To link to this article: DOI:10.4028/www.scientific.net/AMR.188.116
http://dx.doi.org/10.4028/www.scientific.net/AMR.188.116

To cite this version:

Campa Francisco Javier, López de Lacalle Luis Norberto, Urbicain Gorka, Lamikiz Aitzol, Seguy Sebastien, Arnaud Lionel *Critical thickness and dynamic stiffness for chatter avoidance in thin floors milling.* (2011) Advanced Materials Research, vol. 1880. pp. 116-121. ISSN 1662-8985

Critical Thickness and Dynamic Stiffness for Chatter Avoidance in Thin Floors Milling

Campa Francisco J.[1, a], LÓPEZ De Lacalle Luis Norberto[1,b], Urbicain Gorka[1,c] , Lamikiz Aitzol[1,d] , Seguy Sebastien[2, e], and Arnaud Lionel[3, f]

[1]Escuela Técnica Superior de Ingeniería, Alameda Urquijo s/n, C.P. 48013, Bilbao, Spain

[2]INSA, Université de Toulouse, 135 av. de Rangueil, 31000 Toulouse, France

[3]École Nationale d'Ingénieur de Tarbes, 47 av. d'Azereix, 65000 Tarbes, France

[a]fran.campa@ehu.es, [b]norberto.lzlacalle@ehu.es, [c]bckurpeg@ehu.es, [d]aitzol.lamikiz@ehu.es

[e]sebastien.seguy@insa-toulouse.fr, [f]arnaud@enit.fr

Keywords: Chatter, Stability prediction, Thin parts milling.

Abstract. A common problem in the aeronautical industry is the chatter vibration due to the lack of dynamic stiffness in the milling of thin walls and thin floors. The present work proposes a method for chatter avoidance in the milling of flexible thin floors with a bull nose end mill. It allows the calculation of the thickness previous to finish milling or the minimum dynamic stiffness that the floor must have to avoid the chatter vibration appearance. To obtain these values, the stability model algorithm has been inverted to estimate the thickness or the dynamic stiffness required in a floor to allow a stable milling. This methodology has been validated satisfactorily in several experimental tests.

Introduction

The lack of dynamic stiffness is the cause for chatter vibrations in the finish milling of flexible thin walls and floors. This means that a bad surface finish or even marks appear on the final surface and the part has to be rejected or needs manual finishing. Regenerative chatter in milling of thin flexible floors appears when there is a variable component of the chip thickness in the normal direction to the floor surface. It happens when ball-end mills, bull-nose end mills or tools with inserts with a cutting edge lead angle κ below 90º are used. In aeronautical machining, bull-nose end mills are frequently used to leave a fillet radius between thin floors and walls, so dynamic problems machining floors arise.

To solve this problem, there are solutions based on intelligent devices: fixtures, actuators for active damping, etc. [1,2]. Smith and Dvorak proposed the use of a flat end mill for the floor and a ball end mill for the fillet radius milling [3]. The lead angle of 90º of the flat end mill avoids the excitation of the floor, and the milling at low spindle speeds with the ball end mill takes advantage of the process damping effect. Other authors propose the combination of an online variation of the spindle speed to more stable speeds with the predetermined increase of the feed speed in the more compliant areas of the piece .

Another solution to avoid chatter is the use of stability lobes calculated from a dynamic model of the process. Since the beginnings of the XXth century and especially for the last twenty years, a huge effort to understand, predict and avoid chatter vibrations has been done [4]. The stability lobes calculation allows the selection of chatter-free axial depths of cut and spindle speeds that maximize the material removal rate. Budak and Altintas proposed a linear model for spindle-tool chatter avoidance [5]. Alternative algorithms such as semi-discretization, temporal finite elements analysis or Chebyshev collocation methods, allow a faster obtention of the lobes [6,7].

