

# PARAMETRIC STUDY OF THE STIFFNESS CONSTANT, NATURAL FREQUENCY AND DAMPING CONSTANT IN THE TURNING OF TITANIUM

Milton F. Coba Salcedo<sup>1</sup>, Martha Sofia Orjuela Abril<sup>2</sup>, Guillermo Valencia Ochoa<sup>3</sup>

<sup>1</sup>Materials Engineering and Manufacturing Technology Research Group – IMTEF, Universidad del Atlántico, Carrera 30 Número 8 - 49, Puerto Colombia – Colombia

<sup>2</sup>Business Science Faculty, Universidad Francisco de Paula Santander, Cucuta – Colombia

<sup>3</sup>Efficient Energy Management Research Group, Universidad del Atlántico, Carrera 30 Número 8 - 49, Puerto Colombia – Colombia  
guillermoevalencia@mail.uniatlantico.edu.co

**Abstract:** The chatter is an undesirable phenomenon that occurs in the machining of complex surfaces, especially at high cutting speeds, and which negatively affects the machining process in terms of cutting performance, tool life, final surface finish and the integrity of the machine itself. The chatter, which is defined as a regenerative vibratory state, is a complex phenomenon and difficult to control due to the numerous variables present in it. This study presents the influence of three important variables in the process, which are the natural frequency of the machining system, its stiffness constant and its damping constant. The variation of each of these factors particularly affects the machining process. For its study, the well-known stability graphs based on the Altintas and Budak model have been used. In addition, a new study method has been introduced that generates three-dimensional graphs in order to visualize in a different way the influence that the variable under study has on the variables of the process, cutting speed and penetration.

**Keywords:** Chatter, Stability Lobes in 3D, natural frequency, stiffness constant, damping constant.

## I. INTRODUCTION

Chatter has been investigated for more than a century and remains a major obstacle to achieving automation of most machining processes, including turning, milling and drilling [1]. Its nature creates certain problems on machining processes, such as poor surface finish[2], [3], reduction of the material removal rate (MRR), low productivity [4] and significant reduction of the useful life of the tool [5].

Chatter is a complex of high level that can be used as a component of the cutting system, the cutting material, the working material, the structure of the tool and the cutting parameters [6]. Titanium alloys have been widely used in the aerospace industries, biomedical, automotive and petroleum due to their good strength/weight and superior corrosion resistance. However, it is very difficult to machine them due to their poor machinability [7]. For this reason, it is necessary to analyze the stability lobes diagram for each material in order to obtain information about the stability of the cutting process for turning operations; with them it is possible to know the ranges of speeds of rotation of the spindle and chip thicknesses to which the cutting operation will be dynamically stable and free from the undesirable phenomenon of chatter.

In this work, 3D stability lobe diagrams were analyzed for a titanium alloy (6Al, 4V), which is subjected to a turning process, whose input parameters are the natural frequency of the system, constant damping, constant of stiffness and constant of specific cutting force. In addition to that, the third Cartesian axis is chosen, which for this particular case corresponds to the damping constant, these results are presented later and with them, the conclusions concerning to this material are made.

## II. THEORETICAL FUNDAMENTATION

### 2.1 Orthogonal cutting mechanics

Although the most common cutting operations are three-dimensional and geometrically complex, the simple case of orthogonal cutting in two dimensions is used for general mechanics in manufacturing processes by chip removal. The mechanics of the three-dimensional oblique band operations are most frequently subjected to evaluation by models of the geometric and kinematic transformation applied to the orthogonal cutting process. The schematic representations of the orthogonal and oblique cutting processes in Figure 1. The orthogonal section resembles a forming process with a straight tool whose cutting edge is perpendicular to the cutting speed ( $V_c$ ), where a chip width metal ( $b$ ) and a cutting depth ( $h$ ) is cut the piece. In the orthogonal cut, the cut is assumed uniform along the cutting edge; For this reason, it is a deformation process with efforts in two dimensions without lateral expansion of the material. Consequently, the shear forces are exerted only in the uncut directions of the chip, and are known as tangential forces ( $F_t$ ) and feed forces ( $F_f$ ). However, in the oblique cut, the cutting edge is oriented with a radial inclination angle ( $i$ ).

