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Robotic High Speed Machining of Aluminum Alloys

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Key Words: Robotic-machining/ Vibration response / Degree of stability/Power Spectral Density/ Finishing operations/ Aluminum alloys / Surface roughness/ cutting forces.

Abstract. The robotic machining is one of the most versatile manufacturing technologies. Its emerging helped to reduce the machining cost of complex parts. However, its application is sometimes limited due to the low rigidity of the robot. This low stiffness leads to high level of vibrations that limit the quality and the precision of the machined parts. In the present study, the vibration response of a robotic machining system was investigated. To do so, a new method based on the variation of spindle speed was introduced for machining operation and a new process stability criterion (CS) based on acceleration energy distribution and force signal was proposed for analysis. With the proposed method the vibrations and the cutting force signals were collected and analyzed to find a reliable dynamic stability machining domain. The proposed criterion and method were validated using data obtained during high speed robotic machining of 7075-T6 blocks. It was found that the ratio of the periodic energy on the total energy (either vibrations or cutting forces) is a good indicator for defining the degree of stability of the machining process. Besides, it was observed that the spindle speed with the highest ratio stability criterion is the one that has the highest probability to generate the best surface finish. The proposed method is rapid and permits to avoid trial-error tests during robot programming.

Introduction

The robotic machining is one of the emerging technologies for cost reduction in manufacturing processes. Robots are flexible and can be used for versatile tasks. They offer high degrees of freedom and permit to shape complex parts. Nevertheless, they have two major limitations which are their limited accuracy and their low stiffness. These two disadvantages limit the applications of the robot for high precision machining. For these applications, the industrials prefer CNC machine-tools, known for their rigidity and accuracy. However, the low cost of the robotic cells compared to that of the CNC machine-tools, encouraged many companies to investigate the use of the robots for advanced machining operations. Many companies succeeded to implement their own robotic cells for machining, deburring and polishing [1]. Other companies are selling packaged solutions for robotic machining cells. Most of the existing robotic machining cells are filling the actual companies' needs. Nevertheless, these cells are not used at their optimal efficiency [2]. A long setup time is needed to program these robotic machining cells. In addition generally, the optimization package for cutting conditions is not delivered with the robotic machining cells. The selection of cutting conditions is mostly based on the programmer experience and trial-error tests. During the last few years, many researches were conducted in order to rationalize robotic machining

Pan et al. [2] proposed a method for chatter detection during robotic machining. The authors studied high metal removal rates and demonstrated that the coupling mode is the main cause of chatter during robotic machining. Abele et al. [3] proposed an analytical method to predict the compliance of robotic machining system. The authors analyzed the behavior of the stiffness during the milling process; the experiments were done for high rate of material removal. Matsuoka et al. [4] presented an exhaustive study on the end milling method using an articulated robot. To accommodate the low stiffness of the robot, the authors used high spindle speed to reduce the cutting forces. The cutting forces were reduced by 50 to 70 % during the machining of the 6063S-T5. The authors considered a roughing operation with a depth of cut of 1 mm. It was observed, that many researchers were interested in the roughing operations with robotic machining systems. In fact, the limitations of the robot performance (in term of accuracy and stiffness) restrain their use to roughing operations.

The robotic machining systems are characterized by a low rigidity compared to machine tool system. To overcome this limitation the machinists use low depth of cuts and low feed rates. The low depths of cut and the low feed rates help to reduce significantly the cutting forces. The reduction of cutting forces can reduce the vibration amplitude. In addition, the low feed rate will result in a low chip load. Thus low chip reduction will help to avoid regenerative chatter. In fact, for finishing operations, at low chip loads (2.5 μm to 5 μm) and low depth of cuts (less than 0.5 mm) there is no chip formation. The obtained "chip" is a sort of dust. Thus, the regenerative chatter will rarely occur because, it is known that the regenerative chatter doesn't occur at very low depth of cuts [5]. However, this strategy of reducing the chip load and the depth of cut will increase significantly the cycle time. Also, this strategy will not permit to avoid chatter problems that can be caused by mode coupling or spindle speed modulation.

In addition, in finishing operations it is required that the machined surfaces have good surface roughness. If the surface roughness is relatively high, it will result in a long cycle time for the upcoming finishing operations (such as polishing). Therefore, it can be concluded that there is a need for selecting adequate machining parameters, during the finishing operation, to:

1. Reduce cycle time of the machining operation.
2. Avoid chatter problems (regenerative, coupled mode).
3. Obtain an acceptable surface roughness.

The first goal (in the above list) can be achieved by increasing the feed rate and the depth of cut to the maximum permissible values. The permissible values are essentially limited by the robot maximum load in each direction.

The two last goals (in the above list) can be achieved by selecting stable machining conditions. To select the stable cutting conditions one should firstly define a stability criterion. A detailed list of several criteria for detection of dynamic instabilities was proposed by Sims in the book of: Machining Dynamics [6]. Once the instability criterion is chosen, an experimental technique for detecting the instability should be selected .A multitude of instability detection techniques were proposed in the literature. A detailed summary of these techniques was presented in [7].

The majority of existing methods1 for stability detection characterizes a machining operation as a "stable operation" if it is not an "unstable operation". However, for a finishing operation, it is more interesting to detect "the most stable operation" instead of detecting the "unstable operation". The authors of the present paper, proposed the use the notion of degree of stability instead of using an instability criterion. Using this notion of degree of stability, it is possible to find the most stable operation among several operations. To do so, an experimental methodology is proposed to associate a degree of stability to a given combination of cutting parameters. The adopted methodology is explained in the following section.

In the present study, a high speed finishing operation with low material removal rate was studied. The finishing operation of low hardness materials (such as aluminum alloys), doesn't need high rigidity which makes the application of the robot an adequate choice. This choice is acceptable if the cutting conditions are well selected, otherwise the produced part quality will be unacceptable either for bad surface finish or due to the high level of vibrations marks. To limit these two factors (surface roughness and vibration level) a new method with the variation of the spindle speed was proposed in this paper. The paper begins with more details on the problematic of robotic machining, followed by the proposed methodology for overcoming this problematic in the third section. The fourth section presents the analysis and discussion of the results. The last section presents the conclusions and recommendations.

Methodology

A new method with variable spindle speed is proposed. With the proposed method, it is possible to obtain the vibration response for seven spindle speeds in one test with duration fewer than 30 seconds only. A multi-axis contouring test with a variable spindle speed for each three seconds was designed and tested. **Figure 1** presents the applied concept for testing several spindle speeds varying from 30 to 60 krpm with a step of 5 krpm.

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[1] A detection method is a combination of instability criterion and technique of detection of the considered criterion.

The proposed approach was then programmed in Catia V5□® to generate the APT program. The APT program was then post-processed using a C++ code, after which the program was tested offline on a robotic platform of simulation (robot-studio®). The experimental setup used to test the final program is described in the following section.

