ROUGHING OPTIMIZATION IN 5 AXIS SIMULTANEOUS OF GAS TURBINE COMPONENTS USING CHATTER CONTROL

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Abstract. *The objective of this work is to optimize the rough milling process of a aluminum stator in simultaneous 5-axis using the aid of chatter control. The method employed is the use of an impact hammer and an instrumented accelerometer where the accelerometer is fixed on the edge of the cutting tool and a hit with the hammer is applied in order to get the Frequency Response Function - FRF of the set: tool, fixation system and spindle. With the FRF, the optimum rotation is calaculated and roughing milling tests are performed in order to obtain the maximum axial depth through the sound spectrum. With this work it was possible to increase the rate of the material removal and reduce the roughing time at a rate greater than 70% compared with usual practices in the industry.*

***Keywords**: Milling, five axis, Chatter, FRF.*

1. INTRODUCTION

The manufacturing of products with complex surfaces, which have to meet requirements such as mechanical strength, low weight, dimensional accuracy, is continuously increasing. The geometry complexity in turbine components is a consequence of the project requirements to improve efficiency. Thus, complex CAD/CAM operations and 5-axis machining are often applied.

Conventionally, the roughing operation of gas turbine components, such as a stator, is performed in three axis simultaneous with positioning of 2 (3+2 axis), in order to reduce the gradient force on the tool edge in high material removal conditions. However, it is often accomplishment in simultaneous 5-axis milling, because there is no sufficient space for the alternation of positioning on 2 axis. In this case, the forces in the tool/part/chip interface vary continuously, decreasing the quality of the machining operation. Thus, it is justifiable the study of these forces variation in simultaneous five-axis in order to assist the development of cutting strategies and determination of cutting parameters for machining.

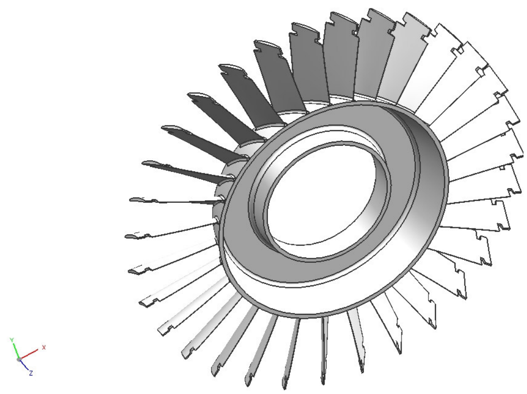
Another factor to be considered is the maximum vibration amplitude of the machining. In milling operations, what determines the tolerable level of vibration is mainly the effect that vibration has on the tool life (Altintas, 2000). The appearance of vibrations during the milling process is a function of the chip thickness variation and the lack of the material homogeneity. In this context the chatter control in simultaneous 5-axis machining contributes to adequacy of the machining conditions.

This work aims to optimize the simultaneous 5-axis roughing in a aluminum alloy gas turbine stator with the aid of the chatter control.

2. MATERIALS AND METHODS

The tests were performed in a machining center model Hermle C600U, with maximum rotation equal to 16,000 rpm and a Siemens Sinumerik 840D numerical control. In he rough milling tests, a carbide cutting tool with a diameter equal to 12 mm, two teeth, overhang equal to 55 mm and 20 mm cut length was used. Its fixation is hydraulic, using a HSK 63 Tool Holder. Aluminum alloy 7075-T6 was the material machined. The machining test considered the stator represented in Fig.1.

The software used to program the cutting strategies was the Siemens NX5.



External diameter: 302.0 mm
Thickness: 30.5 mm

Figure 1. Aluminum stator.

Figure 2 summarizes the procedure performed to determine the optimal rotation values, maximum depth cut and the frequency response function (FRF) as input.