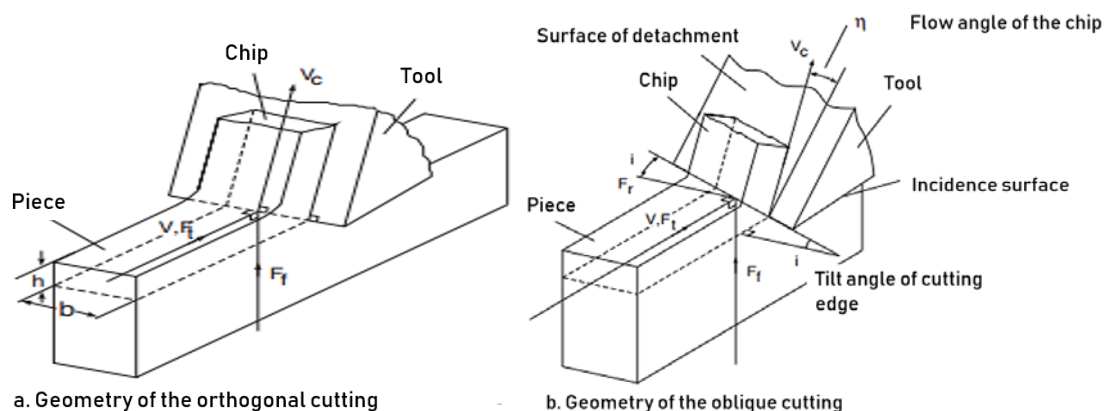


Figure 1. Geometry of the orthogonal and oblique cutting[8].

In a cutting process, there are three zones of deformation as can be seen in Figure 2. As the edge of the tool penetrates the piece, the material in front of it is sheared in the primary zone to form a chip. Then this is partially deformed, and moves along the detachment surface of the tool in the secondary zone. The friction zone, where the flank of the tool rubs the newly machined surface, is known as the tertiary zone. Initially, the chip adheres to the tool's detachment surface, known as the adhesion zone, until the friction stress equals the shear force for flow of the material (elastic limit) and forces the chip to move on the adhered material. Subsequently the chip stops adhering and begins to slide on the surface of detachment with a constant coefficient of friction until it loses contact with this surface. For the analysis of the primary zone, Merchant[9] developed a model in which he assumes that this area is a very thin plane. Others, such as Lee and Shaffer[10], based their analysis on a zone of gross deformation, proposing a model of "Prediction of the angle of cut" according to the laws of plasticity.

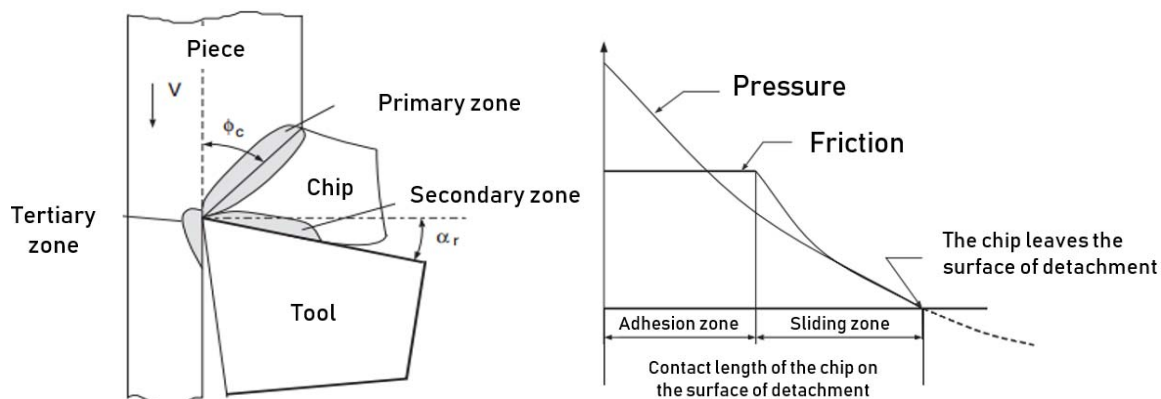


Figure 2. Deformation zones in the orthogonal section[8].

