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STABILITY ANALYSIS ON TURNING PROCESSES USING A SIMPLIFIED 3-DOF MODEL

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Abstract. Chatter is a self-excited vibration which is an obstacle to machining processes, because its effects leads machining processes to instability, causing poor surface finish and high levels of tool wear. In this way a strategy for chatter prediction was adopted, a 3-DOF considering 3 different lathe components was developed and Nyquist stability criterion was used to generate stability lobes diagrams, to understand the stability behavior of turning process. Through the developed 3DOF model, the influence of some parameters on the process stability were simulated and analyzed. In the conclusion of this paper it is presented the advantages and drawbacks of this type of model in analysis, as well as the exposition of the main results obtained from the analysis performed.

Keywords: Regenerative chatter, Turning, Vibrations, Stability lobes

1. INTRODUCTION

In the past few years many researches have been carried on the study of machining processes and ways to maximize production without loss of the quality of surface finish. It is known that using a certain combination of parameters it is possible to reduce the machining process time, but it may lead to abrupt chip width variation, which causes chatter, a selfexcited vibration that increases at each iteration of the tool in the workpiece Munoa *et al.* (2016).

Accordingly, as chatter is a phenomenon that hinders the improvement of machining processes, many authors have been searching ways to predict and suppress these effects. Liao and Young (1994) proposed an on-line monitoring method to suppress the regenerative chatter vibration during the machining process by regulating the spindle speed based on the chatter frequency which is determined by the signal of dynamic cutting force collected from a dynamometer. Pan *et al.* (1996) and his co-workers tried to utilize different control methods to undermine the chatter effect, hence they have reduced the chatter magnitude by approximately 20dB. Tarng *et al.* (1999) and his collaborators utilized a piezoelectric actuator coupled on the tool holder as an active control method to reduce the chatter effect on turning and they noticed that with this method it was possible to increase the depth of cut up to six times the usual. Venter *et al.* (2016) applied the same technique of Tarng and his collaborators, using a piezoelectric actuator to reduce chatter, however in her study the model developed takes into account the non-linearities of the turning process. Mahdavinejad (2005) developed a mechanic lathe on a FEM software in which several modal analyses were made with different machine component combinations in each of them to understand which of those components have influence in the process. After this, stability lobes diagrams were generated and it was noticed that the presence of the tailstock increased the process stability.

Since a recurring phenomenon such as chatter is a major impediment to increasing productivity in machining processes, one of the main concerns nowadays is to develop more refined analytical models to predict this effect and thus optimize the cutting parameters in the different processes known. In this way, Ozturk *et al.* (2016) developed time and frequency domain models analytically to predict stability limits in two types of parallel turning processes. Using simulation methods they were able to determine the best set of parameters to increase productivity without the risk of leading the process to instability. Siddhpura *et al.* (2017) have developed an analytical model considering 2 DoF, the tool and the workpiece, in the workpiece's case they made two different models, one without tail-stock and other taking it into account. For both models and a third one considering a more rigid workpiece, they choose some parameters as variables and have fixed others, at the end of the research they have found that their models were reasonably precise with the experimental results. Jiang *et al.* (2018) considers it essential to develop analytical models nowadays since they make it possible to optimize cutting parameters and maximize production. In this way, they used a two-step verification to determine the nonlinear coefficients of turning forces, as well as characterization tests to verify the force model they proposed. Once the nonlinearities were identified, they were able to develop an analytical model that presented great precision with the experimental results.

The present study is focused in developing a more complete analysis of the chatter phenomenon on the turning process. Tarng et al made a vibratory model of 1 degree of freedom (DOF) taking in consideration only the tool with the tool holder, this choice might have been taken because the stiffness of the other components would be much greater than the tool holder's stiffness, hence these components would not have influence in chatter phenomenon. For this work, a 3DOF simplified model was developed based on Balachandran and Magrab (2009) physical model which takes into account the tool holder, machine turret and bed, the development of this model is made to study the influence of other components in the chatter. With the development of a mathematical model of the problem allied to computational resources it was possible to make turning process simulations taking the chatter effect into account and identifying if the process is stable or not for certain combination of machining and physical parameters. Stability lobes diagrams (SLD) for one and three DOF can also be generated to compare them and notice if the machine components do have influence on chatter phenomenon, and if they do, how stiff they can be to have this, two different 3-DOF models with different machine components stiffness were used to observe the influence of this property in process stability.