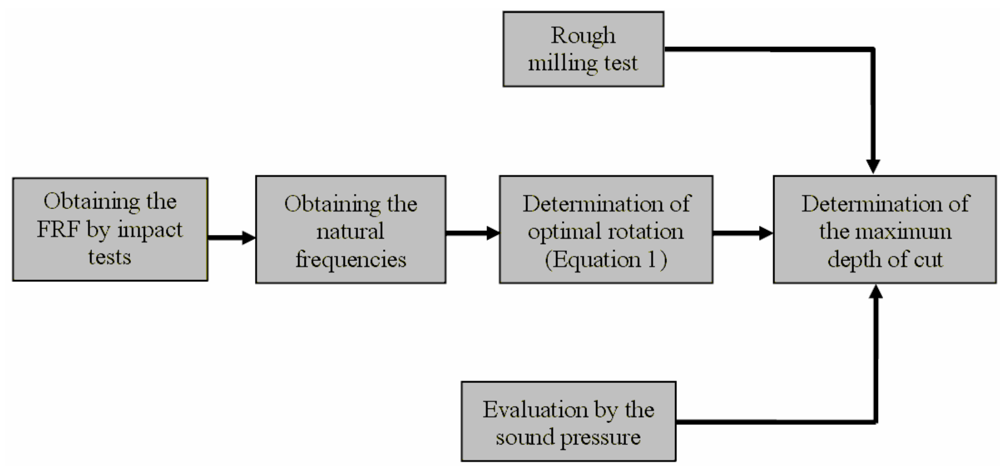


Figure 2. Flowchart to determine the optimal parameters.

The frequency response functions (FRF) were acquired by impact test with the hammer/accelerometer set (Table 1) and the use of RT Pro software Photon 6.21 from LDS.

Table 1. Equipment characteristics to obtain the curve response in frequency.

Accelerometer
Model: 353B17 ICP
Manufacturer: PCB Piezotronics
Sensitivity (± 10%): 1.02 mV (m/s^2)
Measurement Range: ± 4905 m/s^2 (pk)
Resolution (1 Hz to 10,000 Hz): 0.05 m/s^2 (rms)
Non-Linearity: ≤ 1%
Weight(without cable): 1.7 gm

Impact Hammer
Model: 086C03
Manufacturer: PCB Piezotronics
Sensitivity (± 15%): 2.25 mV/N
Measurement Range: ± 2200 N (pk)
Frequency Range (-10dB): 8 kHz
Non-Linearity: ≤ 1%
Hammer Mass: 0.16 kg

This method consists in the use of a hammer and an accelerometer instrumented. The accelerometer was fixed to the tip of the cutting tool with wax (Fig. 3), which was excited by a shock with the hammer in the region diametrically opposite to the accelerometer. The signals of the accelerometer and the hammer were acquired using a dynamic signal analyzer, determining the FRF of the assembly, which gets its natural frequencies of vibration of different modes. To calculate the FRF, 5 measurements were used which were selected according to the quality of the curve generated by the impact of the hammer which showed no interference.

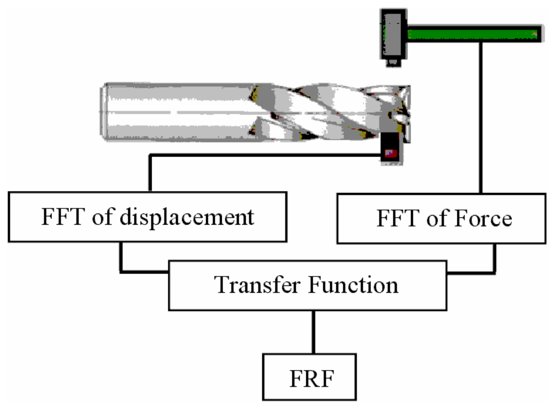


Figure 3. Procedure to obtain the FRF of the assembly.

The concept of stability lobe diagrams (Fig. 4) consists of a chart that identifies the boundary between regions of stable and unstable cutting for milling in a two-dimensional diagram of the primary control parameters, respectively, axial depth of cut (a_p = Y-axis) and rotation (n) of the spindle (X-axis) (Tobias and Fishwick, 1958).

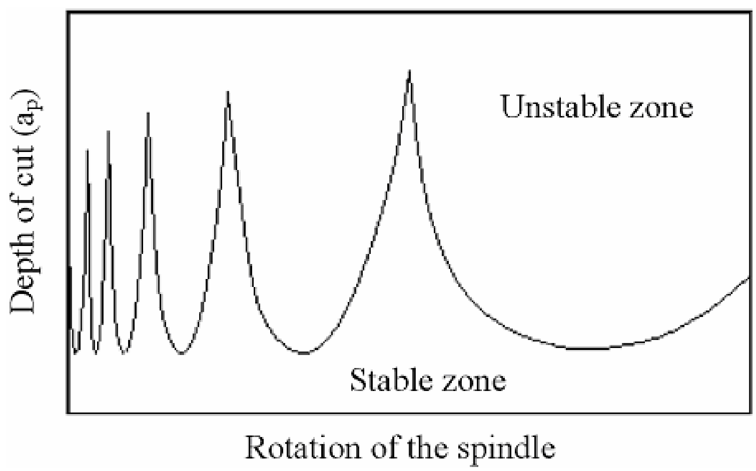


Figure 4. Example of stability lobe diagram.