The geometry of the deformation and of the shear forces for the orthogonal cutting is shown in Figure 3. It is assumed that the cutting edge is sharp and without chamfer, and that the deformation occurs in the plane of infinitely thin shear. The cutting angle ( $\phi_c$ ) is defined as the angle between the direction of the cutting speed ( $V$ ) and the shear plane. It is further assumed that the shear stress ( $\tau_s$ ) and normal stress ( $\sigma_s$ ) on the shear plane are constant; the resultant force ( $F_c$ ) on the chip, applied in the plane of shear, is in equilibrium with the force ( $F_c$ ) applied to the tool on the chip-tool contact zone on the peeling surface. The contact forces from the tertiary zone are assumed to be zero, and all the cutting forces are the product of the cutting process or of the chip-surface contact. Starting from equilibrium, the resultant force ( $F_c$ ) is formed from the advancing force ( $F_{fc}$ ) and the shearing force ( $F_{fc}$ ):

$$F_c = \sqrt{F_{tc}^2 + F_{fc}^2} \tag{1}$$

The advance power is given in the direction of the thickness of the chip without cutting, and the tangential cutting force in the direction of the cutting speed. The cutting forces acting on the tool have the same amplitude but opposite senses with respect to the forces acting on the chip.

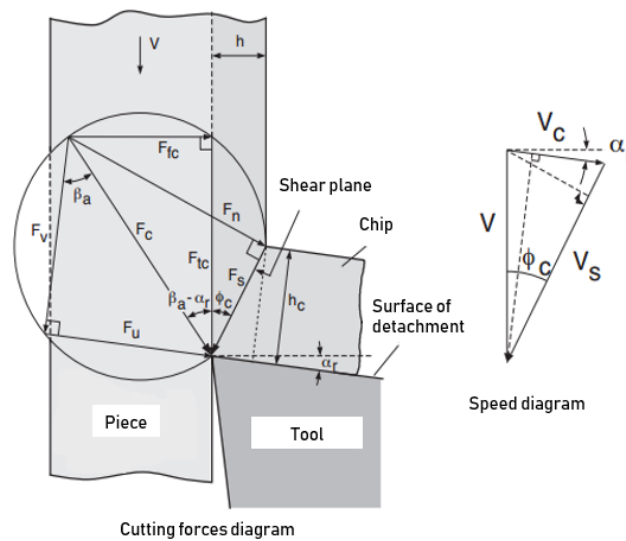


Figure 3. Orthogonal cutting mechanics[8].

## 2.2 Chatterin machine tools

In addition to free and forced vibrations, there are self-excited vibrations common in machine tools. A self-excited vibration is a type of vibration in which the source of vibration is inside the system. In machining, the auto-excited vibrations usually give place to the phenomenon of chatter. It should be noted that the chatter can also be caused by forced vibrations, but in general it is not a major problem in machining because the external force or dynamic flexibility of the machine structure can be reduced to reasonable levels when the external force that causes the chatter is identified[11].

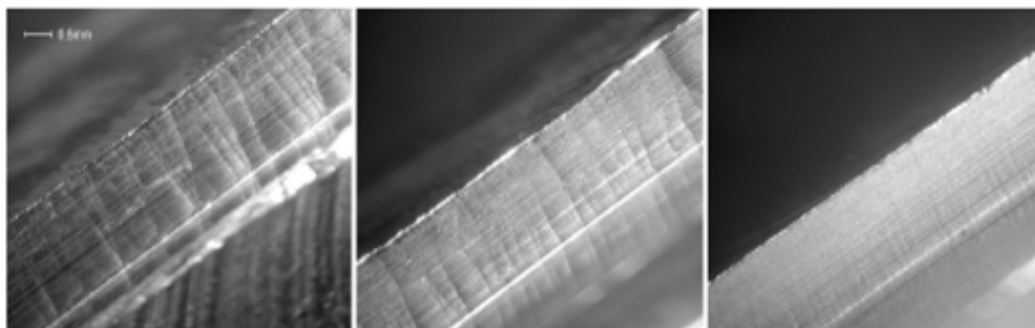


Figure 4. Milled surfaces with chatter (left and center: for 12,000 rpm and 10,000 rpm, respectively) and without rewinding (right: 11,000 rpm)[12].

