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Application of short-term fractional Fourier transform to identify both chatter and structural damage from cutting force signals

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ABSTRACT

This paper proposes a new approach to analyze the stability of a disc with defects during a turning process. The cutting tool is assumed to be rigid but the work-piece is really deformable. Consequently, a self-excited vibration commonly named chatter phenomenon appeared causing poor surface finishing, premature cutting tool wear and undesirable noise. As defects, we consider structural damages like cracks and hard inclusions masked in the matter of the work-piece which can appear on the machined surface. In the two cases, the measured cutting forces are perturbed and the corresponding signals are almost contemned by uncertainties. A time-frequency representation using the short-term fractional Fourier transform was applied to extract, from cutting force signals that contain multiple non-stationary components, the required information relating to the existence of chatter and structural damages. In order to simulate damage, a longitudinal crack is voluntarily created on the cylindrical surface of a disc and the cutting forces are measured for different cutting conditions during machining operations. The spectrograms of the measured signals revealed the incontestable capacity of this method to detect the chatter phenomenon by its characteristic frequency in the time domain as well as the local damages in the frequency and time domains.

INTRODUCTION

During machining, the work-piece vibrations can occur following a deficiency of its rigidity if the tool is assumed to be rigid. This self-excited vibration « chatter » is an unfavorable phenomenon causing instability of the machining system; poor surface quality and premature damage of the cutting tools. For this reason, there has been an industrial and academic interest topic in manufacturing for many years. Active chatter elimination methods require the chatter to be detected before the control reacts. Researchers have studied how to detect, to identify, to avoid, preventing, to reduce, to control, or to suppress chatter. Fofana *et al*. (2003) investigated the influence of the interactions between chatter instability and tool-wear in turning operations by measuring the tool-wear and the corresponding cutting forces at varying time intervals. The variations in the wear parameters and the cutting forces are compared with the changes in stability charts of the turning operation and then explicit analytical expressions are derived for predicting the onset of chatter instability and tool-wear. Lacerda and Lima (2004) applied an analytical method in which the time-varying directional dynamic milling forces coefficients are expanded in Fourier series and integrated in the width of cut bound.The cutting forces are evaluated by an algorithm using a mathematical model derived from several experimental tests with a dynamometer. By plotting the stability lobes, the curves relate the spindle speed with axial depth of cut permit to separate stable and unstable areas allowing the selection of cutting parameters resulting in maximum productivity with acceptable surface roughness and absence of chatter vibrations. Lacerda and Tsao (2006) proposed a new approach to