2. DYNAMIC MODEL OF TURNING VIBRATIONS

As previously stated, this work has the objective of study the influence of other machine components in chatter phenomenon. Fig. 1 shows the physical model utilized for this study.
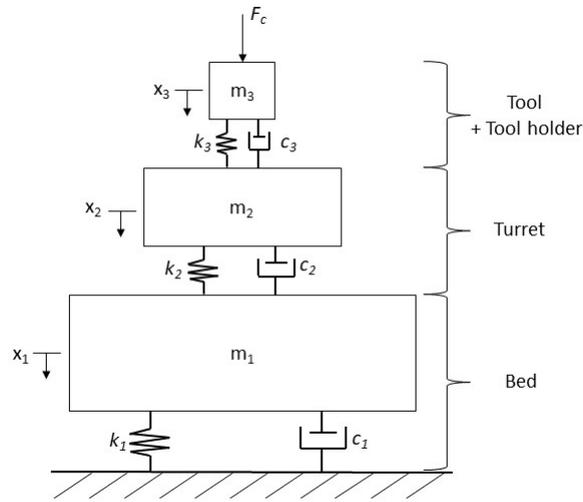

Figure 1. 3-DOF physical model of turning process.

In this model m, k and c are mass, stiffness and damping coefficients of the machine components respectively. The indexes 1, 2 and 3 make reference to the machine bed, turret and tool coupled to the tool holder respectively. Fc is the instantaneous cutting force caused by the turning process which takes into account the regenerative chatter overlap effect. A mathematical model was made for this representation of turning process, Eq. 1 represents the motion equation.

$$[M]\{\ddot{x}(t)\} + [C]\{\dot{x}(t)\} + [K]\{x(t)\} = F_c(t) \tag{1}$$

where $[M]$, $[C]$ and $[K]$ are mass, damping and stiffness matrices respectively, considering $[C] = \alpha[K]$. If transformed to the Laplace domain, Eq. 1 can be expressed by the Eq. 2.

$$([M]s^2 + [C]s + [K])\{x(s)\} = F_c(s) \tag{2}$$

The instantaneous cutting force in time domain, considering the chatter overlap effect can be expressed by the Eq. 3.

$$\vec{F}_c(t) = [B](aD)\{\vec{x}(t) - \vec{x}(t - T)\} - [B]D_p\frac{2\pi}{N}\{\dot{x}(t)\} \tag{3}$$

in Eq. 3, $[B]$ is a vector that indicates in which DOF the force is acting, D is the cutting constant of the process, a its the width of cut of the process, D_p is the process damping constant, N is the spindle speed used in the process, and T is the time between each pass of the tool in the workpiece, which means the expression $(\vec{x}(t) - \vec{x}(t - T))$ is the part of equation that considers the overlap effect of chatter in the model. With some algebraic manipulations and transforming the Eq. 3 to the Laplace domain, the Eq. 4 is obtained.

$$F_c(s) = [B](aD(1 - e^{-sT}) - D_p\frac{2\pi}{N}s)\{x(s)\} \tag{4}$$

. With further algebraic manipulations with the Eq. 2 and 3 it is possible to obtain the characteristic equation which is represented by the Eq. 5.

$$\{[B](aD(1 - e^{sT}) - D_p\frac{2\pi}{N}s)[M] - [I]\}\{F_c(s)\} = \{0\} \tag{5}$$

Using the characteristic equation it is possible to determine the stability of the process utilizing the Nyquist stability criterion as demonstrated in Altintas (2012), which was used to determine the stability of the process for a huge variation of parameters and generate the stability lobes diagrams presented in the section 3 of this paper.

For the calculations and simulations, some parameters were adopted based on studies of Jen and Magrab (1996) which considered a similar 3-DOF model for the turning process. The tool and tool-holder equivalent masses and stiffness were taken into account based on a commercial device that was measured and weighted. The physical parameters used for the simulations are presented in the Tab. 1, accordingly to the different models used, as previously stated in section 1.