The modelling of the milling of thin floors with bull nose end mills presents three main problems:

- *Variable modal parameters:* Modal parameters are variable in the machining of every flexible part, due to several reasons: the material removal which reduces the mass and the stiffness of the part, the displacement of the tool over the modes of vibration of the part and the variation of the modal parameters in the cutting area [8,9].
- *Similar stiffness of the part and the tool:* In the finish milling the dynamic stiffness of the thin floor and the tool can be very similar which means that the combined flexibility of the tool and workpiece has to be taken into account [10].
- *Variable geometry of the cutting edge:* When the dominant modes of the system have a low dynamic stiffness in the tool axis direction, the cutting edge lead angle has a strong influence on the chatter appearance. The lower the lead angle, the higher is the self-excitation of those modes. Bull nose end mills have a variable cutting edge lead angle as well as variable cutting coefficients which complicate the stability model [11].

An alternative solution to modelling can be the increase of the initial thickness of the part to stiffen it. A higher the bulk of material previous to milling increases the stiffness of the part, but also the material waste. However, although machinists know the importance of the thickness of a part previous to the finish milling, there are no criteria to estimate the thickness necessary to provide enough stiffness yet maintaining a reasonable material waste. Nevertheless, the modelling of the process can help to estimate a thickness that provides sufficient stiffness to the part.

In this article the authors propose a method to improve the thin-walled parts milling through the estimation of the mechanical characteristics, thickness and dynamic stiffness, that a thin floor has to meet to be milled without chatter. Experimental tests are provided to assess the viability of the method. The article will end with some conclusions.

Critical thickness and dynamic stiffness of the floor

The stability of the finish milling of a flexible part depends on the dynamic stiffness, which is a function of the initial and final thickness of the part. The final thickness is imposed by the final geometry but the initial thickness can be selected by the CAM programmer, who selects which is the bulk of material (BOM) that has to be removed in the finishing. The BOM can be used to improve the dynamic response of the part. The critical thickness is the initial thickness that allows a stable machining of a flexible part independently of the spindle speed, that is, if the stability lobes for the milling of the part were obtained, the critical axial depth of cut (CDOC) would be higher than the depth of cut needed to remove the BOM. The minimum dynamic stiffness (MDS) is the inverse of the maximum value of the module of the dynamic flexibility in the frequency response function (FRF) of a part that has a critical thickness. To obtain those critical values, the classical stability algorithm of Budak and Altintas has been somewhat inverted, see Fig.1. Starting from the desired cutting conditions and the tool characteristics, the minimum requirements that the part must meet, critical thickness and minimum depth of cut, can be calculated.

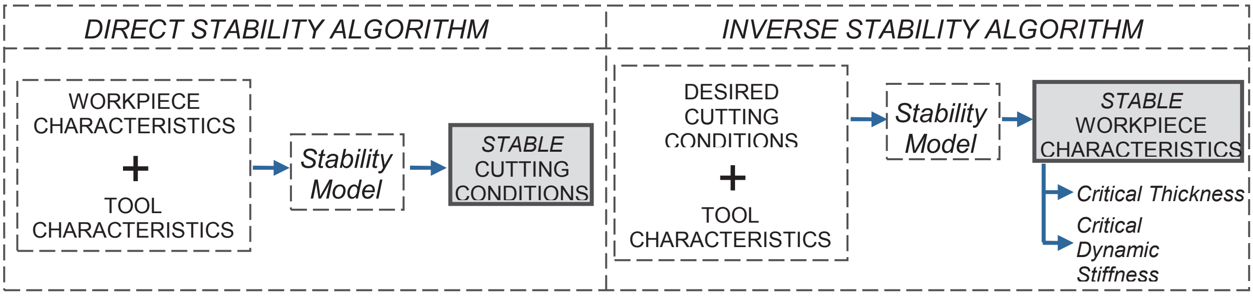

Figure 1. Inversion of the classical stability algorithm.