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analyze the stability of a turning process where the deformation of the work-piece as a result of the application of an external force by the cutting tool is considered. Partial differential equations and a set of dynamic equations are developed by considering the interaction between the tool and the work-piece to describe the cutting process. Having performed Laplace transformation, the stability of the cutting system can be analyzed. The relationship between the critical chip width and the cutter spindle speed is investigated under a range of cutting and work-piece conditions. Vela-Martinez *et al.* (2008) proposed a multiple degree of freedom model for chatter prediction in turning based on compliance between the cutting tool and the work-piece taking into account the effect of the dynamic characteristics of the cutting tool. A linear stability analysis of the model in the frequency domain is performed and the effect of the dynamics of the cutting tool on the stability of the process is analyzed. Altintas *et al.* (2008) presented frequency and discrete time domain chatter stability laws for milling operations. By averaging time and varying directional factors at chatter pitch intervals, the stability lobes are solved directly and analytically. When the process is highly intermittent, the stability lobes are more accurately solved either by taking higher harmonics of directional factors in frequency domain or by using semi-discretization method. The stability solutions against the numerical solutions are compared to the experiments providing comprehensive mathematical details of both fundamental stability solutions. Mann *et al.* (2008) proposed a new theoretical model for helical end-mill cutting forces with the convenience in implementing the developed expressions for vibration prediction. Specifically, the presented force model is used to predict cutting forces with a Fourier series expansion and chatter vibration with an updated temporal finite element analysis. The developed analyses are compared and validated through comparisons with prior works. Altintas *et al.* (2008) proposed a cutting force model which has three dynamic cutting force coefficients related to regenerative chip thickness, velocity and acceleration terms respectively. The dynamic cutting force coefficients are identified from controlled orthogonal cutting tests with a fast tool servo oscillated at the desired frequency to vary the phase between inner and outer modulations. It is shown that the process damping coefficient increases as the tool is worn, which increases the chatter stability limit in cutting. The chatter stability of the dynamic cutting process is solved using Nyquist law and compared favorably against experimental results at low cutting speeds. Two control strategies are developed by Hajikolaei *et al.* (2010) to suppress chatter vibration in the turning process including a worn tool. In the first stage, a sinusoidal spindle speed variation around the mean speed is modulated to disturb the regenerative mechanism. The optimal amplitudes of the speed modulations are found to be based on a genetic algorithm so that the input energy to the turning process is minimized. In the second stage, an adaptive controller is designed to improve the response of the system which is associated with small ripples under the steady state condition where the provided external force is the input variable. It is shown that chatter vibration is suppressed innless time without any ripples at the steady state condition if both control approaches are applied simultaneously. A novel approach is presented by Mahnama and Movahhedy (2010) to investigate the effects of various conditions at the beginning of chatter vibration using finite element simulation of chip formation which is combined with dynamic analysis of machine tool to determine the interaction between the two phenomena. By repeating the simulations under various widths of cut, it is shown that the onset of chatter can be detected. The stability map obtained from simulations is compared to experimental data attained through orthogonal cutting tests and reasonable agreement is observed between the two sets of results. The paper of Siddhpura and Paurobally (2013) focuses on the stability of chatter vibrations and tool wear prediction by constructing stability lobes of an orthogonal turning operation using simulations. A tool wear equation is derived which investigates the effects of self-excited chatter vibrations on tool wear in order to predict the tool life. This new tool wear equation clearly indicates that the tool wear increases very rapidly in the presence of chatter. The proposed analytical model and the tool wear equation have been validated with the orthogonal turning experimental results. In a recent work, Hynynen *et al.* (2014) propose a new chatter detection method based on a coherence function of the acceleration of the tool and an audio signal. The proposed method was experimentally tested in turning and the obtained results show that chatter can be detected in an early stage, allowing correcting control actions before the chatter influences the surface quality of the work-piece. The study proposed by Urbikain *et al.* (2012) deals with the problem of chatter prediction in straight turning of non-rigid parts. A stability model has been developed using the Chebyshev collocation method which is applied to a SDOF system by means of a specially designed test part and demonstrates its usefulness to determine chatter-free conditions.

In addition to chatter phenomena, cracks, bubbles and hard inclusions which are generally masked in the matter of the work-piece, generate shocks each time the tool comes into contact with these defects during machining. The detection of these defects can be made by analyzing the cutting force signals by the same methods proposed by Djebala *et al.* (2007), Zhang and Randall (2009), Raj *et al.* (2011) in the case of bearings and by Djebala *et al.* (2012), Li and Liang (2012), Omar and Gaouda (2012) in the case gears.

One of the time-frequency representation methods is certainly the fractional Fourier transform which proves a success for the analysis of pseudo periodic signals in order to detect gears defects (Luo *et al.* 2012). Zhou *et al.* (2011) proposed an adaptive filter based on the fractional Fourier transform to remove the noise from vibratory signals and to highlight the signal components indicating the presence of the dynamic defects of the machines. In this approach, adaptive filters in the field of the fractional Fourier transform are used by optimizing the transformation order and the filter parameters. The transformation order is selected when the signal gathers the highest energy, and the filter parameters are determined by evolution rules. Capus and Brown (2003) showed that the fractional Fourier transform is a powerful tool for the analysis of the pseudo periodic signals but it fails to locate the frequency contents required in certain applications. The short term fractional Fourier transform is proposed to solve this problem because it allows a combined time-frequency representation with a good bidimensional resolution (Tao *et al*. 2010). An optimal order of fractional transformation must correspond simultaneously to energy density and signal intensity in both temporal and frequency domains (Catherall and Williams, 2010).