From the FRF, rotations of interest are calculated corresponding to some peaks and / or valleys of the FRF. According to Cabral (2007), the regenerative effect for cutting tool with 2 teeth is reduced, with predominance of forced vibrations. Thus, for two teeth cuting tools, preferred rotation for high or low depths of cut can be found in the valleys of the FRF. The optims rotation can be determined using the Eq. (1).

$$\Omega = \frac{60 \cdot fn}{j \cdot z} \tag{1}$$

Where:

Ω [rpm]: spindle rotation;
z: number of teeth;
fn [Hz]: natural frequency;
j: integer (1,2,3 ,...), adjusted so that the rotation did not exceed the estimated maximum rotation available in machine-tool.

The maximum axial depth of cut was determined by simultaneous 5-axis roughing in the stator, as the section machined in Fig. 5.

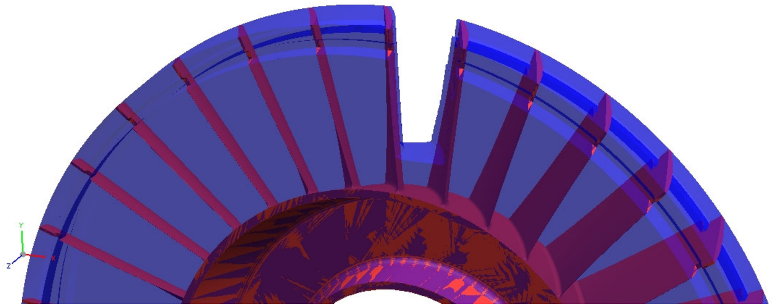


Figure 5. Section machined.

The critical depth is the one where it initiates the appearance of dynamic instability, marked by the presence of different peaks in the frequency of passage of the teeth and its harmonics or sub-harmonics in the machining sound spectrum.

Audio signals were acquired through a set microphone/amplifier signal (Table 2) using the software SignalCalc Date of Physics to analyze the signals.

Table 2. Equipments characteristics.

Precision Condenser Microphone
Model: 377B02
Manufacturer: PCB Piezotronics
Nominal Diameter: 1/2"
Sensitivity (at 250 Hz): 50 mV/Pa
Frequency Response: Free-Field
Frequency Range (± 2 dB): 3.15 to 20,000 Hz
Dynamic Range (3% Distortion Limit): 146 dB

Microphone Preamplifier
Model: 426E01
Manufacturer: PCB Piezotronics
Nominal Diameter: 1/2"

The sound spectrum , the time of machining and material removal rate were analyzed from two rotation conditions, set according to the response in frequency (FRF) of the set being tested. The chosen rotations are function of their frequencies to the two valleys 2100 Hz (15750 rpm) and 2900 Hz (14500 rpm) (Fig. 6).

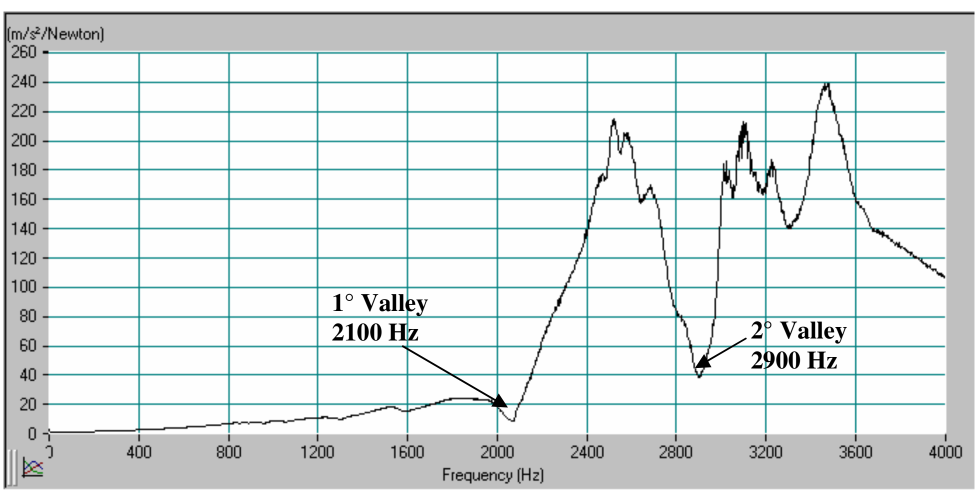


Figure 6. Selection of the first two valleys of the FRF of the assembly.