Obviously, there are other factors must be taken into account to be able to use this technique: excessive wear of the tool, length of the flutes, etc. However, it must be considered as a cheap alternative in parts where the major restriction is the chatter vibration. In this work, two different diagrams are proposed to estimate if the initial thickness of a thin floor is enough to guarantee a stable milling.

Critical Depth of Cut vs. Bulk of Material Diagram. The steps to create this diagram are the following:

1. Select a critical point of the machining of a thin floor and generate the geometry of the part in that point for several BOMs. The radial depth of cut is also defined here.
2. Calculate the modal parameters introducing an experimentally obtained damping.
3. Solve the stability problem and calculate the corresponding CDOCs. For this purpose, the stability algorithm proposed by Campa *et al.* for milling of thin floors with bull nose end mills has been used [11,12].

The diagram is calculated taking into account the characteristics and the cutting coefficients of the tool. If the dynamic stiffness of the tool is similar to that of the part, it must be considered in the stability algorithm. Representing the CDOC vs. the BOM, the resultant diagram is shown in the left of the Fig. 2. The blue line represents the CDOC obtained for the different BOMs in the floor, while the dashed line represents the points where the CDOC is equal to the depth needed to remove the bulk of material. When the blue line is above the discontinued one, A area, an stable milling is possible independently of the spindle speed, see Fig.2, right. In the B area, the CDOC is lower than the BOM, which means that only some spindle speeds allow a chatter-free milling. In the C area, which is represented but not calculated, because of the small floor thickness, the part is too flexible and the milling not possible at any spindle speed. In this diagram, the addition of the BOM at the intersection of the blue and the dashed line and the final thickness of the floor is the value of the *critical thickness of the floor*.

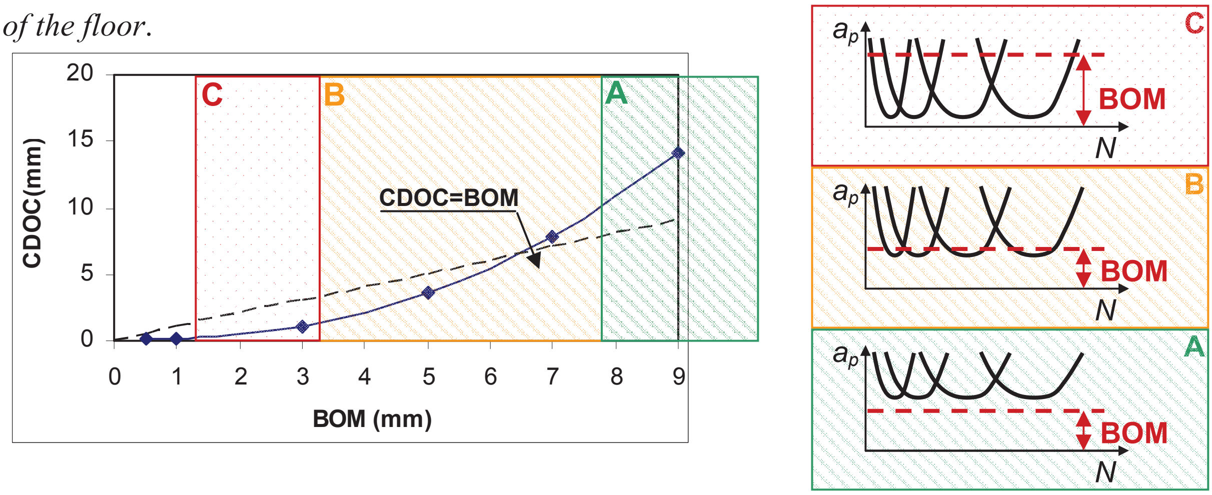

Figure 2. Critical axial depth of cut (CDOC) vs. Bulk of Material (BOM) Diagram, and stability lobes diagram shape in each area.