The present work aims at the detection of the chatter phenomena in temporal domain and the structural defects in frequency domain using time-frequency representations offered by the short term fractional Fourier transform based on the treatment of the measured cutting forces signals. An expert system can be implemented for the diagnostic and the control of chatter phenomenon and for the detection of the structural defects during machining.

Formulation of The Method:

The fractional Fourier transform is a method recently developed for the analysis and the treatment of the pseudo periodic signals as a generalization of the classic Fourier transform. It can be interpreted by the rotation of an arbitrary angle αin the time-frequency domain giving additional degrees of freedom to the fractional Fourier transform in the signal treatment.

In the real cases, a signal is not linearly modulated but it can even be multi-components. Nevertheless, if the instantaneous frequencies of the signal components change slowly along a certain direction in the time-frequency plan, we can find the fractional domains where the signal is better concentrated. The shot-term fractional Fourier transform allows finding these fractional domains, leading to possible improvements in the time-frequency representations (Fig. 1).

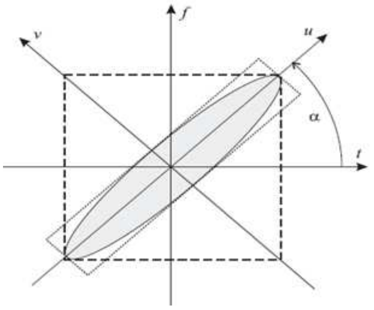

Fig. 1 : Principal (t, f) and fractional (u, v) plans

The short-term Fourier transform of a signal x(t) is given by:

$$\mathrm{STFT}[x](t,f)=\int_{-\infty}^{\infty} x(t+t_0)g^*(t_0)e^{-j2\pi t_0 f}dt_0 \tag{1}$$

For a better representation, the window $g^*(t_0)$ can be adjusted according to the type of the signal, the direction of time or frequency.

The fractional Fourier transform of a signal x(t) can be expressed as:

$$\mathrm{FrFT}[x]_\alpha(u)=\int_{-\infty}^{\infty} K(\alpha,t,u)x(t)dt \tag{2}$$

Where the Kernel $K(\alpha,t,u)$ is given by:

$$K(\alpha,t,u)=\frac{\exp(\frac{j\alpha}{2})}{\sqrt{j\sin\alpha}}\exp(j\pi\frac{(t^2+u^2)\cos\alpha-2tu}{\sin\alpha}) \tag{3}$$

With the rotation-type relationship (cf. Fig. 1) is given by:

$$\begin{pmatrix} t \\ f \end{pmatrix}=\begin{pmatrix} \cos\alpha & -\sin\alpha \\ \sin\alpha & \cos\alpha \end{pmatrix}\begin{pmatrix} u \\ v \end{pmatrix} \tag{4}$$

The short term fractional Fourier transform of the signal x(t) is given by:

$$\mathrm{STFrFT}[x]_{\alpha}=\exp\left[j\pi(uv-tf)\right]\int_{-\infty}^{\infty}x(t+t_0)\left[\mathrm{FrFT}\left[g(t_0)\right]\right]_{-\alpha}^{*}\exp(-j2\pi t_0)dt_0 \qquad (5)$$

We conclude that the short term fractional Fourier transform of the signal x(t) in the fractional domain can be calculated directly as fractional Fourier transform normal by using a window which is the fractional Fourier transform of the first window g(t), followed by the rotation of the reference system.

Using the fractional Fourier transform moments of the signal and an adapted window followed by a rotation of the coordinate system, a better temporal localization of the frequencies contained in the signal can be obtained. The signal width in the temporal or in the frequency domains can be estimated from its second order central moment in the fractional domain P_{α} according to Stanković *et al*. (2003) by:

$$p_{\alpha}=p_0\cos\alpha^2+p_{\pi/4}\sin\alpha^2)+\left[w_{\pi/4}-m_0m_{\pi/2}-(w_0-w_{\pi/2})/2\right]\sin 2\alpha \qquad (6)$$

Where:

p_{α} is the second-order central fractional Fourier transform moment;

m_{α} is the first-order moment at arbitrary angle α;

w_{α} is the second-order moment at arbitrary angle α.