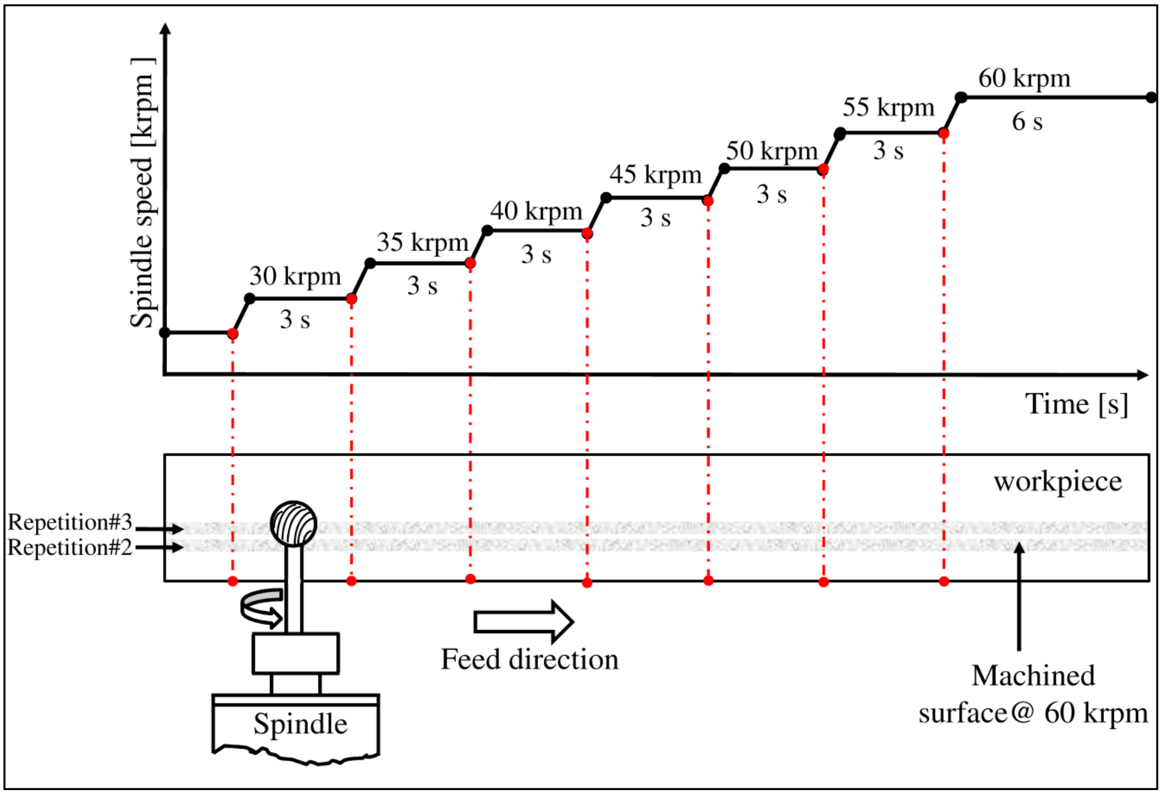

Fig. 1: The proposed approach for testing several spindle speed in one single machining test at a constant feed rate

Experimental setup. The used experimental setup is presented in figure 2. This figure shows the used ABB-IRB1600 robot (1) on which an aluminum bracket (2) was screwed for handling a high speed spindle SLF FS33-60/0.15 (3). The cutting tool, a solid carbide tool (4) was fixed manually on the spindle. This tool will be used to machine the surface of an aluminum alloy block [AA 7075-T6] (5). The block (127 x 177.8 x 76.2 mm) was fixed on a three axis dynamometer, Kistler table 9255B (6) using a three metric screws with a tightening torque of 40 N.m. The assembly (block + screws+ dynamometer) was fixed on a T-slotted table that was leveled before installing the assembly. The dynamometer was used to estimate the cutting forces during the machining operation. In addition, a tri-axial accelerometer (ENDEVCO, Model 63B-100, SN10526) was screwed on the work piece for measuring the vibrations. Another accelerometer of the same model was screwed on the spindle bracket to measure the vibration on the spindle. A third "dog watch" uni-axial accelerometer was used for controlling and checking the obtained results and it was fixed on the work piece with wax. The used coordinate system and the accelerometers positions are presented in **figure**

3. The same coordinate system and the same robot configuration were kept for all machining tests.

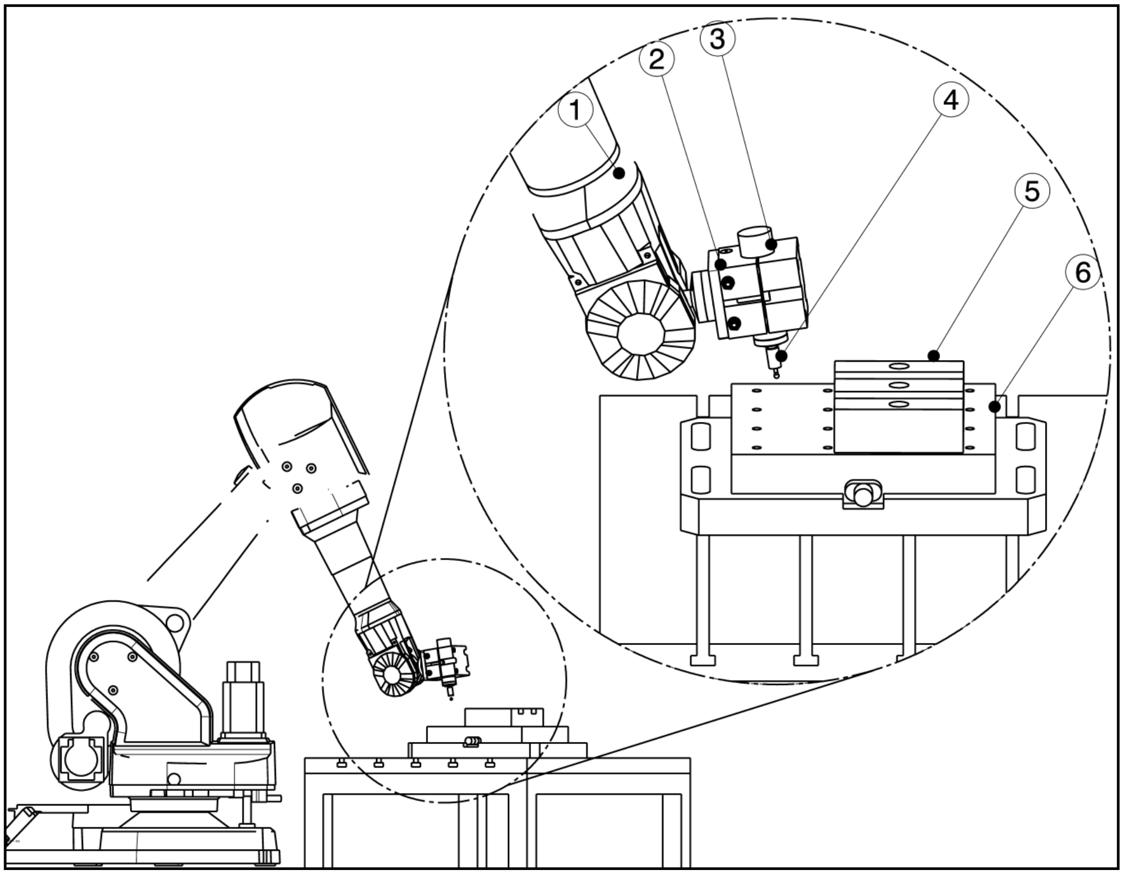

Fig. 2 The experimental setup used during the machining tests (1) ABB-IRB 1600 robot (2)The aluminum bracket (3) SLF FS33-60/0.15 spindle (4) solid carbide tool (5) work piece [AA 7075-T6] (6) 3 axes dynamometer Kistler table, 9255B.