Critical Depth of Cut vs. Minimum Dynamic Stiffness Diagram. This diagram relates the MDS of a floor with the CDOC. For a given tool, it is calculated sweeping several values of the dynamic stiffness of the floor for one mode and calculating the CDOC. This approach assumes that the dominant modes of the thin floor are decoupled, which is usual in thin parts. As an example, in the Fig. 3 it is shown the diagram for three values of the radial depth of cut and a bullnose end mill of 16 mm, 2 cutting edges, and 2,5 of corner radius. Stable and unstable areas for a radial depth of 12 mm are highlighted. The line shows the MDS that a floor must have to be milled with a given tool and a radial depth of cut without chatter at any spindle speed, that is, the *critical dynamic stiffness*. This diagram is more universal than the previous one since it is calculated independently of the part geometry.

If a bulk of material of 5 mm has to be removed from a floor with a MDS of $5 \cdot 10^5$ N/m, the diagram indicates that it is not possible without chatter at a radial depth of cut of 12 mm, where the CDOC is below 5 mm. The radial depth of cut has to be set to a lower value, 4 mm for example.

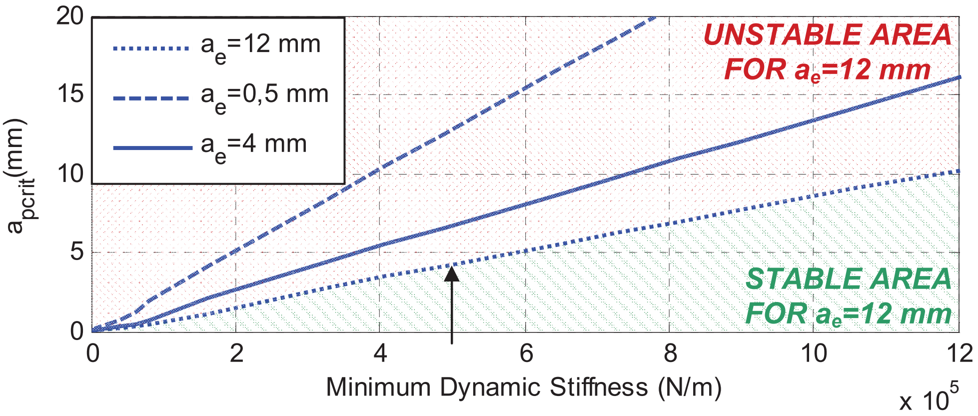

Figure 3. Critical Axial Depth of Cut-Minimum Dynamic Stiffness.

Experimental tests

The test consists on the milling of an aluminum pocket with a cantilever thin floor at the maximum spindle speed of the machine, 24.000 rpm. The machine is a Kondia HS1000. Four tests have been performed finish milling the floor to a thickness of 1 mm starting for several BOMs: 5, 6, 8 and 9 mm. The milling strategy in down-milling has been divided into 8 steps and, for this study, only the milling of the step 4 has been considered, see Fig. 4. The radial depth of cut is 9,67 mm and the feed per tooth is 0,05 mm. All the tests have been made with a bull nose end mill with a diameter of 16 mm, 2 cutting edges, a corner radius of 2,5 mm and a helix angle of 30º. The chatter appearance has been detected by means of the surface measurement and the microphone and a light accelerometer glued to the part. On the other hand, to calculate the diagrams, a FEM modal analysis has been done in the middle of the step for several BOMs: 0,5, 1, 3, 5, 7 and 9 mm. The damping coefficient has been obtained from the modal fitting of the FRFs of several impact tests.