In order to find the fractional domain where the signal has an extreme width, it is easy to note that the first derivative of P_{α} is equal to zero for a given value of $\alpha=\alpha_e$:

$$\frac{dp_{\alpha}}{d\alpha}=(p_{\pi/2}-p_0)\sin2\alpha+\left[2(w_{\pi/4}-m_0m_{\pi/2})-(w_0+w_{\pi/2})\right]\cos 2\alpha \qquad (7)$$

Consequently, the fractional transformation angle is calculated as follows:

$$\tan2\alpha_e=\frac{\sin2\alpha_e}{\cos2\alpha_e}=\frac{2(w_{\pi/4}-m_0m_{\pi/2})-(w_0+w_{\pi/2})}{p_0-p_{\pi/2}} \qquad (8)$$

As we can see, the signal reached its minimal width for a value α_e corresponding to the $\cos\alpha_e$ when it has the same sign as $(p_{\pi/2}-p_0)$. The other value of α_e in the interval [0, π] corresponds to the maximum width of the signal.

Experimental Setup:

Fig. 2 shows the flexible steel disc mounted on the lathe and the rigid tool fixed on the Kistler device. Before the turning tests, some imperfections are voluntary created as grooves of 2 mm of depth on the cylindrical surface of the disc. The cutting force signals are recorded in the three directions when the tool machined the work-piece.

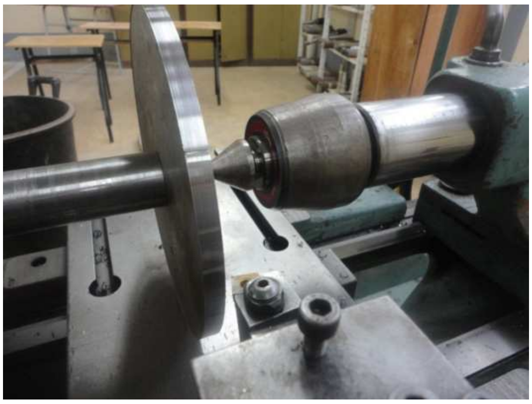

Fig. 2: Experimental setup

The first eight cases of table 1 concern the disc with a single defect on its surface. The corresponding cutting conditions are programmed following the orthogonal standard plan of Taguchi (2^3). The cutting conditions, in the case when the disc has two defects spaced by 90°, are presented by the last three cases.

Table 1:

Case	1	2	3	4	5	6	7	8	9	10	11
Disc speed N (rpm)	1400	1400	1400	1400	355	355	355	355	1400	710	355
Feed f_a (mm/rev)	0.08	0.08	0.16	0.16	0.08	0.08	0.16	0.16	0.08		
Depth of cut a_p(mm)	0.5	1	0.5	1	0.5	1	0.5	1	0.5		

During the turning process, the cutting forces were measured by a three component force dynamometer (Kistler 9257 B) which is connected to a computer. The measured signals of F_x, F_y and F_z components are amplified with a charge amplifier type 5019B. However, the acquisition and the treatment of the cutting forces signals are carried out under the DynoWare software which provides a good real time visualization of the curves that can be exported as a text files.

After the adjustment of the Kistler device parameters, in particular a sampling frequency of 12000Hz and the measurement time, the tests were carried out according to experimental cases mentioned above. An example of the measured signals of the cutting forces corresponding to case 1 are presented in Fig. 3.

