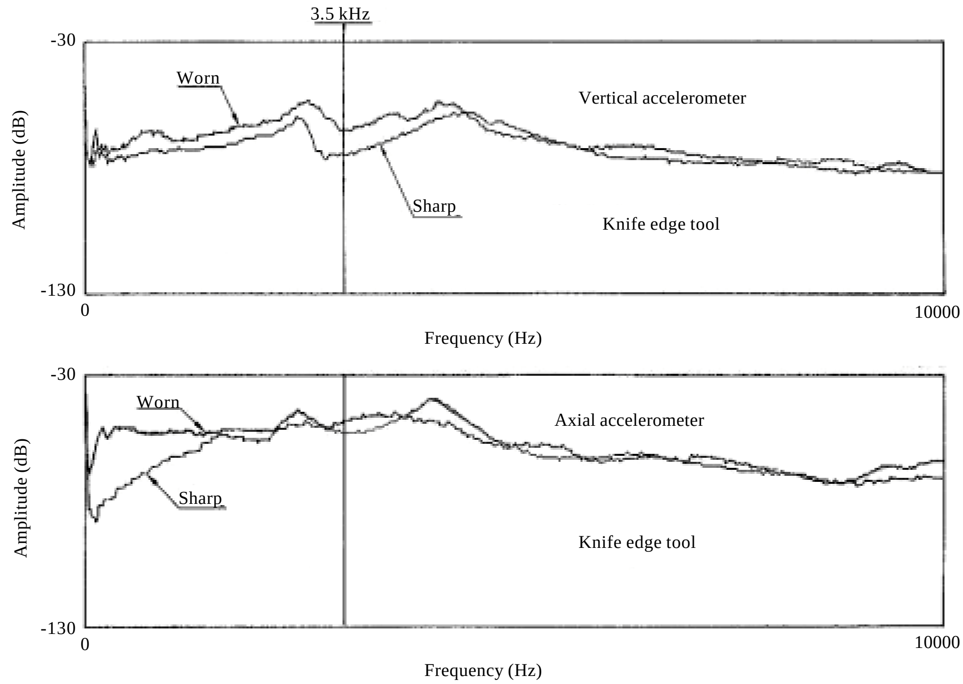

Fig. 3: Spectrum of vibration signal for knife edge tool in depth of cut 1 mm (spindle speed 150 rpm; feed rate 0.084 mm rev^{-1}; rake angle 14 deg; tool overhang 30 mm)