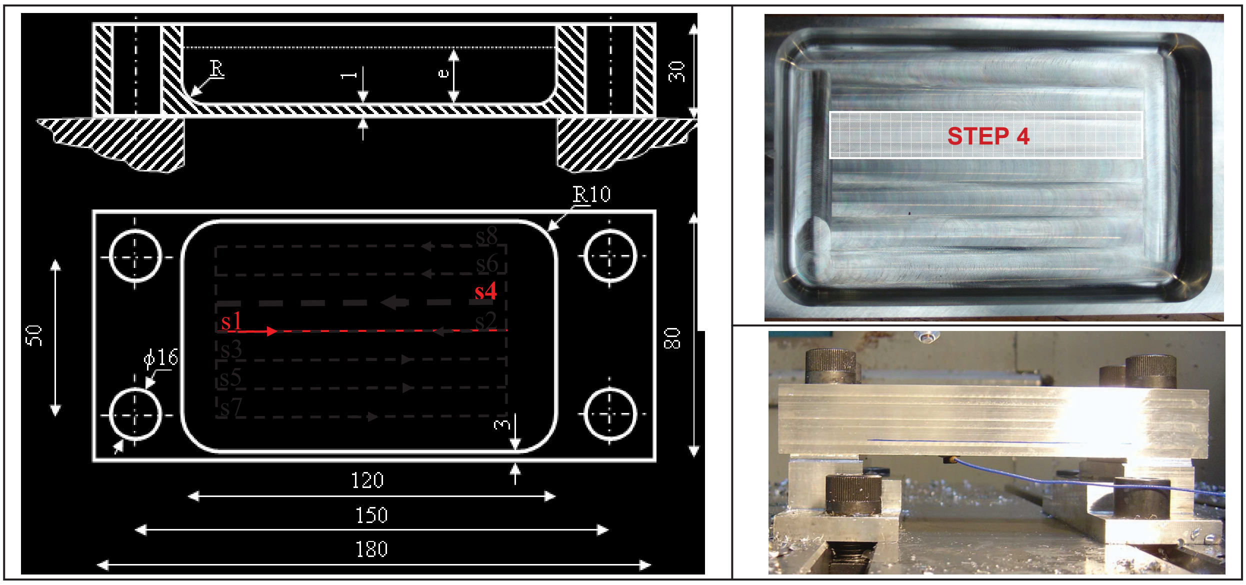

Figure 4. Geometry of the test part and milling strategy. Area of study (step 4). Fixturing of the part showing the floor overhang used to reduce the stiffness of the part.

The resultant surfaces and the corresponding mean R_a in several areas are shown in the Fig. 5. With a BOM of 8 mm the mean surface roughness R_a is 1,4 µm. For 9 mm, the mean R_a varies from 0,3 to 1,4 µm. Both cases have proven to be stable. On the other hand, the tests with a BOM of 5 and 6 mm have been unstable, with a higher roughness and even some clear chatter marks in the finish.