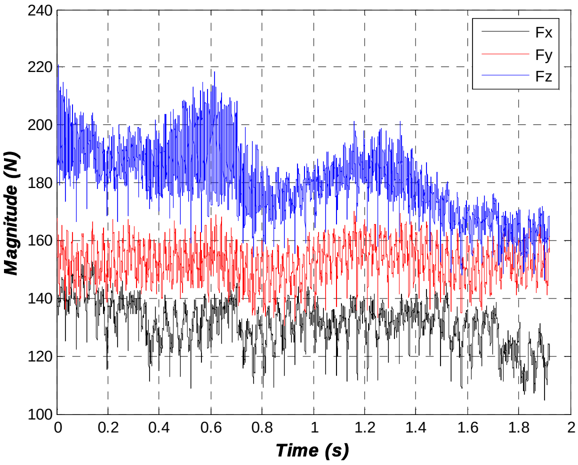

Fig. 3: Cutting force signals in case 1

Treatment of Results:

A first treatment of the measured signals is obtained by the application of the fast Fourier transform in order to determine the frequency signatures such as the rotating frequency and its harmonics, the natural frequencies or others. The tangential cutting force which is measured according to the direction of the disc rotation is chosen to represent the FFT spectrum since this parameter is generally the most significant.

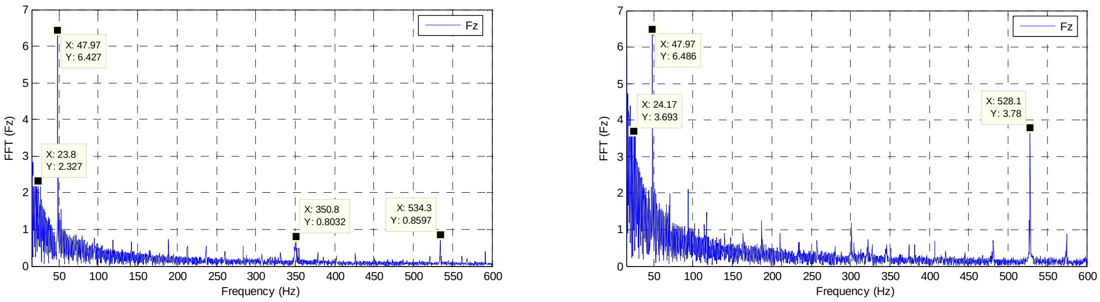

Fig. 4: Spectrum of Fz cutting force for case1 (left) and case 2 (right)

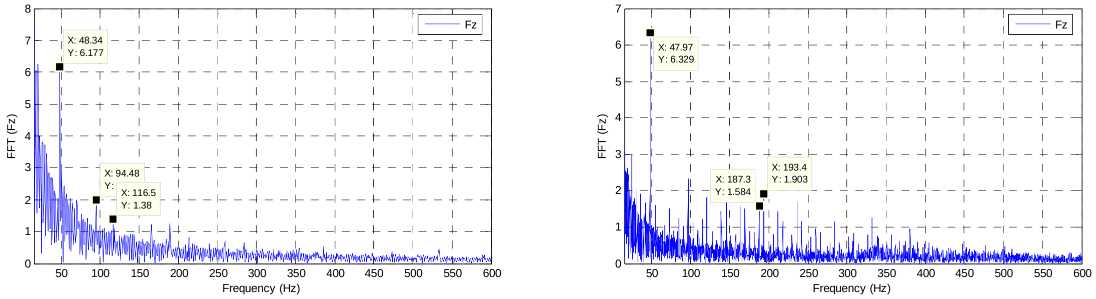

Fig. 5: Spectrum of Fz cutting force for case 9 (left) and case 10 (right)

According to the FFT spectrums presented in (Figs. 4-5), peaks representing the rotational frequencies and their harmonics are definitely visible. In addition to rotational frequencies, a characteristic peak appears roughly to 48Hz in all cases. As the amplitude of the corresponding peak is higher than that of the rotational frequency itself, we confirmed thereafter that this frequency corresponds to the electrical frequency of 50Hz resulting from an electrical defect by modal tests with the Pulse instrument working on its battery independently to the electrical Network.