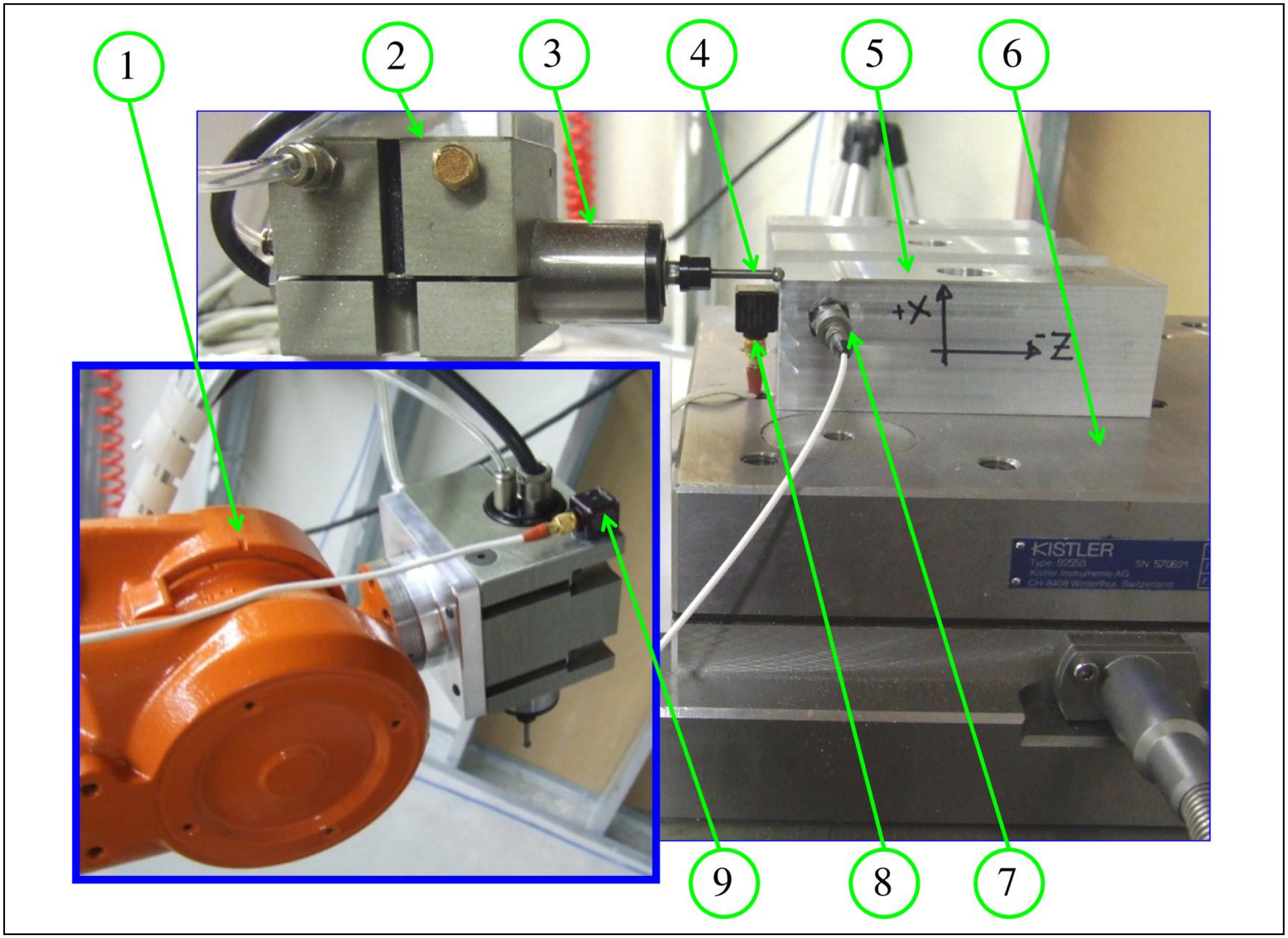

Fig. 3 Two photos of the experimental setup, showing the coordinate system and the position of the accelerometers. (1) ABB-IRB 1600 robot (2) The aluminum bracket (3) SLF FS33-60/0.15 spindle (4) The solid carbide tool (5) work piece [AA 7075-T6] (6) 3

axes dynamometer [Kistler table 9255B] (7) Uni-axial accelerometer PCB (8) Tri- axial accelerometer (ENDEVCO, Model 63B-100) fixed on the part, (9) Tri-axial accelerometer (ENDEVCO, Model 63B-100, SN10526) fixed on the spindle.

Data acquisition. Two systems were used to acquire the data generated during these tests. First, a Matlab-based data acquisition system for force measuring was used with a DT acquisition card (Data Translation 3000). The sampling frequency was set at 48 kHz for an acquisition time of 30 seconds. No filtering was applied on the signals, in order to detect any slight chatter signals. The second acquisition system was an LMS Scada III system for vibration measuring. Seven of the eight channels of this system were used for acquiring the vibration signals. The system was set at a sampling frequency of 40960 Hz for an acquisition time of 30 seconds. The obtained signals of the cutting force and the signals of the vibrations were exported to Matlab for further analysis.

Results and discussions

After the experimental phase, four replications of the vibration responses and the measurement of cutting force were realized. Each repetition consists of six recordings of the signals in three axes XYZ of the robot system. The replications ensure the repeatability of the obtained robot during machining. Figure 4 shows the vibration signals and cutting forces for one repetition. The first row in figure 4 presents the variation of the vibrations during the machining process; it can be observed that the signal amplitude is dependent on the spindle speed (see the sudden change in the signal profile). The same effect is observed when observing the cutting force signals.

The signals are acquired by testing seven spindle speeds ranging from 30 krpm 60 krpm. The duration of machining operation at each speed is 3s. The proposed variable speed method is schematized in **Figure 5**. In figure 5.a complete vibration signal versus machining time in the x direction is presented. The dashed line presents the instant of speed change. These instant are detectable through the spectrogram of the same signal presented in figure 5.b