These two conditions were compared with a typically condition recommended by cutting tool manufacturers, which considers only the interface tool/chip. The others parameters were kept constant (fz = 0.1 mm / tooth; ae = 12 mm, with linear interpolation) (Table 3).

Table 3. Tests characteristics.

Conditions	n (rpm)	a_p (mm)
A Condition	15750	2; 3; 4; 5; 6
B Condition	14500	2; 3; 4; 5; 6
C Condition – recommended by cutting tool manufacturers		

Due to the thin thickness of the blades, characterizing different situations of the areas of rigidity to the machining process, the regions between the blades have been divided in four levels to machine (Fig. 7). According to Souza (2006), the strategy of dividing the machining of blades in levels is recommended to minimize the effects of vibration during machining.

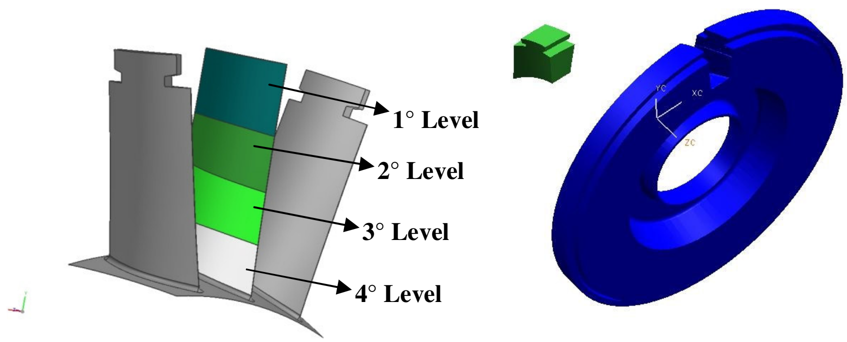


Figure 7. Levels of the region machined and unit volume removed between the blades.

3. RESULTS AND DISCUSSIONS

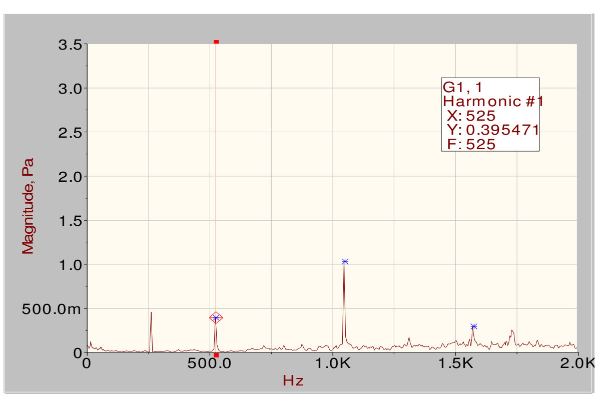
During the machining, the audio signals were collected for each rotation by varying the axial depth of cut (a_p). The sound spectrum graphics are represented in Fig. 8.

For the stable cutting the peak occurs in the frequency of passages of teeth, 525 Hz (15750 rpm) and 483.33 Hz (14500 rpm), which characterizes a function of forced vibrations. The others observed peaks correspond to harmonics of the frequency of passages of the teeth. The sub-harmonics are associated with the eccentricity of the system.

When sharp peak amplitude out of the frequency of passages of teeth and its harmonics appear, it represents dynamic instabilities in the process. These peaks are associated with regenerative vibration, which is the instantaneous variation of the chip thickness.