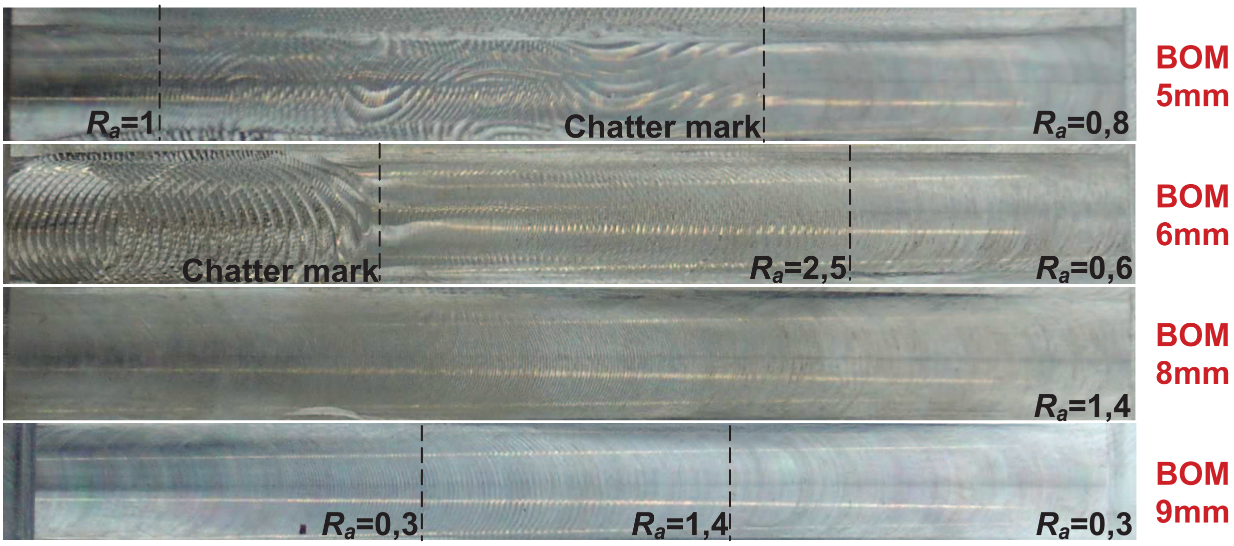

Figure 5. Mean Ra in µm in the step 4 of the test part for a BOM of 5, 6, 8 and 9 mm.

In the Fig. 6, the CDOC vs. MDS Diagram is shown. The MDS in the middle and the depth of cut needed to remove the BOM for the tests is indicated (stable cut: green 'o', unstable cut: red 'x'). To locate these points, it has been superposed the MEF obtained relation between the MDS of the floor and the BOM (red dashed line). The red circles show the mentioned BOMs that have been used to calculate that relation. The intersection between both lines is at a BOM of 6,5 mm. If the final thickness of the floor is 1 mm, that means that the critical thickness of the floor is 7,5 mm. On the other hand, the coincidence between the diagram and the experimental results is acceptable.

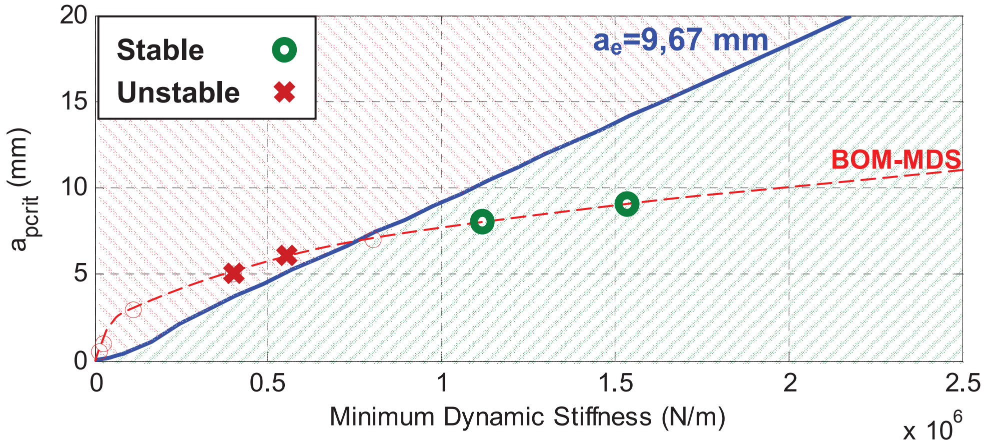

Figure 6. Experimental results on the CDOC-MDS diagram.

The CDOC vs. BOM Diagram is shown in Fig. 7. This diagram corroborates the experimental results and the critical thickness of 7,5 obtained in the previous diagram.

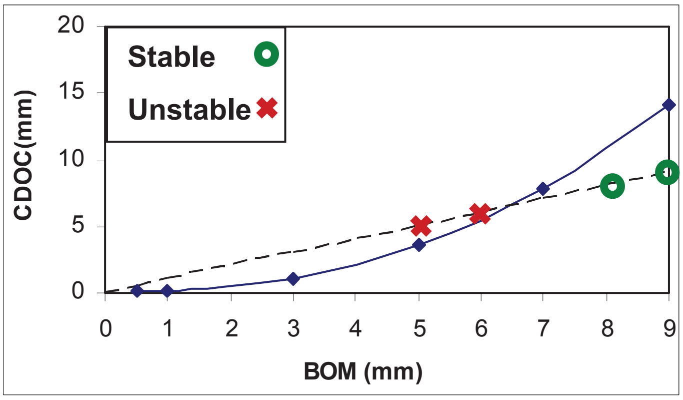

Figure 7. Experimental results on the CDOC-BOM diagram.