Chatter occurs mainly because the structural tool-piece system is initially excited by the cutting forces. It is a problem of instability in the machining process, which is characterized by excessive unwanted vibration between the tool and the workpiece, a loud noise, and consequently, a poor-quality surface finish. It also reduces the life of the machine and the tool and impacts negatively the reliability and safety of the machining operation[13]. Figure 4 shows the part of a machined part with a poor superficial finish product of the chatter.

The most common chatter in the practice of machining operations is the regenerative. It happens when the irregularity of the surface being machined is a product of the consequent variations in the cutting force when on the previous occasion the tool passed over that place, causing a damaging degeneration of the cutting force. Depending on the phase difference between the two successive wave surfaces, the maximum thickness of the chip can grow exponentially while oscillating at a rewinding frequency that is close but not equal to the natural frequency of the system. The growing vibrations increase the cutting forces and produce a poor and wavy surface finish.

### III. METHODOLOGY

#### **3.1 Methodology for the development of a computational algorithm based on the model of Altintas and Budak for generation of stability diagrams in three dimensions for the turning process.**

The main peculiarity of this type of stability diagrams is that it provides a tool with which it is possible to study the role played by the natural frequency, the damping ratio and the stiffness constant on the stability of the vibratory system observing the characteristic behavior of the diagram of lobes of stability before the variation of one of the aforementioned constants within a previously established range for a turning process. It should be noted that it was not possible to establish a precedent for this type of stability diagrams in the literature, and most of the authors study the behavior of the constants in individual diagrams due to the complexity to generate them.

For the generation of stability lobes for turning operations, it is required to know a series of parameters that are related to some physical properties inherent to the material of the piece to be machined and to the nature of the cutting tool; These are the program's input parameters and they govern the behavior of the system. To construct the lobe stability diagrams, this program will output the rotational speeds of the lathe spindle and the critical chip thicknesses for these speeds.

The stability lobes diagrams in three dimensions are generated from a code in Matlab developed by the authors, which uses the code used to generate the stability lobes for the two-dimensional turning process, with the difference that in the entry of the input parameters, the constant to be used as the third cartesian axis is no longer a scalar value, but a vector that has a number of elements ( $j$ ) and a range defined by the user. Three functions were generated, which include a series of variants with respect to the original code, these functions were defined as lobul1, lobul2 and lobul3. It is important to say that each function differs from one another in the variable used as the third cartesian axis and these have the following correspondence: lobul1 uses the natural frequency as the third axis, lobul2 the damping constant and lobul3 the system's rigidity constant.

The output variables used by the code to generate the graphs are:  $m$  which is the data matrix of stability lobes and is of great relevance because it has the values that generate the lobes of stability,  $coe$  which is a vector that contains the polynomial coefficients, calculated with the intersections between the pairs of lobes and used to remove the non-relevant data in the diagram,  $n$  which is a scalar with the ordinal number of the last lobe used for the generation of these using a cycle for, and  $w_m$  for lobul1,  $k_{em}$  for lobul2 and  $z_m$  for lobul3 which are column vectors containing the sets of values that are plotted on the third cartesian axis of the stability lobe diagram.