Two peaks which characterize the disc resonances (Fig. 4) appear during case 1 at 350.8Hz and 534.3Hz but with lower amplitude. The second peak appears only during case 2 at a frequency of 528.1Hz but its amplitude is much more significant. During the two tests, we noted strong vibrations of the disc and an enormous noise characterizing the chatter phenomenon. In a recent work, Urbikain *et al*. (2012) propose a stability criterion to confirm stable and unstable cases during the experimental tests by analyzing the frequency content of the signals. They confirm the case when the frequency peaks appear powerfully near the natural frequency of the system, then chatter occurs. On the contrary, if the frequency peaks coincide with the cutting frequency and its multiples, this state is typically due to forced vibrations and leads to low amplitudes, the machining is considered as being stable.

In this work, we propose to apply an approach based on time-frequency analysis using the short-term fractional Fourier transform to treat the measured signals. The Gauss window is used because it gives a good compromise between the temporal and frequency resolutions. We chose two different widths: very fine (64 points) in order to visualize the non-stationary transient zones and wide (1024 points) to visualize the frequency signatures like that of chatter.

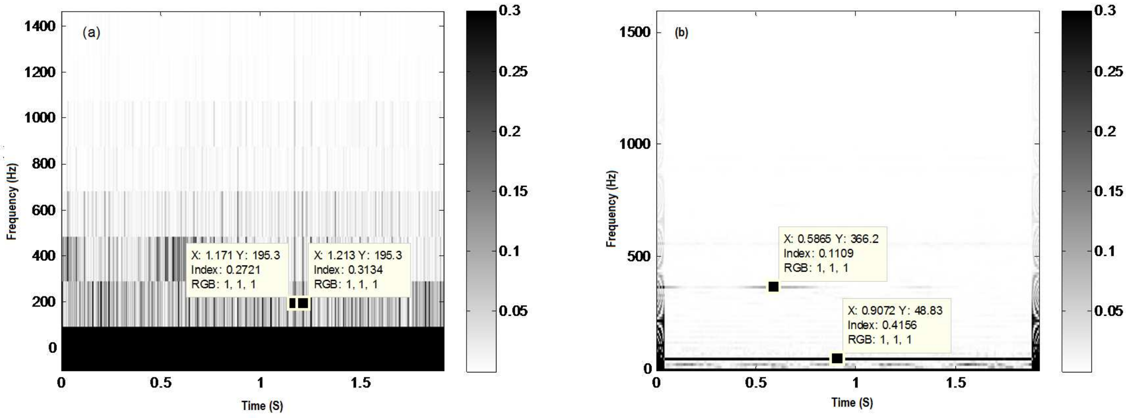

Fig. 6: Short-term fractional Fourier transforms spectrogram for different Gauss window sizes in case 1
(a) M=64 (t=0.002s) and (b) M=1024 (t=0.04s)

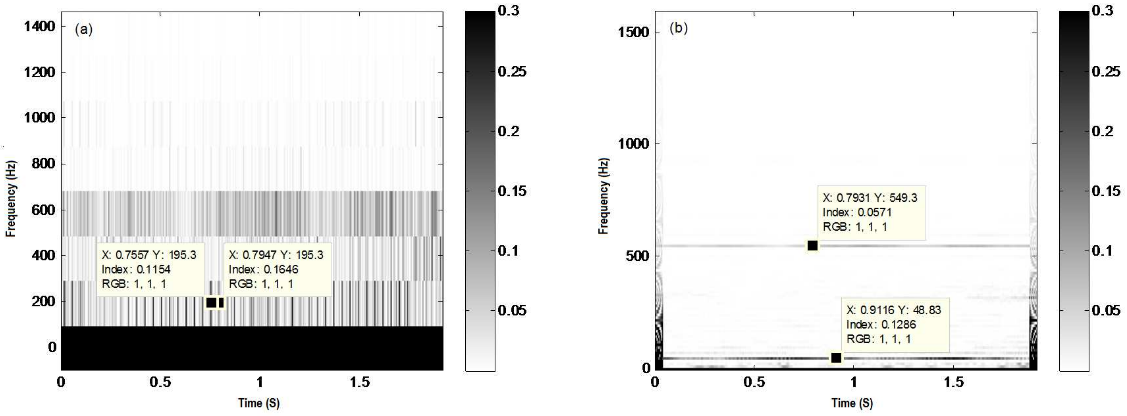

Fig. 7: Short-term fractional Fourier transforms spectrogram for different Gauss window sizes in case 2
(a) M=64 (t=0.002s) and (b) M=1024 (t=0.04s)