Table 1. Physical property values for machine components considered in the different situations and mathematical models.

Physical Properties	Depth of cut Analysis			Damping coefficient Analysis		
	Bed	Turret	Tool[1]	Bed	Turret	Tool[1]
Mass [kg]	274	85	0.09	274	85	0.09
"Flexible" machine components						
Stiffness[N/m]	4.58×10^8	2.1×10^7	2.3×10^6	4.58×10^8	2.1×10^7	2.3×10^6
Damping coefficients [N.s/m]	4.58×10^2	2.1×10^1	2.3	4.58×10^4	2.1×10^3	2.3
"Stiffer" machine components						
Stiffness[N/m]	4.58×10^9	2.1×10^8	2.3×10^6	4.58×10^9	2.1×10^8	2.3×10^6
Damping coefficients [N.s/m]	4.58×10^3	2.1×10^2	2.3	4.58×10^5	2.1×10^4	2.3

[1]Parameters values for 100mm stickout length, the values will change for different stickout values.

3. STABILITY ANALYSIS METHODOLOGY

Since the mathematical model was developed and the Nyquist stability criterion was used to determine if a given set of parameters leads the process to stability or not, it was necessary to develop a logic that could quickly generate stability maps. Initially, all parameter sets were scanned, but this cost a lot of time and computational resources.

It is known that a set of parameters internal to a lobe leads the process to instability, and external to the lobe leads to stability. Thus an algorithm was developed to map the edges of the stability lobes only. The Figure 2 shows a flowchart illustrating the logic used in the MATLAB routine to map the frontiers between the stable and unstable configurations.
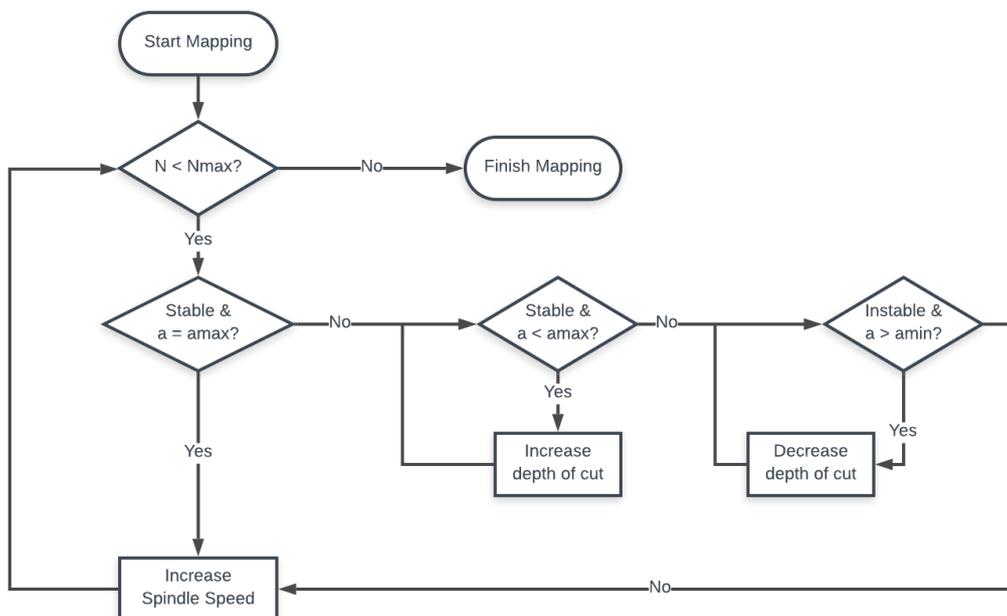

Figure 2. Flowchart of the logic used in the depth of cut analysis.