Figure 5, Figure 6 and Figure 7 show generated 3D stability lobes diagrams:

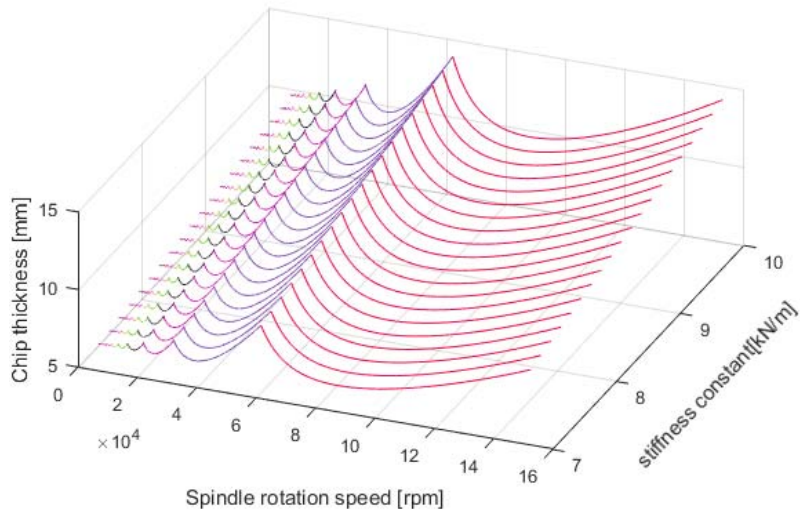


Figure 5. 3D stability diagram, where the lobu13 function is used.

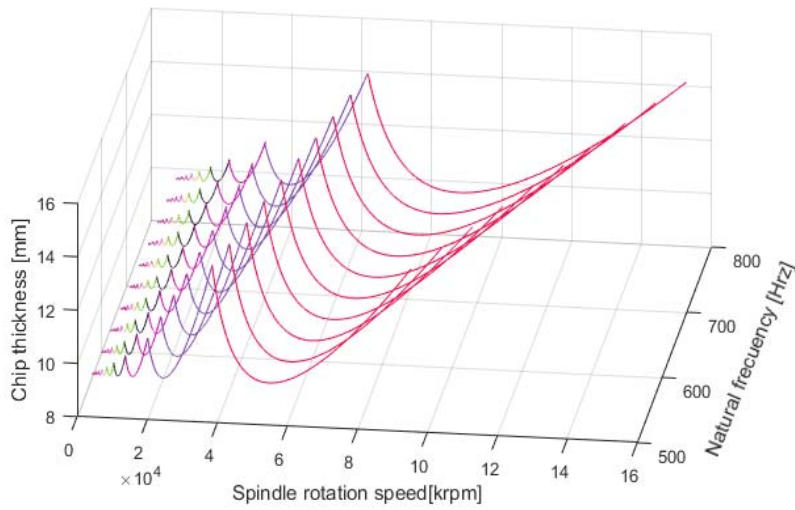


Figure 6. 3D stability diagram, where the lobu11 function is used.

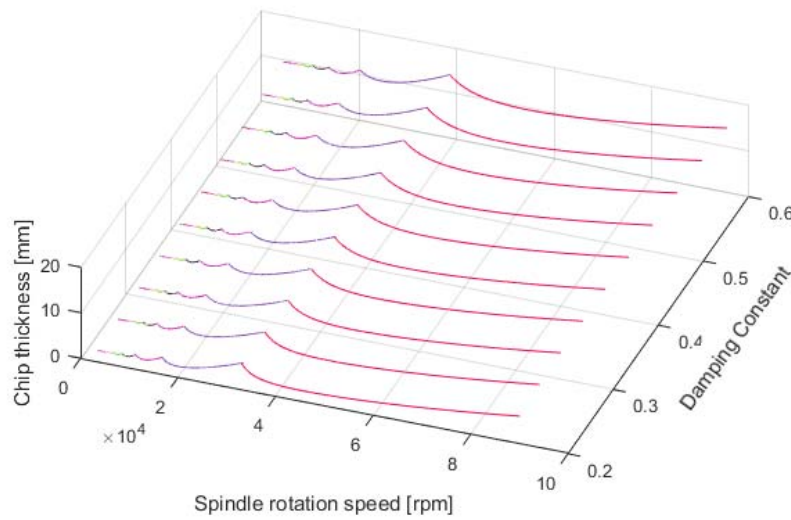


Figure 7. 3D stability diagram, where the lobu12 function is used.