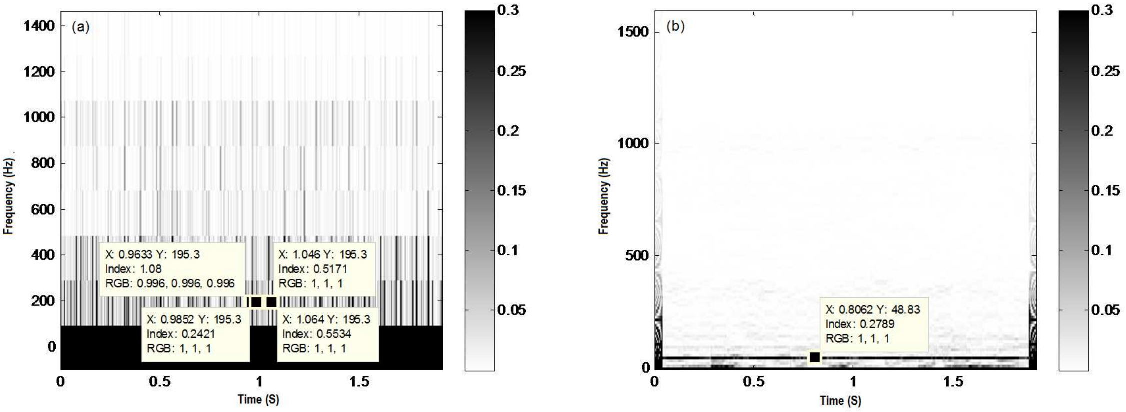

Fig. 8: Short-term fractional Fourier transforms spectrogram for different Gauss window sizes in case 10
(a) M=64 (t=0.007s) and (b) M=1024 (t=0.125s)

The spectrograms show that the used size of the Gauss window has a significant role in the time and frequency resolution. A fine window allows a better localization, in time space, of the tool impacts with the defect making therefore a bad frequency resolution. Spaced impacts of a period of 0.042s correspond to a rotational disc speed of 1400rpm (Fig. 6a) and 0.159s for 355rpm (Fig. 7a) are observed. In the case of existence of two defects, two series of impact are visible (Fig. 8a). A period, equal to 0.084s, which corresponds to rotational disc speed of 710rpm, is observed and it is shifted of 0.022s. This result confirms the presence of two spaced defects of an approximate angle of 90°. Therefore, when this window is extensive, a good localization in frequency domain is reached while losing the temporal resolution. The time-frequency representations resulting from the application of the short term fractional Fourier transform confirm the previous observations with regard to the frequencies of 48.83Hz, 366.28Hz and 549.3Hz. It is clear that the first frequency exists in the spectrograms (Figs. 6b-8b) since it concerns an electrical Network defect. The evolution of the frequency phenomena in time can be continuous for the frequency 549.3Hz (Fig. 7b) and discontinuous in the case of the frequency 366.28Hz (Fig. 6b). In both cases, chatter can excite certain natural frequencies of the disc in a continuous or discontinuous way during machining process since it is a random phenomenon.

Conclusion:

In this work, the time-frequency representations as a result of the application of the short-term fractional Fourier transform method were presented. The method is based on the treatment of the cutting forces signals measured during the turning process of a flexible disc with structural defects. The analysis of the treated signals allowed the detection of the chatter phenomenon when this one happens in frequency domain and we could highlight the impacts corresponding to the contact of the tool with the defects in the temporal domain. We showed that the good choice of the Gauss window width guarantees a compromise between the temporal and frequency resolution. A fine window allows a better temporal localization of the impacts making a bad resolution in the frequency domain. However, if this window is wide, a good localization in the frequency domain is reached while losing the temporal resolution.

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