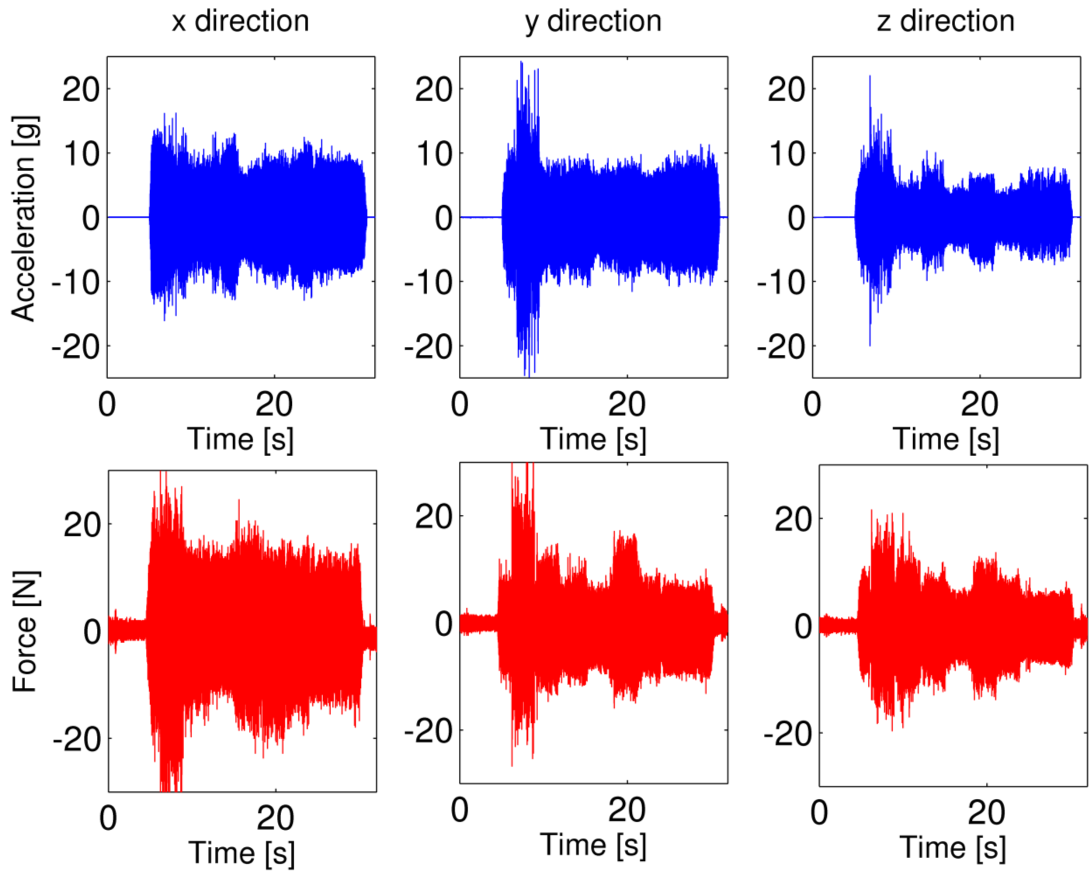

Fig.4 vibration response and cutting force during the robotic machining for three directions XZY.

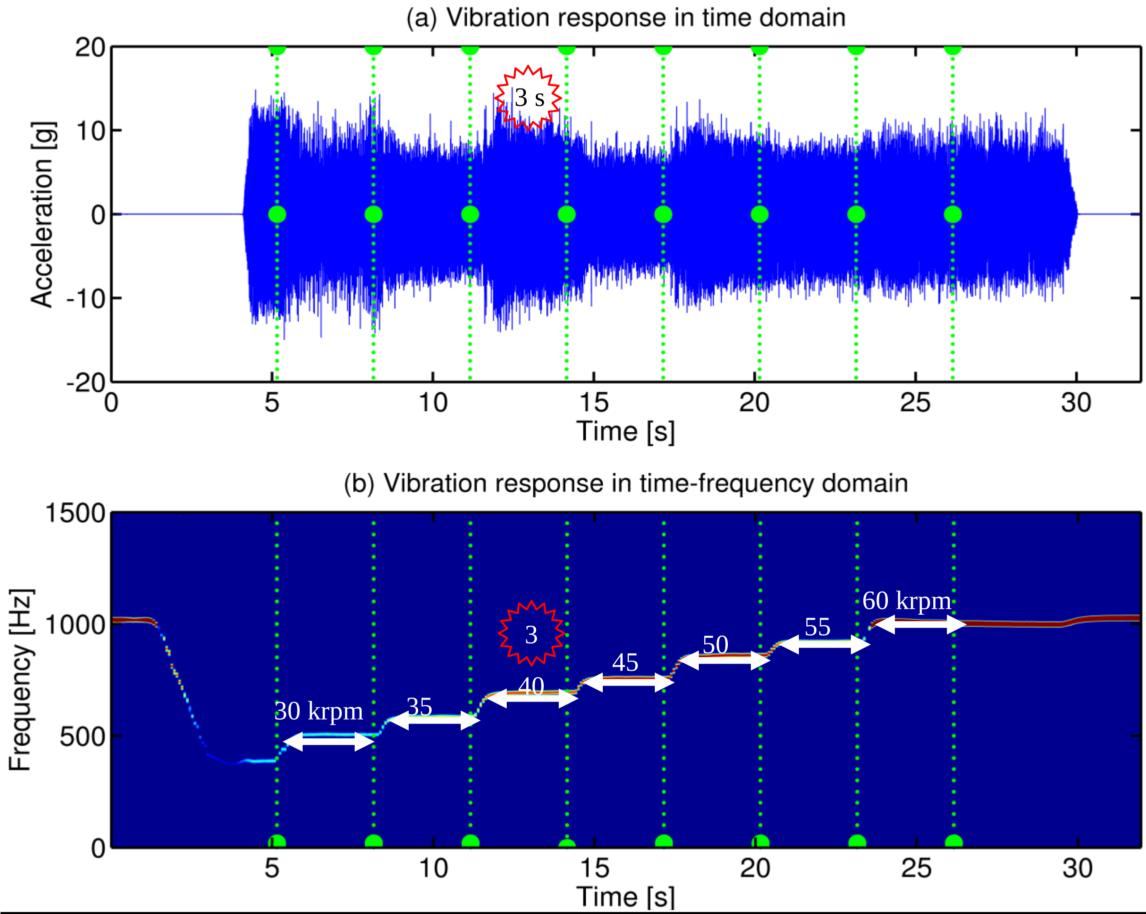

Fig.5 (a) The vibration response in the time-domain in x direction. (b) The spectrogram of the same signal. One portion of the signal corresponding to one spindle speed (ex. Portion 3 corresponding to 40 krpm).

The spectrogram allows for determining the starting point and the finishing point of the permanent regime. Once these two points are known, it is possible to determine the portion of the permanent regime for each spindle speed. The procedure is applied to vibration response and cutting force for XYZ directions. To avoid the effect of side, only the central part of each portion will be analyzed considering a length of 1.5 s. By considering this part of the signal only permanent regime process will be studied. Results are shown in **figure 6**.