Figure 8 shows a diagram of the flow chart that was used to elaborate the lobul1 function code for the generation of a three-dimensional stability diagram for the turning process. It is not necessary to teach the flow diagrams for the remaining functions because they fulfill the same logic, they only disagree in the column vectors that each function gives to graph the third cartesian axis.

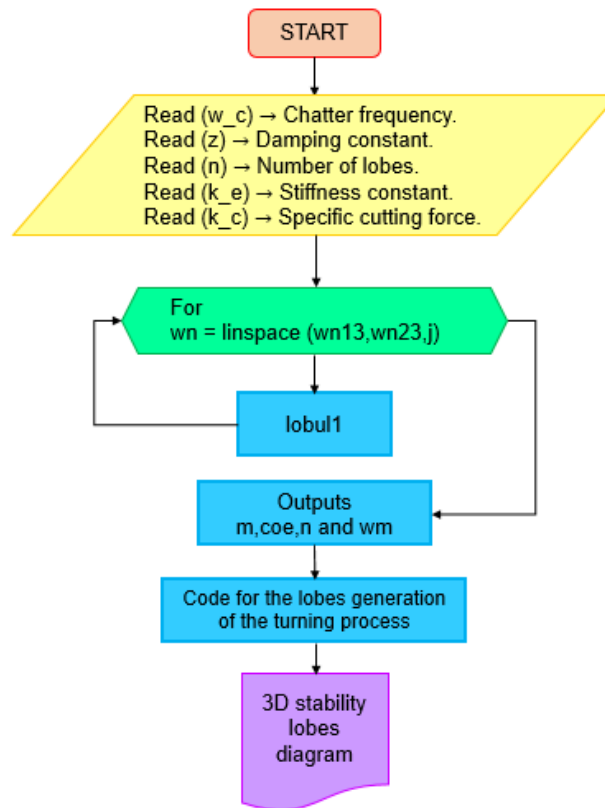


Figure 8. Flow diagram for the generation of a stability lobe diagram in three dimensions for the lobul1 function.

#### IV. RESULTS AND ANALYSIS

##### Results of varying the natural frequency of the system.

To observe the variation influence of the natural frequency of the system in the machining process, we will make a graph, keeping the damping constant and the stiffness constant without variation and taking the values range of  $z$  between 0.2 and 0.6 and  $k_e = 10$  was set and the natural frequency of the system was adjust to the values of 500 Hz, 600 Hz, 700 Hz and 800 Hz. The results obtained are plotted in Figure 9. It shows that to reach a high chip thickness when  $w_n$  increases it is necessary to increase the spindle rotation speed in certain operating ranges.