The Figure 2 shows the logic used in the depth of cut analysis, in which N is the spindle speed of the workpiece and a represents the depth of cut. The decision-making of the developed program based on the flowchart of Fig. 2 can be verified in Fig. 3.
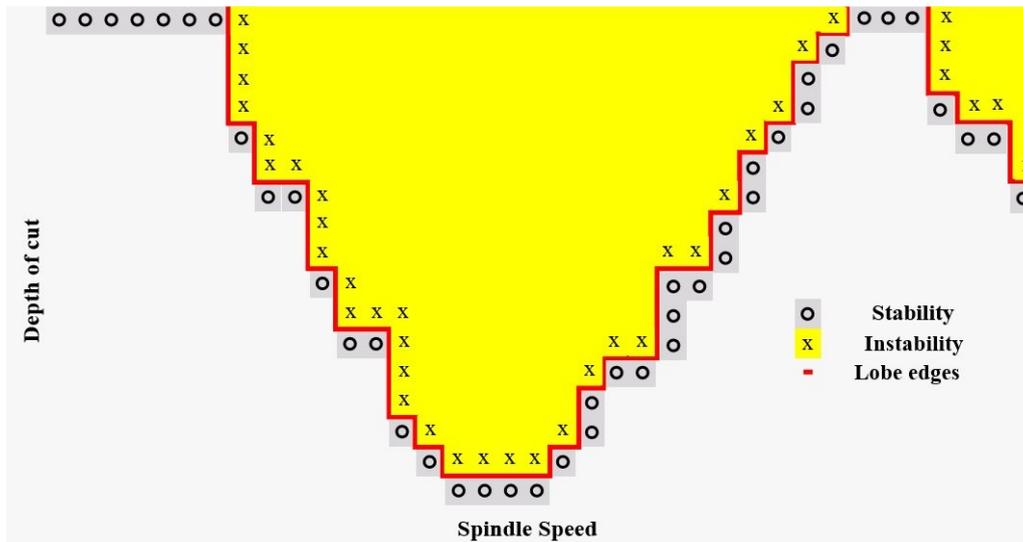

Figure 3. Representation of the decision-making based in developed logic.

In Figure 3 it is possible to verify the sequence of iterations performed by the routine to map the stability lobes, in which 'o' shows a set of parameters that lead to a stable response, and 'x' to a unstable one. The algorithm only tested sets of parameters where there is 'o' or 'x' markers, allowing the fast and optimized determination of the stability lobes' edges for a given analysis, without having to perform an exhaustive search of every parameter combinations.

4. RESULTS

For this article it was proposed to analyze the influence of certain parameters on the stability of the turning process. For each of these parameters two different SLDs were analyzed, one of them considering the damping coefficient of the tool with tool holder as one variable parameter, and the limit depth of cut as the other one variable, each one was used against the spindle speed to generate the two types of SLD.In order to properly identify the influence of the parameter on each of the analyzes performed, all process parameters other than the one under analysis were considered constant. Thus, three different values of the parameter under analysis were selected for the analysis. In each of the analyzes the parameters used will be properly indicated, since some parameter sets allow a better visualization of the influence by a given parameter on SLDs.

4.1 Variation of machine stiffness

In this analyze the focus is to understand how much influence other machine components could have in chatter effect, in this way for each type of SLDs three curves were plotted are these an 1-DOF model, a 3-DOF model with lower stiffness and damping coefficient as described in Tab. 1 from section 2, and a 3-DOF model considering bed and turret with a stiffness 10 times higher. Figure 4 shows the results obtained from all these models together.

(a) SLD for α analysis, $a_{lim} = 1.0$ mm

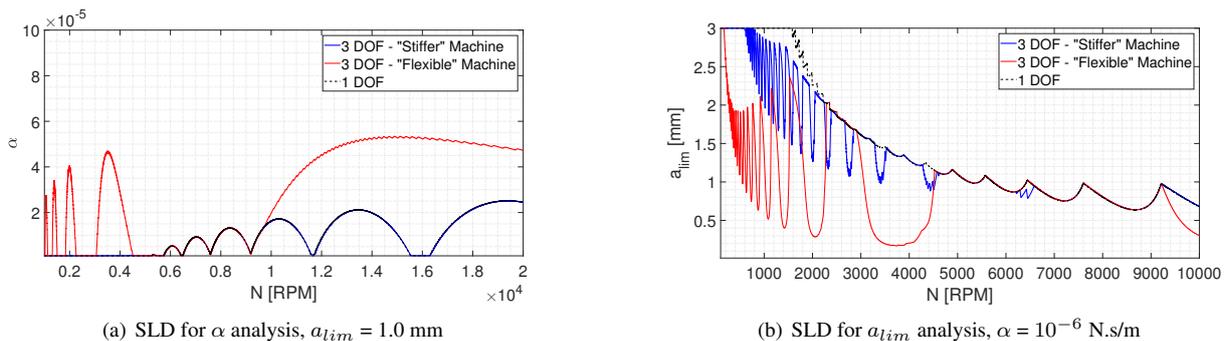(b) SLD for a_{lim} analysis, $\alpha = 10^{-6}$ N.s/m