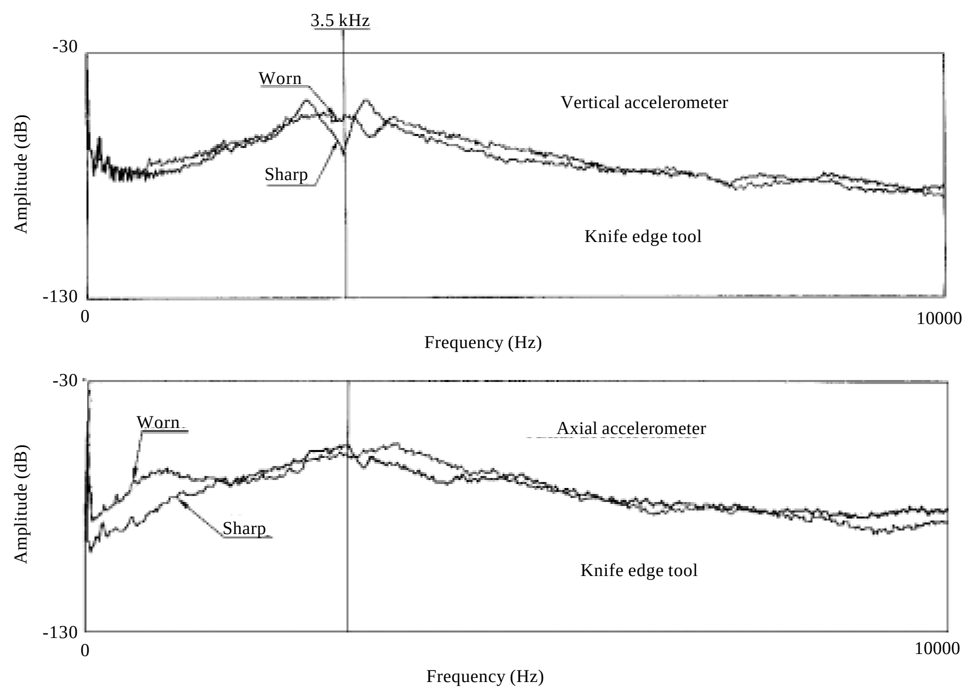

Fig. 4: Spectrum of vibration signal for knife edge tool in depth of cut 1.5 mm (spindle speed 150 rpm; feed rate 0.084 mm rev^{-1}; rake angle 14 deg; tool overhang 30 mm)

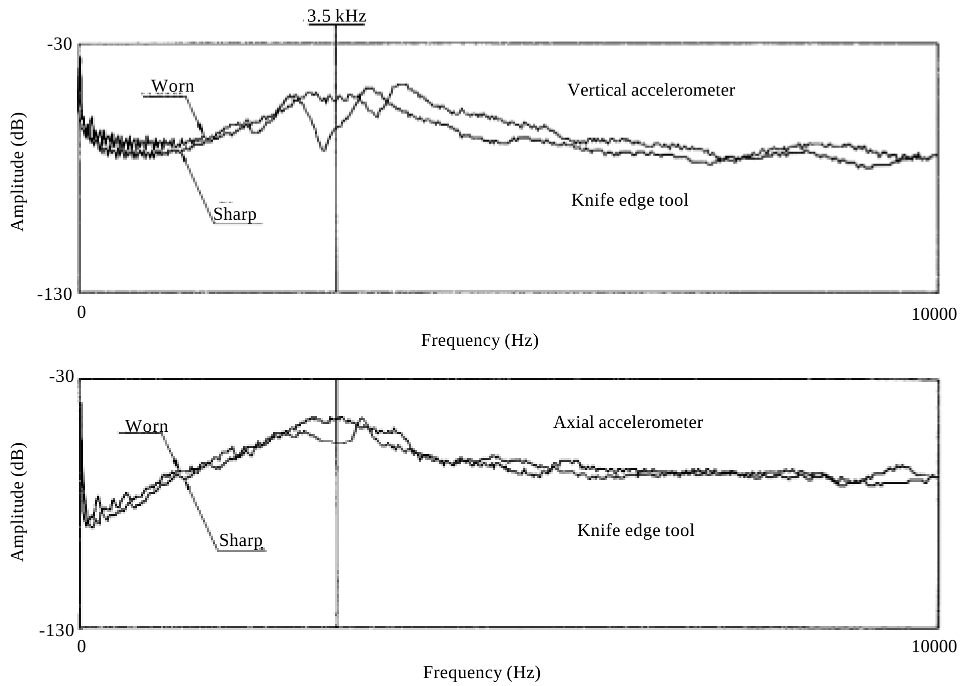

Fig. 5: Spectrum of vibration signal for knife edge tool in depth of cut 2 mm (spindle speed 150 rpm; feed rate 0.084 mm rev^{-1}; rake angle 14 deg; tool overhang 30 mm)