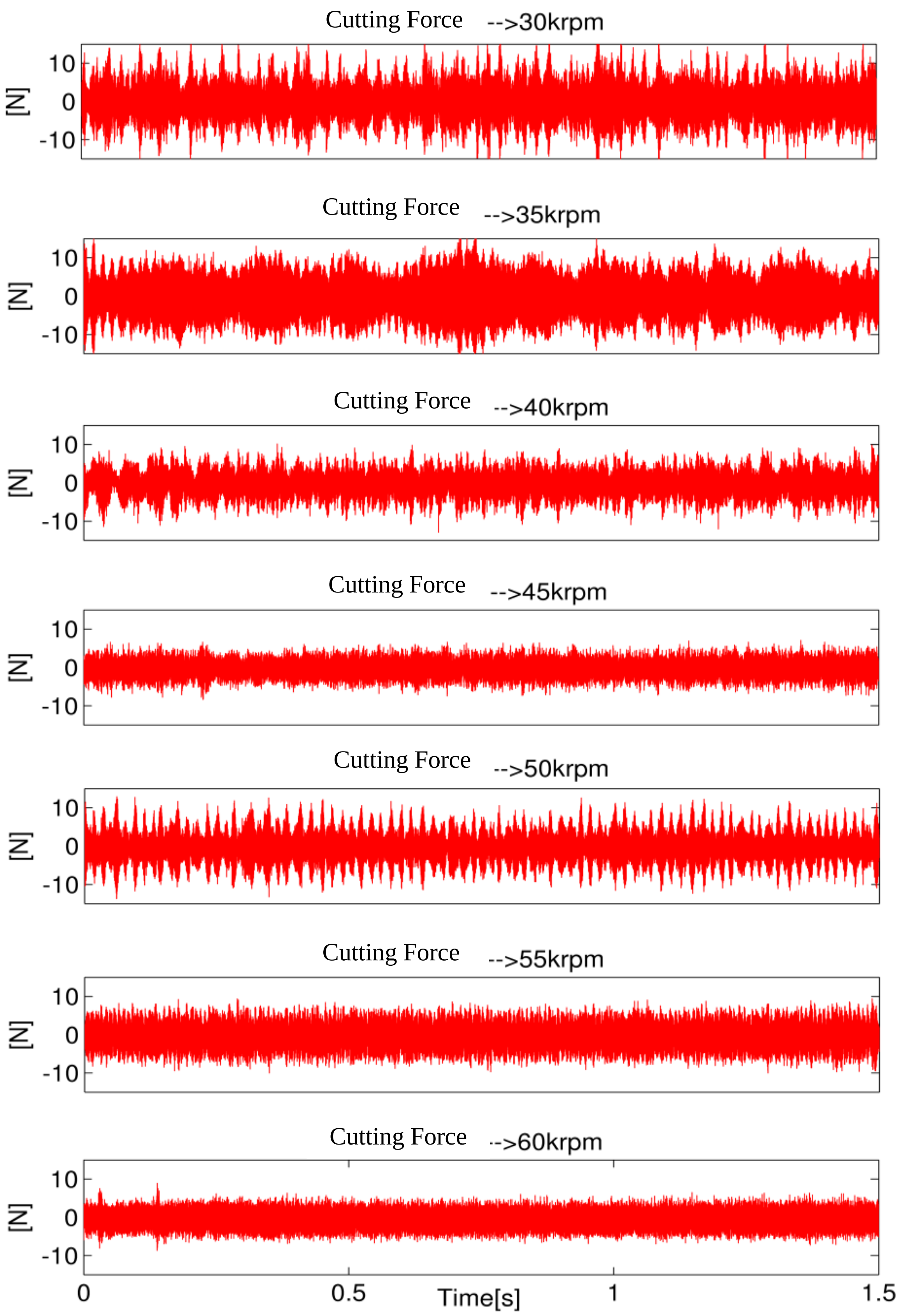

Fig. 6 Cutting force signals for all spindle speed in x direction (over a period of 1.5 s).

Vibrations response and cutting force signals have similar profile; they present the same occurring phenomena. It can be observed that the signals are modulated in amplitude (AM) with spindle speed frequency (**figure 7)**. This is probably may be due to two main factors:

- In some conditions of spindle speed and position of the robot arms, the imbalance can generate an eccentric force applied to spindle; this force tries to change the center of rotation of the spindle (eccentricity). This causes a modulation signal with the Frequency Spindle.
- The low speeds of the robot gearboxes modulate the high frequency of the rotating spindle.

The confirmation of one or other of both of these factors needs a more deep investigation.

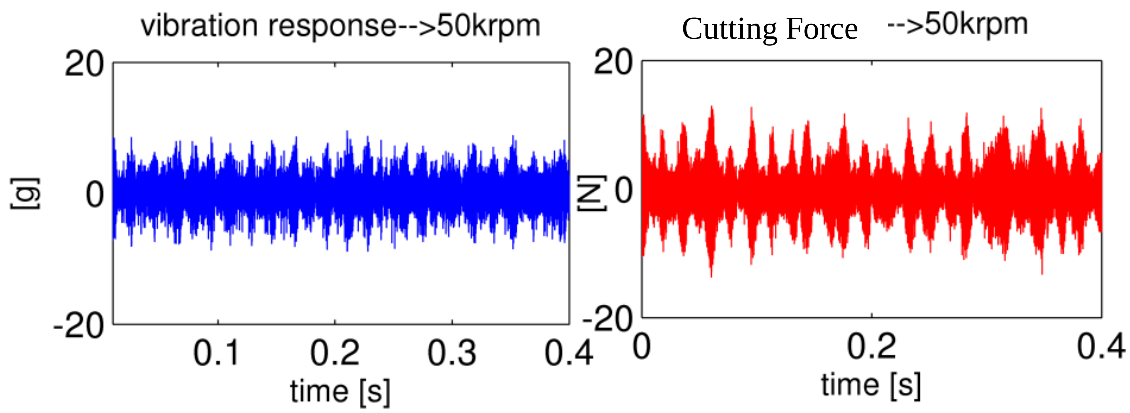

Fig.7 Vibration response and cutting force zoom, this figure shows the amplitude modulation.

From this preliminary analysis it appears that it is interesting to compare the modulation rate or follow the evolution of the instantaneous frequency to search for stable machining conditions: feed, speed and depth of cut for a given tool geometry. To do so, the density spectra of the vibration signals and the cutting forces were analyzed (**figures 8, 9 and 10).**

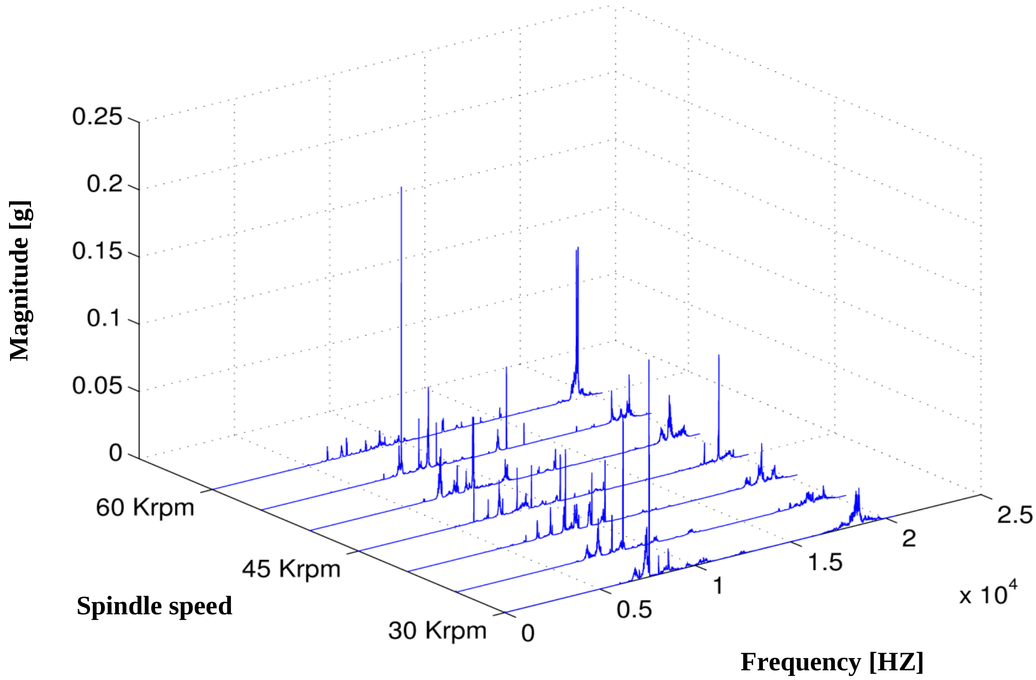

Fig.8 Vibration response density spectra corresponding to all spindle speed in x direction.