Figure 4. Machine variation analysis.

The graphs in Fig. 4 have two well-defined regions, the inner region to the lobes, for which the set of parameters leads the process to instability, and the outer region to the lobes in which the process is stable to the set. of parameters.

From both graphics of Fig. 4 it was possible to notice that other machine components do have influence in chatter phenomenon as expected. In this sense it was also possible to observe in both SLD's the difference between a more flexible machine-tool from a rigid one. In case of a flexible one the instability lobes start earlier for lower rotation speeds in both cases, but in the depth of cut case is possible to see that in some spindle speed ranges the stability behavior of 3-DOF stiffer model is the same of 1-DOF model, but in α vs N SLD that do not occur in greater spindle speed values, the instability lobes are much greater than the 1-DOF model ones, and these go on in all the spindle speed range considered. Another interesting result obtained is that even a stiffer machine still has a non-negligible influence in the process stability. In the α vs N SLD if a greater cut's depth is used the discrepancy between each model becomes greater.

4.2 Time responses analysis

Figure 5 shows a comparison between two different time responses. The Fig. 5 (a) considers a set of parameters outside the unstable lobes of the SLD from the Fig. 4 (a) (N = 10000 rpm, $\alpha = 6 \times 10^{-5}$, a_{lim} = 1.0 mm), where it is possible to observe the stability of the 3 models in this configuration. On the other hand, the Fig. 5 (b) takes into account parameters in which only the 3-DOF "flexible" model is inside the unstable lobes (N = 10000 rpm, $\alpha = 4 \times 10^{-5}$, a_{lim} = 1.0 mm).

(a) N = 15000 rpm, $\alpha = 6 \times 10^{-5}$, $a_{lim} = 1.0mm$ (b) N = 15000 rpm, $\alpha = 4 \times 10^{-5}$, $a_{lim} = 1.0mm$
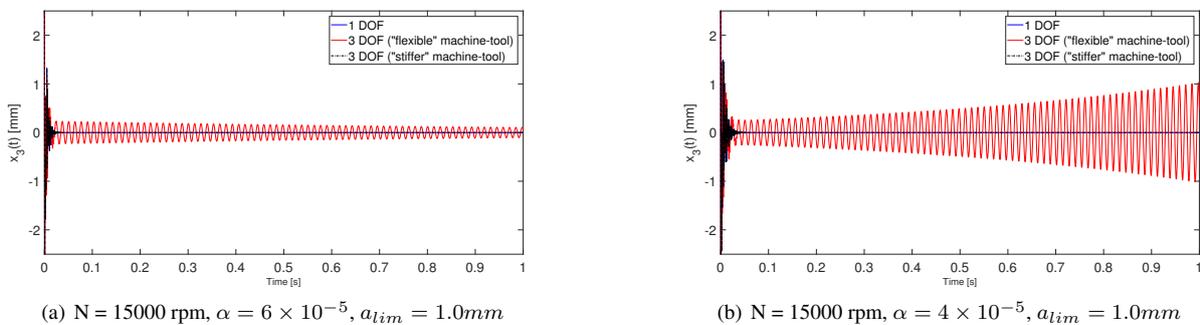
Figure 5. Comparison of stability behavior in the time domain, in two different pairs of parameters.

From the time domain graphs shown in Fig. 5, it is possible to see consistency with the stability maps acquired in the previous analyzes.

4.3 Variation of stickout length

For this first parameter analysis, the focus is to show the influence of the length at which the tool holder is attached to the turret. Shorter stickout lengths were expected to make the process more stable, since reducing the length ensures greater rigidity for this DOF that is in direct contact with the workpiece. The Fig. 6 shows the SLDs obtained for this parameter analysis.