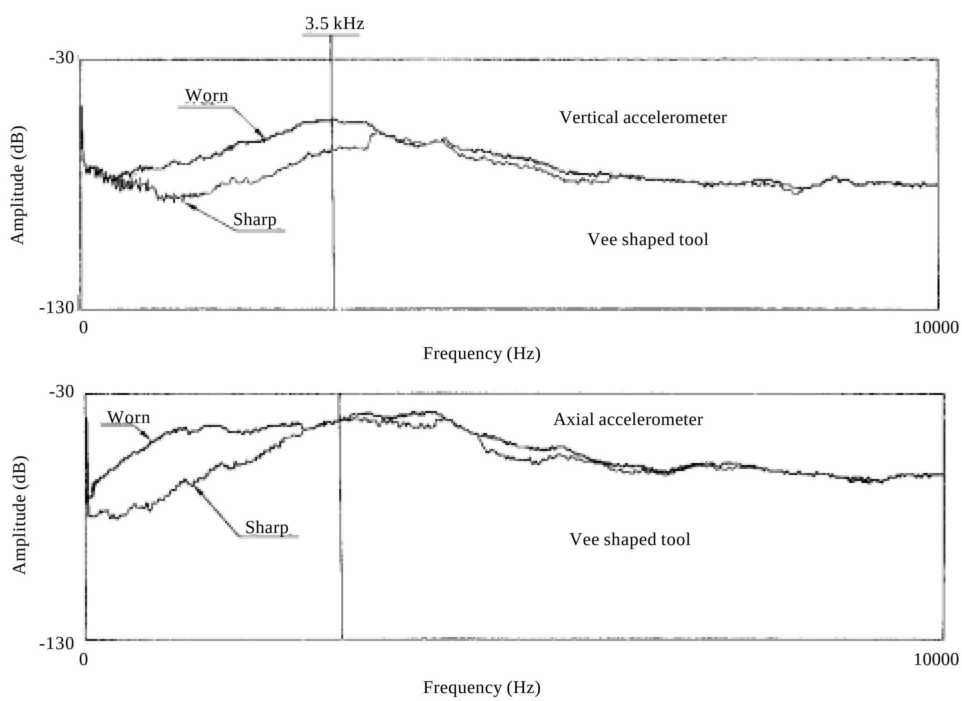

Fig. 6: Spectrum of vibration signal for Vee shaped tool in depth of cut 1 mm (spindle speed 150 rpm; feed rate 0.084 mm rev^{-1}; rake angle 14 deg; tool overhang 30 mm)

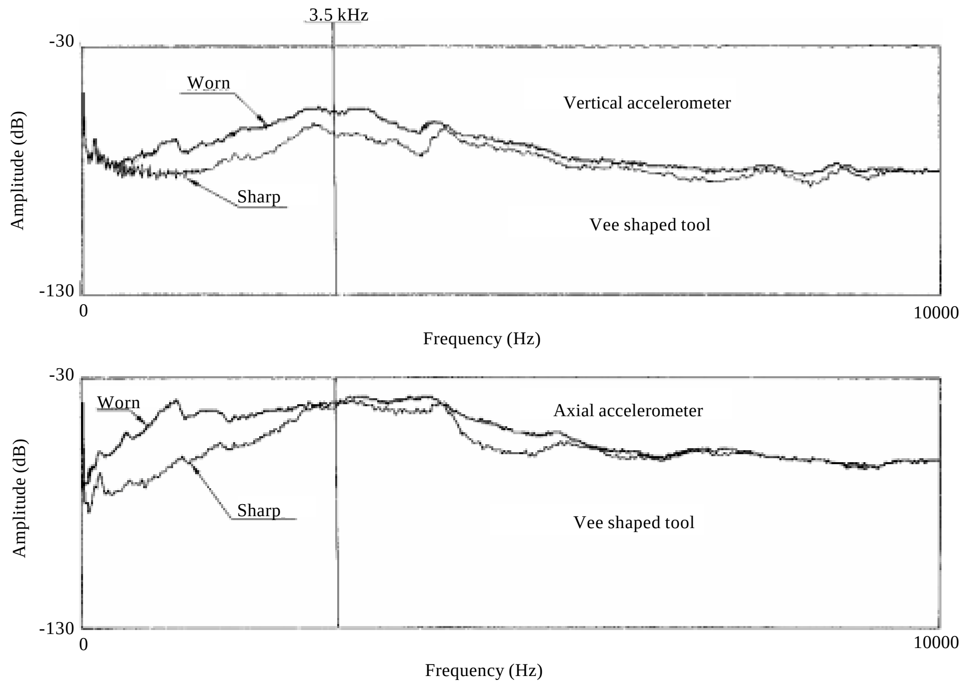

Fig. 7: Spectrum of vibration signal for Vee shaped tool in depth of cut 1.5 mm (spindle speed 150 rpm; feed rate 0.084 mm rev^{-1}; rake angle 14 deg; tool overhang 30 mm)