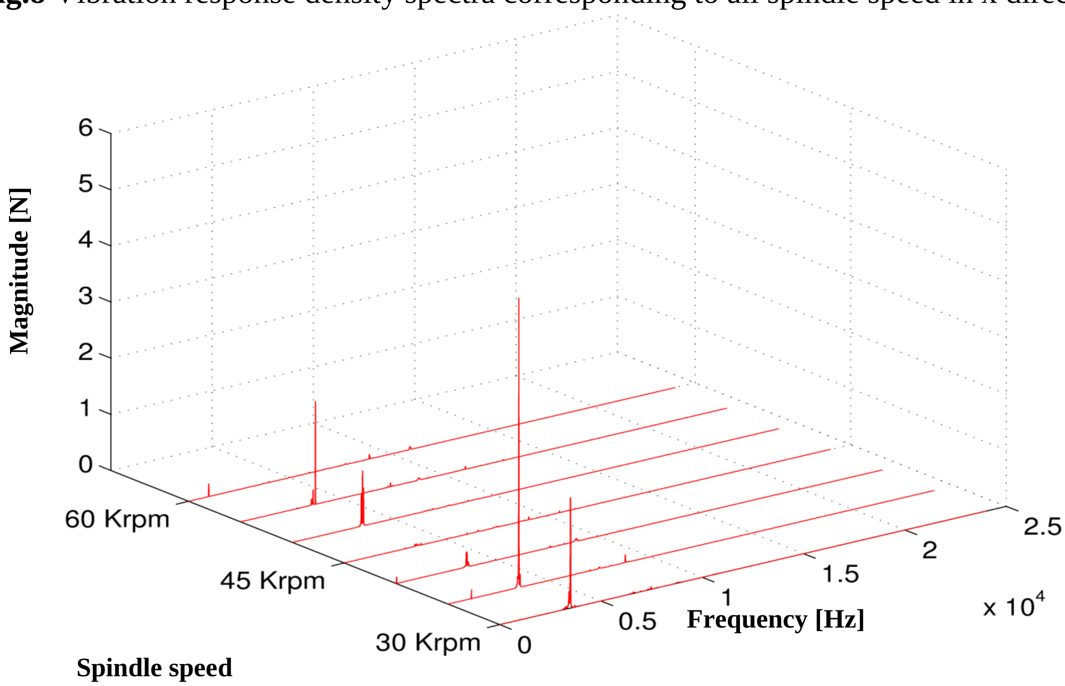

Fig.9: Cutting force density spectra corresponding to all spindle speed in x direction.

The harmonics of the spindle speed frequency appear on the spectrum of vibration response and cutting force. The presence of frequencies other than the spindle speed harmonics (tooth passing frequency harmonics), could be synonym of unstable cutting conditions. With this approach it is possible to conclude if the machining process is stable or not. However, with this approach it is difficult to conclude on the most stable speed among the seven tested speeds. In addition, machine-tools tools present relatively similar rigidity in the two main directions (X and Y), which means that analyzing one of the direction is enough for decision about the process stability. While for robots, this not the case: each direction has its own rigidity (the robot configuration also). Thus it is more interesting to use a combination of three directions of measurement for the analysis; **figure 10** represents spectra using an Euclidean distance for cutting forces.

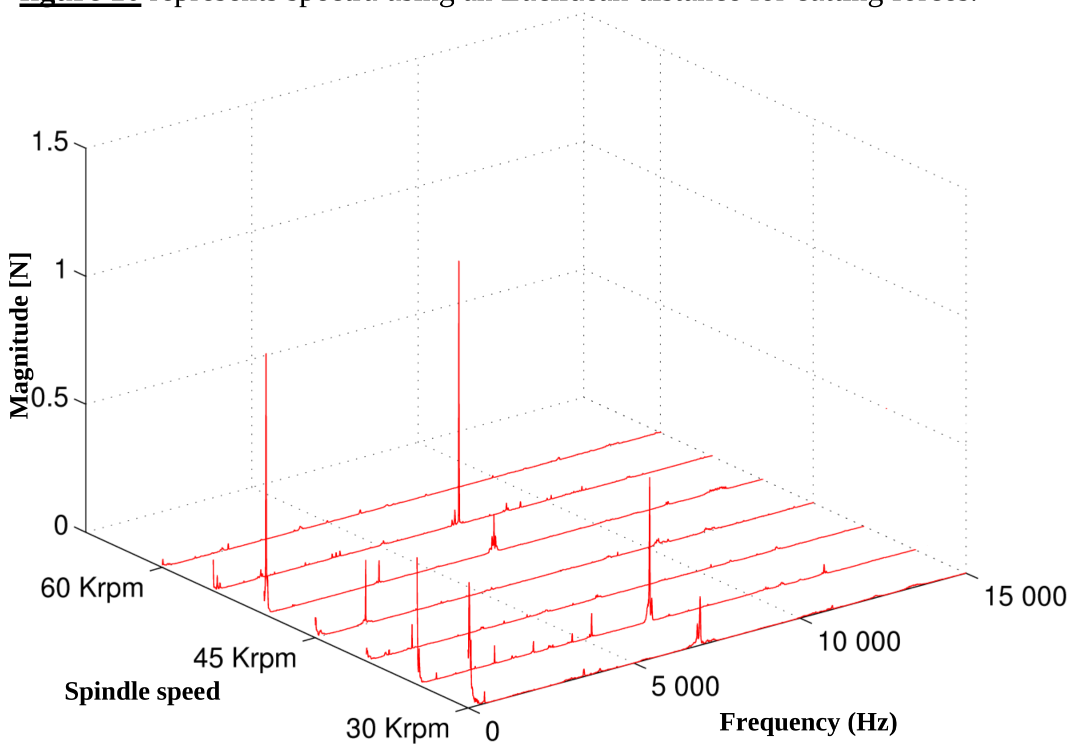

Fig.10 The density spectra for the cutting force amplitude corresponding to all spindle speeds ($Force\ amplitude = \sqrt{F_x^2 + F_y^2 + F_z^2}$)

To find the stable, cutting speed a new stability criterion (CS) based on the energy distribution of acceleration or force signals for each direction is proposed. CS is the minimum ratio between the a-periodic energy E_a and the total energy E of the acceleration signal or force signal for three directions where E_p and E are defined using the following equations:

$$E_p = \sum_{k=1}^{\infty} \left[\int_{kw_\tau - \delta}^{kw_\tau + \delta} PSD_s(w)dw \right] \quad (1)$$

$$E_a = E - E_p = \int_0^{+\infty} PSD_s(w)dw - \sum_{k=1}^{\infty} \left[\int_{kw_\tau - \delta}^{kw_\tau + \delta} PSD_s(w)dw \right] \quad (2)$$

In equations (1) and (2) PSD_S is the power spectral density of the signal S(t) and w_τ is the spindle rotational speed. The interval radius δ was set to 4 Hz. The CS was determined as follows for each direction:

$$CS_D = \frac{E_{a,X}}{E_X}, \quad D = X, Y \ or \ Z, \ 0 \le CS_D \le 1 \quad (3)$$

The CS for the three directions simultaneously, was determined as follows:

$$CS_{XYZ} = \frac{\sum\left\{\frac{E_{a,X}}{E_X},\frac{E_{a,Y}}{E_Y},\frac{E_{a,Z}}{E_Z}\right\}}{number\ of\ directions}, 0 \le CS_{DXYZ} \le 1 \quad (4)$$

This criterion can be interpreted as a quantifier of the observed non-periodic variation in the machining process signals (vibrations or forces). When non-periodic phenomena are present in the signal, the non-periodic energy (Ea = E - Ep) will increase and the criterion CS will decrease. In contrary, when the non-periodic energy in the signal decreases this means the criterion CS tends to the unit. For a given machining direction of the robot, the nearer the CS to the unity the more stable is the cutting process. When the three directions are considered the CS is compared to the reference value 1, also. An ideal machining process will have CS=1. An unstable machining process will have a CS=0. **Figure 11** shows the results obtained when applying this method on the cutting force signals for each direction separately. **Figure 11.a** shows the variation of CS_x, CS_y and CS_z when the spindle speed is altered from 30 to 60 krpm. When the same test was repeated (figure **11.b and 11.c**) a similar pattern for the directional CS was obtained. The CS for the cutting forces was calculated for the three directions simultaneously and presented for three different repetitions (figure 11.d 11.e and 11.f). The same analysis was applied on the vibration signal for the three directions simultaneously and the obtained results are plotted in **figure 12**. It can be observed that for different repetitions the criterion CS is providing mainly to the same information (concerning the delimitation of the stable zone) whether it is applied on vibration signal or on force signal.