(a) SLD for α analysis, a_{lim} = 1.0 mm   (b) SLD for a_{lim} analysis, $\alpha = 10^{-6}$ N.s/m
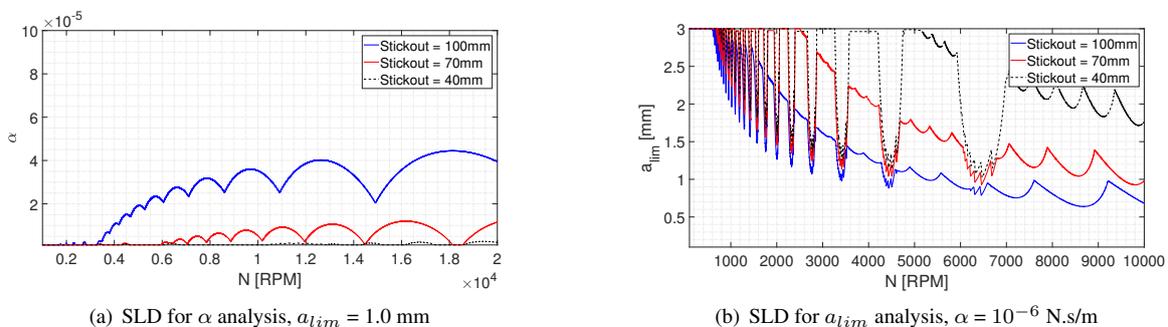
Figure 6. Stickout analysis

As expected, the Fig. 6 shows that the reduction in stickout length made the tool holder stiffer increasing the stable regions on both SLDs. In the case of α vs N SLD it is possible to observe a greater influence of this parameter compared to the depth of cut SLD, since the use of a 40mm length stickout caused an almost total reduction of the presented lobes at a length of 100mm. In the case of depth of cut SLD, a considerable decrement is observed only in the region outside the larger lobes, whereas in these lobes this reduction is not so prominent.

4.4 Variation of the cutting constant (D)

In this analysis the variation of the process cutting constant is taken into consideration for process stability. Since this parameter is directly related to the lathe setup used, it is difficult to experimentally modify, and also the process behavior is not intuitively predictable as in the case of stickout length variation. The Fig. 7 shows the effect of this parameter on the process for both SLDs.

(a) SLD for α analysis, $a_{lim} = 0.5$ mm

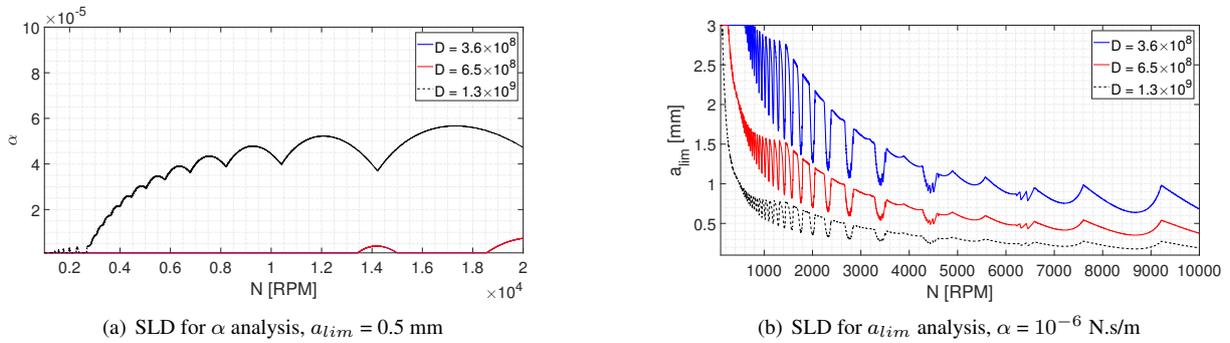(b) SLD for a_{lim} analysis, $\alpha = 10^{-6}$ N.s/m

Figure 7. Cutting constant analysis.