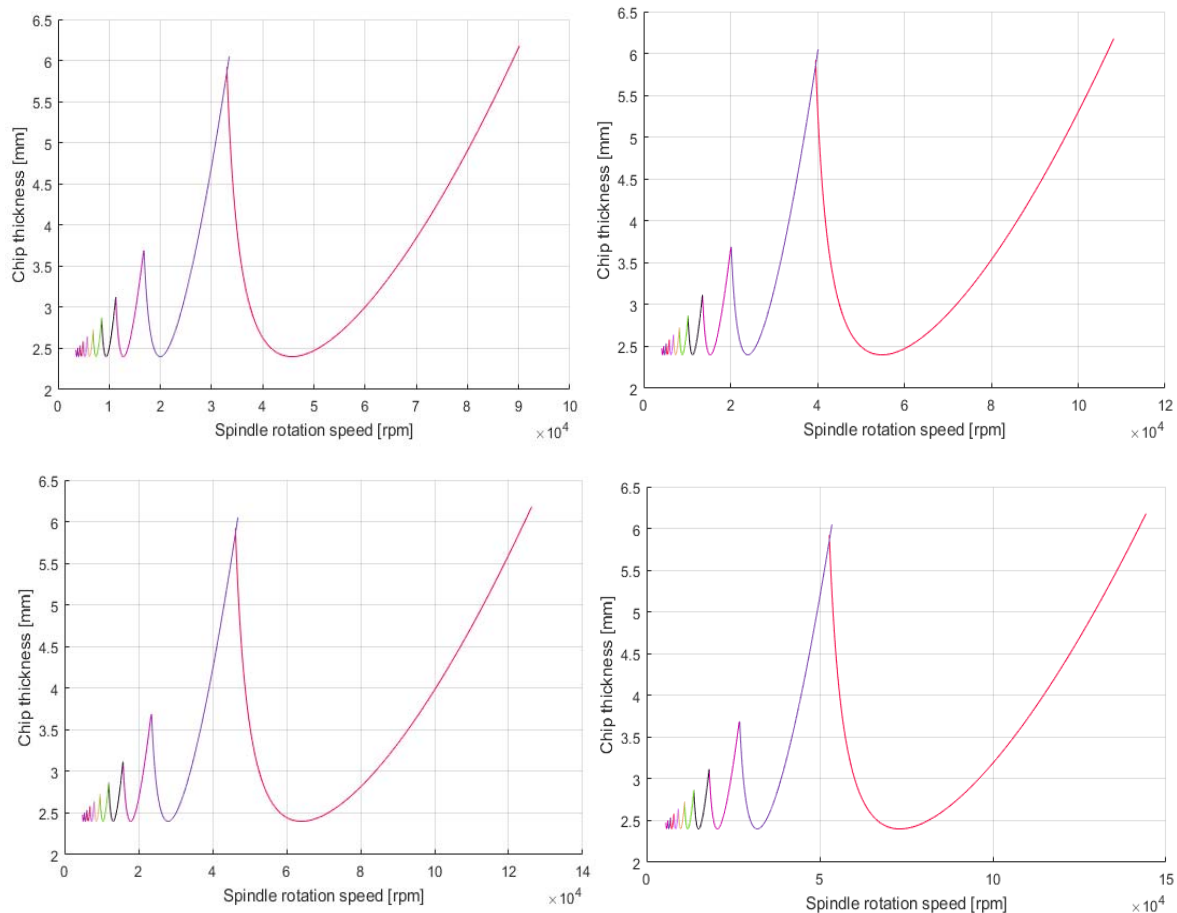


Figure 9. Results obtained for different natural frequencies.

Stability lobe diagrams allow obtaining the highest possible performance of the machine tool (high speed machining) under dynamically stable cutting conditions, achieving high rates of material removal, less wear of the cutting tool and good surface finishes of the mechanized part, increasing significantly the productivity of the manufacturing operation.

After studying the stability lobe diagrams for turning processes, it can be stated that as the rotational speed of the spindle increases, the material removal rate also increases significantly due to the fact that at high revolutions per minute (rpm) there are stable areas (pockets) larger in the diagram where you can select higher cutting depths, on the other hand, at low rpm ( $\leq 2000$  rpm), the stability lobes come very close together making the greater depth of cut that can be reached becomes a constant value, which would be the minimum point of the lobes, known in the literature as the limit of asymptotic stability.

## V. CONCLUSIONS

The stability lobe diagrams provided by the application provide valuable information about the stability of the cutting process for turning and milling operations, specifically it allows to know the ranges of rotation speeds of the spindle and chip thickness at which the cutting operation it will be dynamically stable and free of the undesirable chatter phenomenon, which negatively affects the productivity of the operation, producing a rapid wear of the cutting tool and generating surface finishes of very poor quality, which represents an increase significant in the time of production and therefore of the costs associated with the production process.

The models of Altintas and Budak that were used for the development of the program are applicable to almost all the operations of turning and milling, but there are cases where the method of fastening the tool is special (for example, it has elements that provide certain degree of damping to the tool during cutting) or the geometry of the tool is complex (DC spherical tip models manufactured by the Swiss company Sandvik Coromant), therefore, in those cases, the code will not provide reliable information.

This program can become a tool of great pedagogical utility, allowing future students to study and understand the behavior of machine tools under different cutting conditions and, the incidence of parameters such as damping, natural frequency of the piece and stiffness, in the stability of the system.