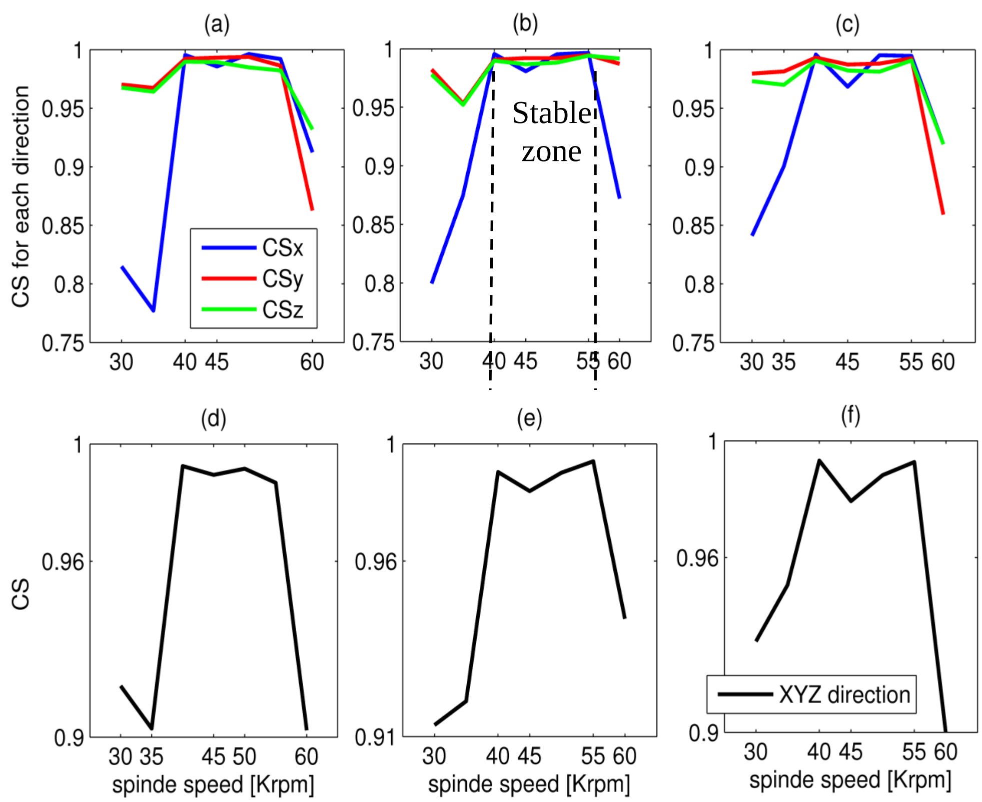

Fig.11 Estimation of the Criterion CS for force signals. (a) CS for three directions Repetition#1, (b) CS for three directions Repetition#2, (c) CS for three directions

Repetition#3, (d) CS of the amplitude force Repetition#1, (e) CS of the amplitude force Repetition#2, (f) CS of the amplitude force Repetition#3.

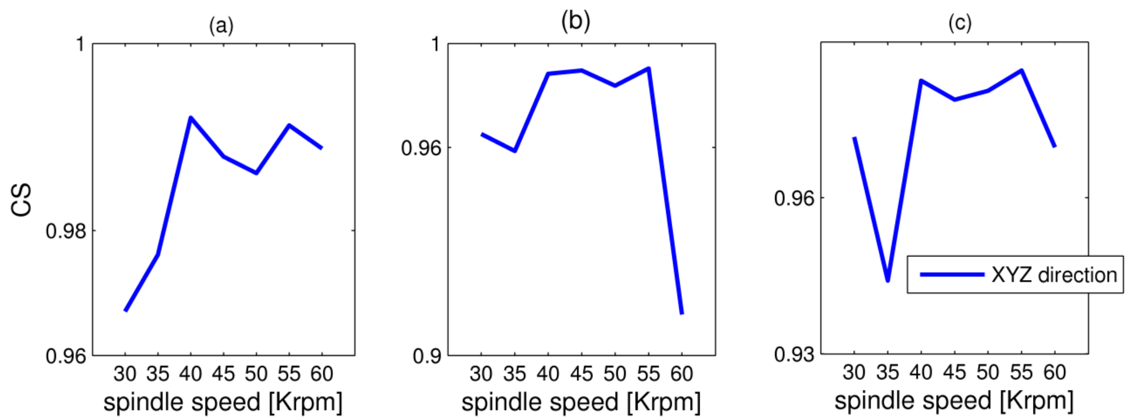

Fig.12 Estimation of the Criterion CS for vibrations signals. (a) CS of the amplitude force Repetition#1, (b) CS of the amplitude force Repetition#2, (c) CS of the amplitude force Repetition#3.

Generally, a stable cutting process is characterized by a good surface finish. To confirm this expectation, a machining test was performed and the vibrations, forces, and the roughness were measured. The machining conditions are presented below:

- Tool: carbide ball nose with a diameter of 4.76 mm (3/16 inch),
- Work piece material: aluminum alloy AA7075-T6,
- Feed: 2 mm/s,
- Depth of cut: 0.254 mm,
- Spindle speed: 30, 35, 40, 45, 50, 55 and 60 krpm,
- Lubrication: dry machining,
- Machining system: ABB robot IRB-1600,
- Test repetition: 6 times.

The roughness of the machined surface was measured using a profile-meter (Mitutoyo Surface Measuring instrument SUFTEST SV 600). The roughness was measured using the ISO1997 conditions with a range of 32000 points. The roughness was measured in three randomly chosen locations. A sample of the different measurements of the machined surface roughness is presented in **figure 13**. In this figure the variation of the arithmetic roughness, Ra, for different spindle speeds is presented with a 95 % confidence interval.