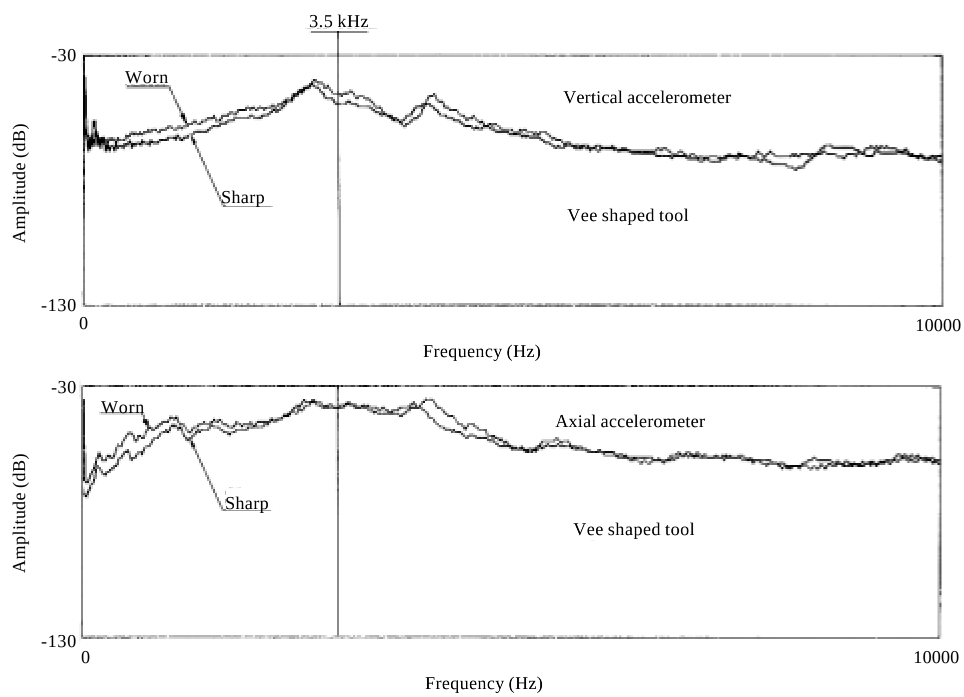

Fig. 8: Spectrum of vibration signal for Vee shaped tool in depth of cut 2 mm (spindle speed 150 rpm; feed rate 0.084 mm rev^{-1}; rake angle 14 deg; tool overhang 30 mm)

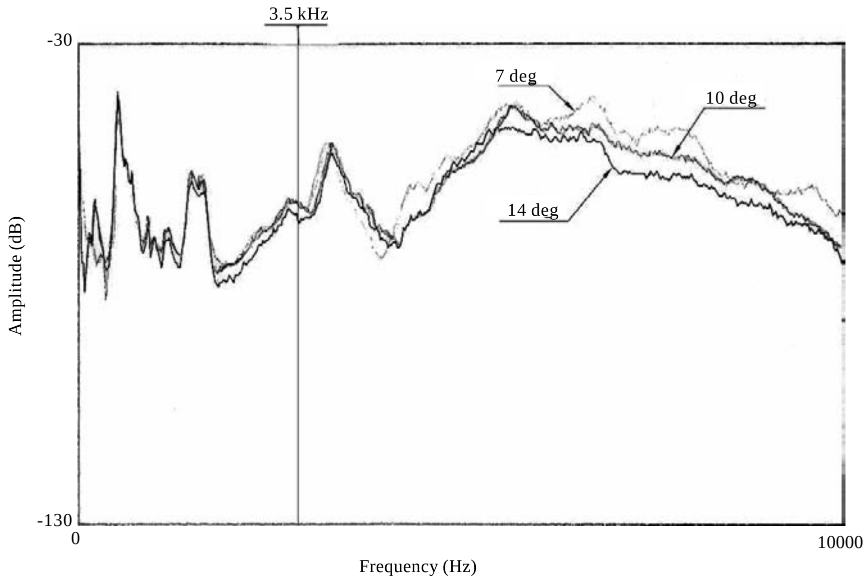

Fig. 9: Spectrum of vibration signal for knife edge tool for different rake angle (depth of cut 1.5 mm; spindle speed 150 rpm; feed rate 0.084 mm rev^{-1}; rake angle 14 deg; tool overhang 30 mm)