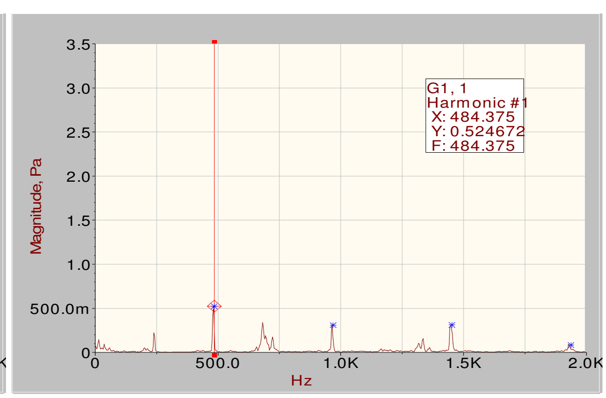
It is observed that for both *A* and *B* conditions, the vibration level for an axial depth (a_p) of 5 mm remained acceptable. In the *A* condition with axial depth (a_p) of 4 mm and 5 mm, peaks out of the frequency of passage of the teeth and their harmonics were more pronounced. However, as the machining length is reduced due to the part geometry, the vibration occurred did not regenerated and therefore did not compromise the machining. For the *B* condition, this phenomenon has not occurred, showing a better dynamic behavior.