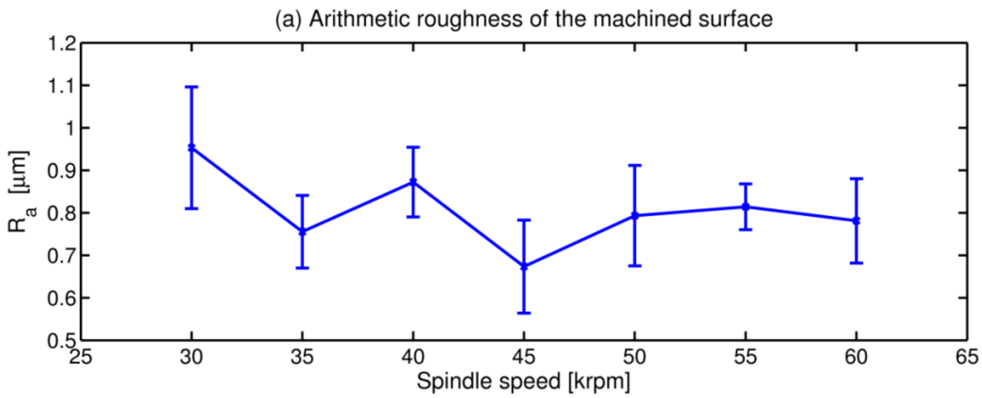

Fig.13 Variation of the arithmetic roughness Ra at different spindle speeds.

The large variation observed (**figure 13.a)** is most probably due to many noise factors that affect the measurement of the surface finish. Such factors are the material homogeneity, the location-measurement, the operator, etc. Due to these non avoidable limitations, it is better not to consider the mean value of the roughness. In fact, the mean value of the roughness cannot be statistically representative of the real surface finish. It was observed that the coefficient of variation (the ratio of the standard deviation to the average value) ranged between 12% and 30% which demonstrates that the use of the average value of the surface finish is not statistically reliable. Thus a different approach was proposed instead of using the average values of the roughness in three locations.

In the proposed approach: for each repetition the spindle speed having the minimum Ra was found among the seven tested speeds. Then, the number of occurrences which is the number of times that this spindle speed generates the lowest roughness for the Ra criterion was counted. **Figure 14** shows the compilation of the obtained results using this criterion: normalized number of occurrences (NON). The spindle speed that has the highest NON is the 45 krpm with NON=58% (meaning: the spindle speed 45 krpm was 7 times out of 12 the speed that generates the lowest Ra). The same procedure was applied for other surface finish criteria such as R_v, R_p, R_q and R_z. As expected, the obtained results show that for the realized test, the speed that leads to the lowest surface finish criteria is the one corresponding to the highest CS_D (Directional CS).

In spite of the probabilistic aspect that governs the two studied quantities: the vibration and the surface finish, it is possible to find a correlation between these two quantities. Therefore, it is possible to rely on the CS_D of the vibration signal of the spindle to predict the spindle speed that generates the best surface finish. So, it can be declared that the spindle speed with the highest CS factor has the highest probability to generate the best surface finish. However this observation is not sine qua none to obtain the best surface finish. In fact, the authors noted that this observation was not always respected.

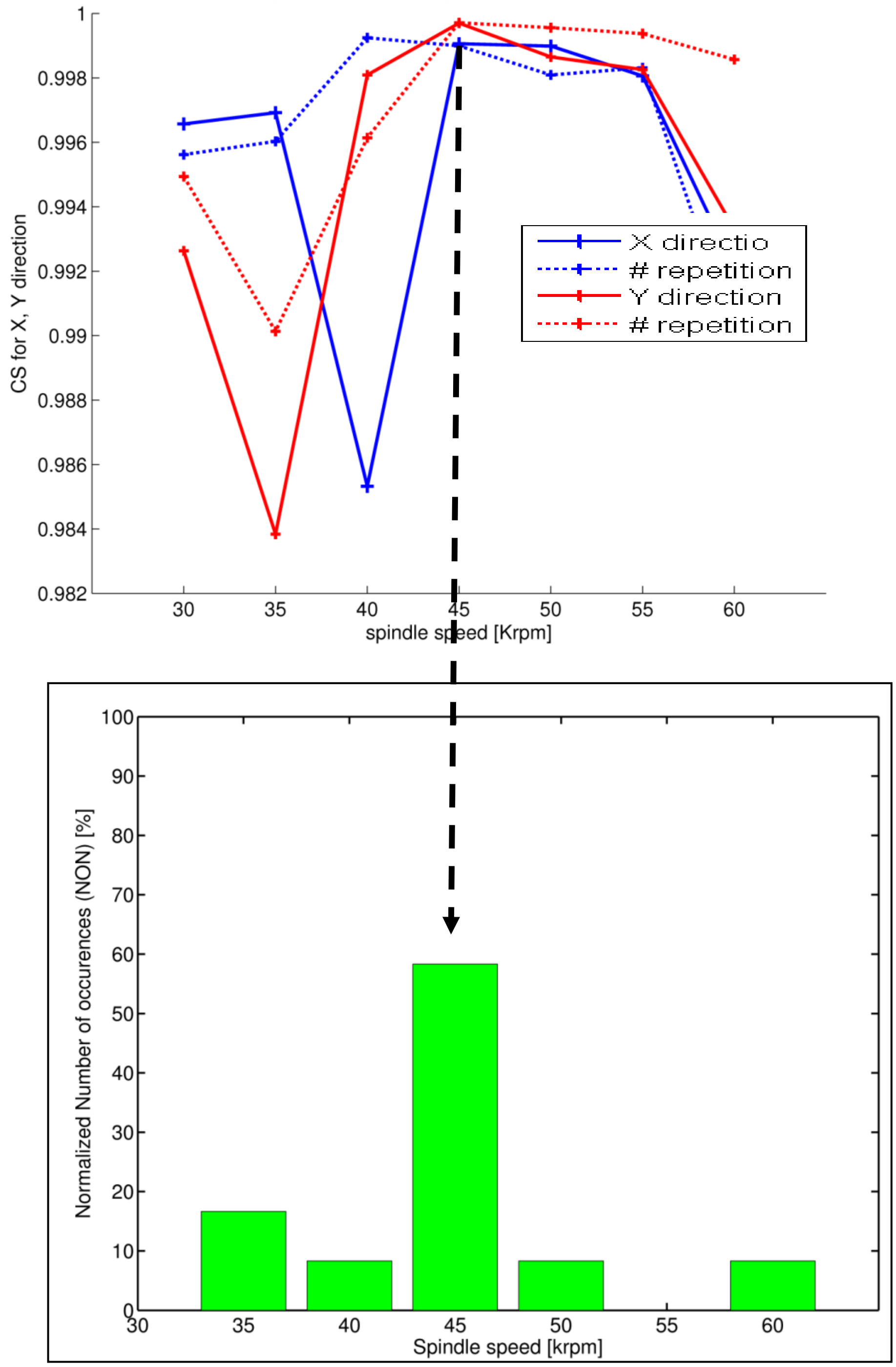

Fig.14 Presentation of the number of occurrences (ON) for different spindle speeds. For the cutting conditions see **figure 12**.

Conclusions

In this work, the dynamic stability of robotic machining and the generated part surface quality were investigated. A new process stability (CS) based on acceleration energy distribution and force signals was proposed and tested.

The proposed methodology demonstrated its efficiency in predicting the cutting conditions that have the highest probability of generating better surface finish and in most cases are the cutting speeds that are dynamically stable. The applied approach is relative, meaning that it is an approach that retrieves the best cutting condition among those tested. The applied concept involves finding the spindle speed that corresponds to the nearest CS to the unit. The proposed criterion CS represents the ratio of the non-periodic energy by the total energy. It was found that the cutting conditions that have a CS near to the unit have the highest probability of generating a stable machining process. This concept can be applied to find the degree of stability of a given cutting parameter combination. The proposed approach can be used in two ways: to find the most stable operation and to avoid dynamically unstable cutting parameters. In fact, unstable cutting parameters will be characterized by relatively low CS.

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