Summary

In this paper it has been proposed a method to estimate the minimum thickness or dynamic stiffness that a floor must have in order to be cut without chatter independently of the spindle speed. Hence, it can help to select the optimal bulk of material or decide whether it is necessary to change the radial depth of cut. It can also be used to estimate how much has to be the part stiffened or damped. Two diagrams have been proposed to obtain those values: the Critical Depth of Cut vs. Bulk of Material Diagram and the Critical Depth of Cut vs. Minimum Dynamic Stiffness Diagram. The obtention of these diagrams is made by means of an inversion of the classical stability algorithms and the FEM study of the modal parameters of the part. The cutting tests made on a test part have proven that the method is reliable. This method can be applied also to the milling of thin walls, or the turning of thin components, which are common operations in the aeronautical industry.

References

[1] Aoyama, T. & Kakinuma Y. Development of Fixture Devices for Thin and Compliant Workpieces. Annals of the CIRP, Vol. 54 (2005), pp. 325-328.

[2] Sims, N.D., Zhang, Y. Piezoelectric active control for workpiece chatter reduction during milling. Proc. of the SPIE, Smart Structures and Materials 2004: Smart Structures and Integrated Systems, A.B. Flatau eds., Vol. 5390 (2004), pp. 335-346.

[3] Smith, S. & Dvorak, D. Tool Path Strategies for High Speed Milling Aluminium Workpieces with Thin Webs. Mechatronics, Vol. 8 (1998), pp. 291-300.

[4] Altintas, Y., Weck, M. Chatter stability of metal cutting and grinding. Keynote paper, Annals of the CIRP, Vol. 53 (2004), pp. 619-652.

[5] Altintas, Y., Budak, E. Analytical prediction of stability lobes in milling. Annals of the CIRP, Vol. 44 (1995), pp. 357-362.

[6] Insperger, T., Stépán, G. Stability of high-speed milling. Proceedings of Symposium on Nonlinear Dynamics and Stochastic Mechanics, Orlando (2000).

[7] Bayly, P.V., Halley, J.E., Mann, B.P., Davies, M.A. Stability of Interrupted Cutting by Temporal Finite Element Analysis. Journal of Manufacturing Science and Engineering. Vol. 125 (2003), pp. 220-225.

[8] Budak, E. Mechanics and Dynamics of Milling Thin Walled Structures, Phd. Thesis, University of British Columbia, Vancouver (1994).

[9] Thevenot, V., Arnaud, L., Dessein, G., Cazenave-Larroche, G. Integration of dynamic behaviour variations in the stability lobes method: 3D lobes construction and application to thin-walled structure milling. International Journal of Advanced Manufacturing Technologies, Vol. 27 (2006), pp 638-644.

[10] Bravo, U., Altuzarra, O., López de Lacalle, L.N., Sánchez, J.A., Campa, F.J. Stability Limits of Milling Considering the Flexibility of the Workpiece and the Machine. International Journal of Machine Tools & Manufacture, Vol. 45 (2005), pp. 1669-1680.

[11] Campa, F.J., Lopez de Lacalle, L. N., Lamikiz, A., Sánchez, J.A. Selection of cutting conditions for a stable milling of flexible parts with bull-nose end mills. Journal of Materials Processing Technology, Vol. 191 (2007), pp. 279-282.

[12] Campa, F. J., Seguy, S., López de Lacalle, L. N., Arnaud, L., Dessein, G., Aramendi, G. Stable Milling of Thin-Walled Parts with Variable Dynamics. Proceedings of the 6th International Conference on High Speed Machining, San Sebastian, (2007).