A Condition

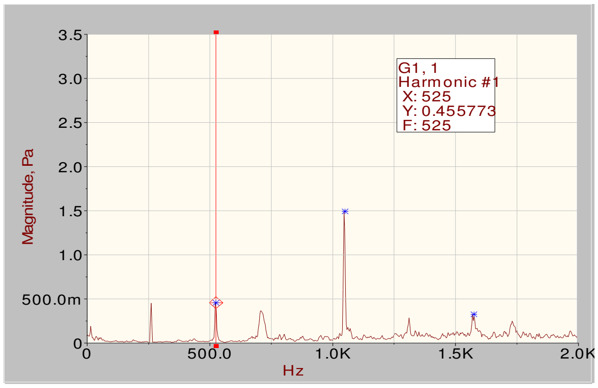


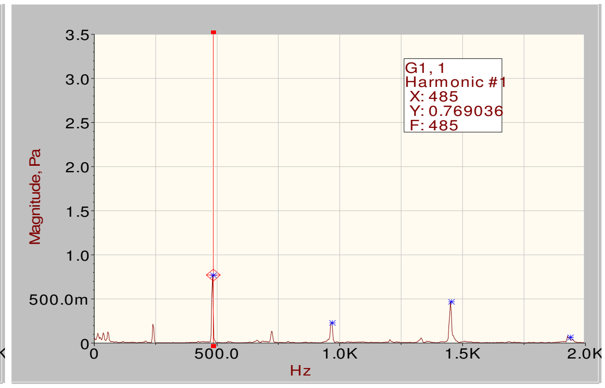
a_p = 2 mm

B Condition

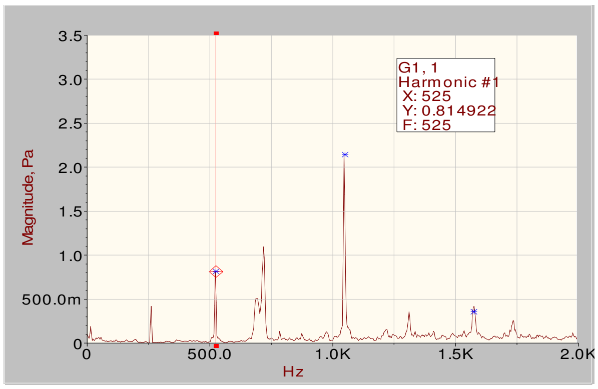


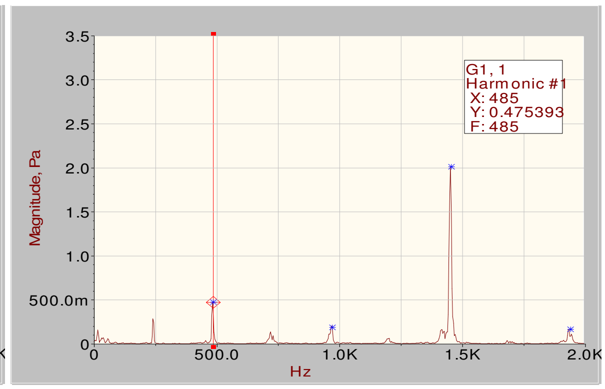
a_p = 2 mm



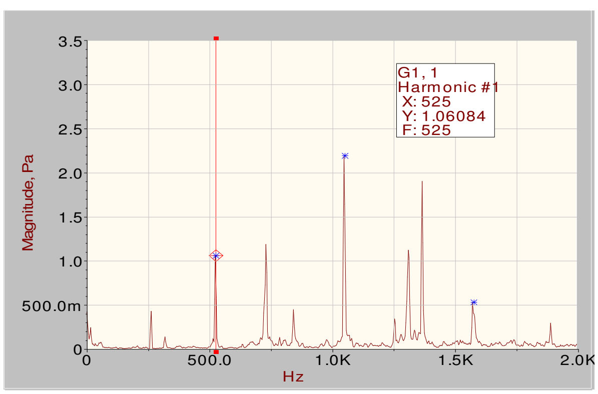


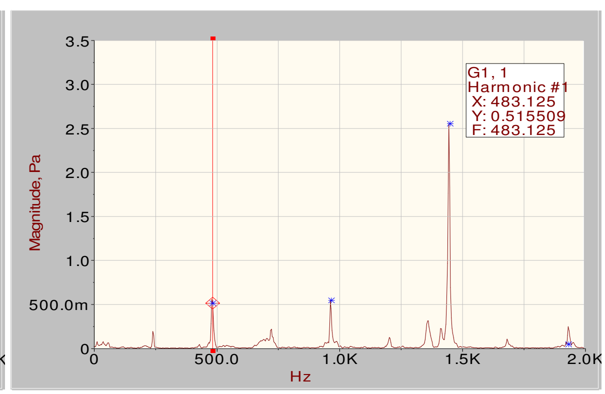
$a_p = 3$ mm $a_p = 3$ mm





$a_p = 4$ mm $a_p = 4$ mm





$a_p = 5$ mm $a_p = 5$ mm

Figure 8. Sound spectrum – (G1;1: Average auto power spectrum and F: frequency of passages of teeth).

The condition of instability, axial depth (a_p) of 6 mm, excessive vibration occured, thus limiting the maximum axial depth for the cutting tool used (Fig. 9).

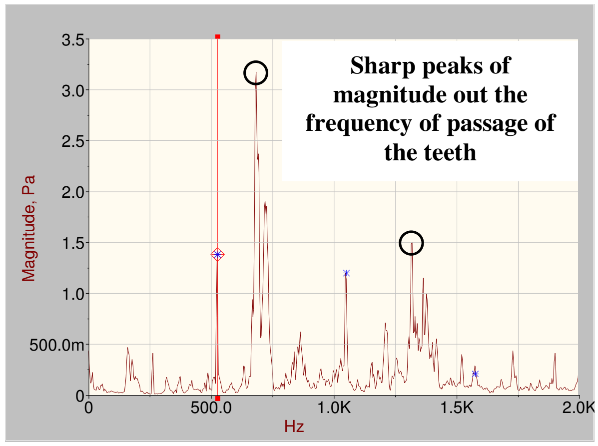


Figure 9. *A* Condition: n = 15,750 rpm, a_p = 6 mm.

Posteriorly these results were compared with the cutting parameters generally used in industries, recommended by the manufacturers of cutting tools (Table 4). The criteria evaluated were the rate of material removal and machining time.

Table 4. Industry Parameters.

Condition	Rotation [rpm]	f_z [mm/tooth]	$a_{p\ max.}$ [mm]	a_e [mm]
C	13800	0.1	3	12

Comparing the machining data in terms of productivity, the rate of material removal and machining time using the chatter control parameters obtained were more efficient than parameters that are generally used in industry. The *A* condition received a gain of 90% and *B* condition a gain of 75% compared with the *C* condition (Table 5).

Table 5. Parameters used by industry x Chatter control parameters.

Condition	Material Removal Rate [cm^3/min]	Time [min]	Method
A	189	24.4	Chatter Control
B	174	25.6	Chatter Control
C	99	43.2	Parameters generally used in industries

4. CONCLUSIONS

In simultaneous 5-axis machining, as being a situation of extreme instability in the interface tool/chip, due to extreme alternation of forces, it is essential the use of chatter control.

The application of chatter control was shown to be highly efficient. Therefore, once the behavior of the set tool/part/fixation system in a section of the part is known, you can safely apply the optimal parameters found.

Taking the machining of an aluminum alloy gas turbine stator (a part with thin walls to be machined on simultaneous 5-axis and high-speed) as a case of study, using a solid carbide tool with two teeth, it can be concluded in this work, that the condition of using the rotation in a valley of frequency, even with the appearance of peaks out the frequency of passage of the teeth, was possible to gain more than 70% of what would be expected without the use of chatter control.

5. REFERENCES

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