## REFERENCES

- [1] M. SIDDHPURA and R. PAUROBALLY, "A review of chatter vibration research in turning," *International Journal of Machine Tools & Manufacture*, pp. 27-47, 2012.
- [2] Y. LIU, T.-x. LI, K. LIU and Y.-m. ZHANG, "Chatter reliability prediction of turning process system with uncertainties," *Mechanical Systems and Signal Processing*, pp. 232-247, 2016.
- [3] S. YAMATO, T. HIRANO, Y. YAMADA, R. KOIKE and Y. KAKINUMA, "Sensor-less on-line chatter detection in turning process based on phase monitoring using power factor theory," *Precision Engineering*, pp. 103-116, 2018.
- [4] G. URBKAIN, L. LÓPEZ DE LACALLE and A. FERNÁNDEZ, "Regenerative vibration avoidance due to tool tangential dynamics in interrupted turning operations," *Journal of Sound and Vibration*, pp. 3996-4006, 2014.
- [5] J. MUNOA, X. BEUDAERT, Z. DOMBOVARI, Y. ALTINTAS, E. BUDAK, C. BRECHER and G. STEPAN, "Chatter suppression techniques in metal cutting," *CIRP Annals - Manufacturing Technology*, pp. 785-808, 2016.
- [6] G. QUINTANA and J. CIURANA, "Chatter in machining processes: A review," *International Journal of Machine Tools & Manufacture*, pp. 363-376, 2011.
- [7] M. BOUJELBENE, "Investigation and modeling of the tangential cutting force of the Titanium alloy Ti-6Al-4V in the orthogonal turning process," *Procedia manufacturing*, pp. 785-808, 2016.
- [8] Y. ALTINTAS, "Mechanics of metal cutting," in *Manufacturing automation*, 2 ed., New York, Cambridge University Press, 2012.
- [9] M. E. MERCHANT, «Mechanics of the metal cutting process. II: Plasticity conditions,» *Journal of Applied Physics*, vol. 16, pp. 318-324, 1945.
- [10] E. LEE and B. SHAFFER, "Theory of plasticity applied to the problem of machining," *Journal of applied mechanics*, vol. 18, p. 409, 1951.
- [11] H. MERRITT, "Theory of self-excited machine tool chatter: contribution to machine tool chatter," *Journal of Manufacturing Science and Engineering*, pp. 447-454, 1967.
- [12] E. BUDAK and Y. ALTINTAS, "Analytical Prediction of Chatter Stability in Milling—Part I: General Formulation," *Journal of Dynamic Systems, Measurement, and Control*, pp. 22-30, 1998.
- [13] M. WEIRICGROCH, "Chaotic vibrations of a simple model of the machine tool-cutting process system," *ASME Journal of vibration acoustics*, vol. 119, pp. 468-475, 1997.

## AUTHOR PROFILE

Milton Coba Salcedo born in Barranquilla, Colombia. Is a full-time professor at the Universidad del Atlántico. Received a degree in Mechanical Engineering from Universidad del Atlántico, located in Barranquilla, Colombia in 2001. Ph. D in mechanical engineering from Universidad Politecnica de Cataluña, España in 2012. He is an associate professor of the Mechanical Engineering Program.

Martha Sofía Orjuela Abril born in Cucuta, Colombia. Is a full-time professor at the Universidad Francisco de Paula Santander. Received a degree in Industrial Engineering from Universidad Libre de Colombia in 2003. Master in Business Administration with a specialization in Project Management from Universidad del Mar in 2014.

Guillermo Valencia Ochoa born in Barranquilla, Colombia. Is a full-time professor at the Universidad del Atlántico. Received a degree in Mechanical Engineering from Universidad del Norte, located in Barranquilla, Colombia in 2005. Master in Mechanical Engineering from Universidad del Norte, Barranquilla, Colombia in 2008. Ph. D in Engineering from the Universidad Pontificia Bolivariana, Medellín, Colombia in 2014. He is an assistant professor of the Mechanical Engineering Program, Specialization in Energy Efficient Management and Master in Energy Management at Universidad del Atlántico.