From Figure 7 it is noticeable that by almost doubling the initial value of this parameter it does not offer changes in process stability when we analyze the α x N stability diagram, however by almost quadrupling the initial value this left the much more unstable process with larger lobes and bands where previously there were no lobes. Thus, it is expected that there is a critical value for this parameter, where it starts to have significant influence on the process stability.

In the case of the depth-of-cut diagram, this effect is not so apparent, it can only be seen that increasing this parameter makes the process increasingly unstable. It is possible to observe a reduction between the distances of the lobes from the second value to the third compared to the distance from the first to the second, possibly from a certain value of this parameter the instability lobes stop increasing.

4.5 Variation of process damping constant (D_p)

Another analysis performed is the influence of the process damping constant on the process stability. The name of this parameter intuitively suggests that increasing it will consequently increase process stability, however the influence of this parameter on each of the SLDs is necessary. The Fig. 8 shows the influence of this parameter in each of the SLDs.

(a) SLD for α analysis, $a_{lim} = 1.5$ mm

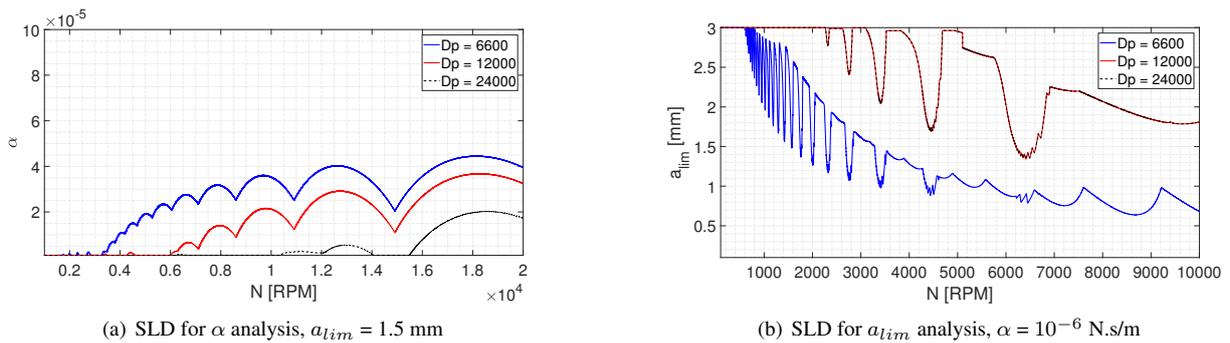(b) SLD for a_{lim} analysis, $\alpha = 10^{-6}$ N.s/m

Figure 8. Process damping constant analysis.

The Figure. 8 shows that the influence of this parameter on process stability is contrary to that of the previously analyzed parameter, since increasing this parameter value reduces process instability.The α x N diagram shows behavior similar to the depth-of-cut diagram of the previous analysis, except that increasing the parameter reduces the size of the instability lobes.

The depth-of-cut diagram is similar to the α x N diagram from the previous analysis, with the change that increasing the value of D_p appears to have a critical value in which the reduction of instability lobes no longer occurs, since there is no difference between the curves of $D_p = 12000$ and $D_p = 24000$.

5. CONCLUSIONS

In specific it was possible to observe that even a simplified 3-DOF model shows the influence of other machine components in the stability of turning process and chatter phenomenon. In this way when the physical parameters of the lathe components are known it is possible to predict with more precision the effect of chatter and maximize the effectiveness of the process with the right choice of parameters. If the chatter frequencies are determined more accurately, may it be possible to undermine his effects using known chatter suppression techniques, such as active damping techniques, for example piezoelectric actuators in these machine components the same way Tarng *et al.* (1999) used in his work, consequently, it will be possible to reduce the instability lobes predicted in the numerical and experimental results.

From the results obtained in the previous section it can be concluded that the analyzed parameters related to the machine have considerable influence on the process stability regarding the iterative chatter phenomenon. Since all these parameters have a strong influence on process stability, it is interesting to use routines like the one developed in this article to predict the process behavior, and thus select a set of parameters that can optimize the process and keep it stable.In addition to what has been said, in future studies it is possible to perform tests on the lathe in order to verify the validity of the results obtained from the developed analytic model and computer simulations.

6. ACKNOWLEDGEMENTS

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