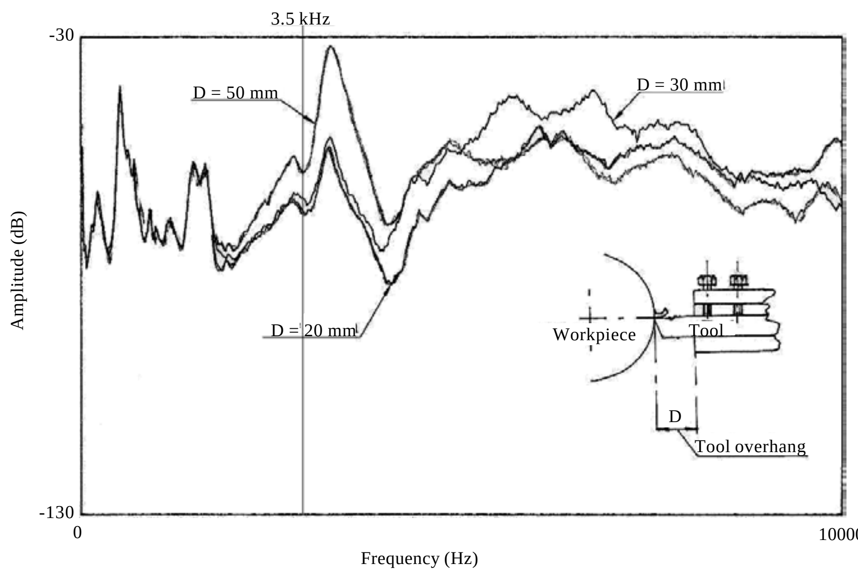

Fig. 10: Spectrum of vibration signal for knife edge tool for different tool overhang (depth of cut 1.5 mm; spindle speed 150 rpm; feed rate 0.084 mm rev^{-1}; rake angle 14 deg)

inspect the amplitude within mentioned frequency range. Therefore by observing the increasing behavior of spectrum energy within mentioned range, the wearing of the tools can be identified.

Robustness study of proposed method against changes of rake angle and tool overhang: For robustness study of the proposed method, spectrums of vibration signals in different rake angle and tool overhang, which are very important in machining process, was extracted. As a sample, the relevant spectrum of the vibration signals in specified conditions (depth of cut 1.5 mm; spindle speed 150 rpm; feed rate 0.084 mm rev^{-1}; rake angle 14 deg; tool overhang 30 mm) were extracted for knife edge tools in different rake angle and tool overhang conditions as they are shown in Fig. 9 and 10, respectively.

It can be seen from Fig. 9 and 10 that the spectrum of the vibration signal is not sensitive to varying of rake angle and tool overhang conditions for frequencies up to the 3.5 kHz in which the proposed method has been applied. The mentioned behavior of sensitivity is because of signal to noise ratio (SNR) that is in the low frequency (<3.5 kHz) and high frequency range (>3.5 kHz), the SNR is high and low, respectively as it is reasonable. In other words, the noise level is very low in the frequencies up to the 3.5 kHz, but in frequencies more than 3.5 kHz, the existence of noise may cause the signal to behave randomly such that the spectrum not to be overlapped. Therefore the proposed method is robust to the changes of the rake angle and tool overhang, which is one of the important results in this work.

CONCLUSIONS

In this study a method was proposed for identifying the worn tools, based on using the vibration signal spectrum. The signal was extracted in the specified conditions during the turning operation of the machine. It was found that the energy of the signal spectrum in the range of the 0 to 3.5 kHz is good indicator for wear tool identification. In other words, it was shown that wearing of tools is accompanied by increasing the spectrum amplitude in the frequency range of 0 to 3.5 kHz. Therefore for detection of the worn tools, it is sufficient to be focused in the specified range for observing the spectrum amplitude. The mentioned result was approved for knife edge and Vee shaped tools in different depth of cut. Also, because of high SNR in the range of interested frequency (0 to 3.5 kHz), it was concluded that the spectrum of vibration is not sensitive to changing of the rake angle and tool overhang conditions. Therefore the proposed wear detection method is applicable for different rake angle and tool overhang conditions.

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