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Methodology of decision support: application to machining chatter

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Abstract:

In this paper a methodology of decision support is developed and applied on the problem of chatter in machining context. After presenting the problematic by review of the state of the art, a new improved modeling of decision making is presented. This methodology includes all the steps necessary to accurately analyze a problem of chatter milling. The methodology developed is focus to guide an operator in the complex task of decision making, in order to solve chatter problem. Then a method for chatter reduction is presented. Finally, the methodology is illustrated on a representative industrial problem and the interest of this work is demonstrated.

Key words: Decision support, methodology, machining, chatter.

1 Introduction

Operations of high-speed machining are currently limited by complex vibratory phenomena. They cause a severe deterioration of the machined surface, increase the rate of tool wear and reduce the spindle life span. These phenomena are problematic, because the vibrations lead to scrap, non-conformities and lower productivity for the company.

The detailed analysis of these phenomena has led many scientific works since the fifties, see e.g. [1]. The theoretical approach offers efficient modeling, studying in particular the stability of the process, representative of chatter [2,3]. These approaches emerge the existence of optimal windows – axial depth of cut and spindle speed – to reduce the impact of chatter. In addition, many solutions of chatter reduction have been published, see e.g. [4-6]. However, in many cases, the detection of this phenomenon is not obvious. And often, operators are not guided in the process for the optimal choose of the parameters, improving the operation.

Another field of research is devoted to the decision support system, to guide a user through a complex process of decision-making [7]. These works aim to decompose a complex process, in more steps easier to carry [8]. Some works have focused on the characterization of the process of collaborative decision-making [9]. Recent work has shown the interest of the application of knowledge management for heath monitoring of aircraft structures [10]. The application of evolutionary approaches is use to improve the modeling and the optimization of end milling process [11]. The application of semantic representations improves the design phase of machine tool [12]. However, to the best knowledge of the authors, the decision-making approaches have not been applied to improve the chatter reduction, like in milling process.

The objective of this paper is to combine an operational approach and a decision-making approach to propose a methodology of decision support to solve a problem of machining chatter. This article is organized as follows. The state of the art on decision making and the adaptation of a new model on the context of machining chatter is presented in Section 2. Then, a particular approach for solving vibration problems is explained in Section 3. Finally, the methodology is illustrated on a representative industrial case and the interest of this work is demonstrated in Section 4. Finally, a conclusion of this work is presented in Section 5.

2 Decision support

2.1 State of the art

Decision making is a complex activity, based on a serie of mechanisms leading to a decision. It is possible to materialize this sequence by a decision making process composed of several steps. The literature offers several models of decision making. Simon is among the first to propose a formalization of the decision as a sequence of different steps forming a process [7]:

- "intelligence", phase of data gathering the problem to solve and its context,
- "design", phase of development of potential solutions to answer the problem,
- "choice", phase of choice and implementation of the best solution to the problem according to the selected evaluation criteria,
- "review", phase of supervision, which takes place after the application of the decision taken.

This last step can be seen as a step of evaluation process to validate the decision to apply (Fig. 1).

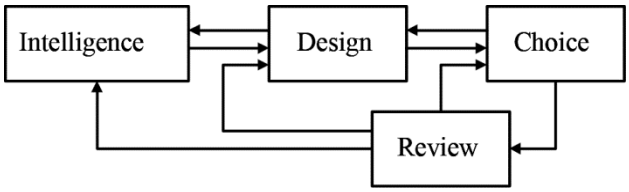

FIG. 1 – Classical model of decision making [7]

Others works are based on those of Simon, have detailed some steps. Courbon proposed a model of decision making, allowing cyclic form a loop and a readjustment as the process evolves [8]. Lavergne developed another decomposition steps leading to a decision. In his work, six steps are identified, reflecting the decision making process [13]. Stal-Le Cardinal et al. also contributes to the modeling of the decision process to investigate failures in the choice of actors [14]. The model called IDPT (Integrated Decision and Process Technology) is based on the perception of the decision process as a part time, taking place in several stages. More recently, other authors have been interested in modeling the decision, considering the capitalization of knowledge [15].

The models presented here, despite their particularities, have several similarities:

- analysis of the problem and its environment,
- research information on this problem in order to build solutions,
- evaluation of these solutions, depending on the selection criteria,
- selection of the best solution, given the criteria and the problem considered,
- application of this solution,
- monitoring and capitalization of this solution after application.

These models of decisional process show the sequence of steps required for taking a decision and the complexity of activities and mechanisms underlying.

2.2 Methodology proposed

In order to propose a methodology to solve a vibration problem, we develop in this section a model, adapted to the context of machining. The model is shown in Fig. 2. It takes four steps necessary for decision making.

The first phase of "intelligence" includes the search of informations about the process, these constraints, in order to select the initial cutting conditions. Often, the cutting conditions are given by the tool manufacturer.

The second part "design" is to select and analyze possible solutions to reduce machining vibrations. There are numerous, more or less, effective solution to reduce chatter. We can separate two main families: the approach "mechanistic" and the approach "dynamic".

The approach "mechanistic" aims to reduce displacement. This approach is widely used industrially. Its objective is:

- to add dampers (for example, addition of foam),

- to increase the rigidity of the machine,
- and to reduce the cutting conditions (spindle speed) in order to limit the forces.

These approaches are often based only on experience, it's difficult to automate this in a decision loop. This is why we do not develop in this work. However, it is perfectly possible to add in this methodology.

The approach "dynamic" allows to limit the regeneration of the surface. It is possible to distinguish three types of solution:

- The use of stability lobes to select cutting conditions ensuring chatter free machining.
- The design of special tool in order to reduce the vibration only to the cut concerned. Often the special tool is specific for a given vibration problem.
- The spindle speed variation during the machining. The goal is to break the regularity of the cutting frequency and to avoid the vibration during machining.

To end the process, a step of "choice" aims to select the best solution. In our approach, the surface roughness is the criteria used for the selection of the optimal solution.

And finally, there is an important step to capitalize the knowledge acquired in a database. This step will, thereafter, to have knowledge available directly usable by the operator. This can be very useful in the future occurrence of vibration problem.

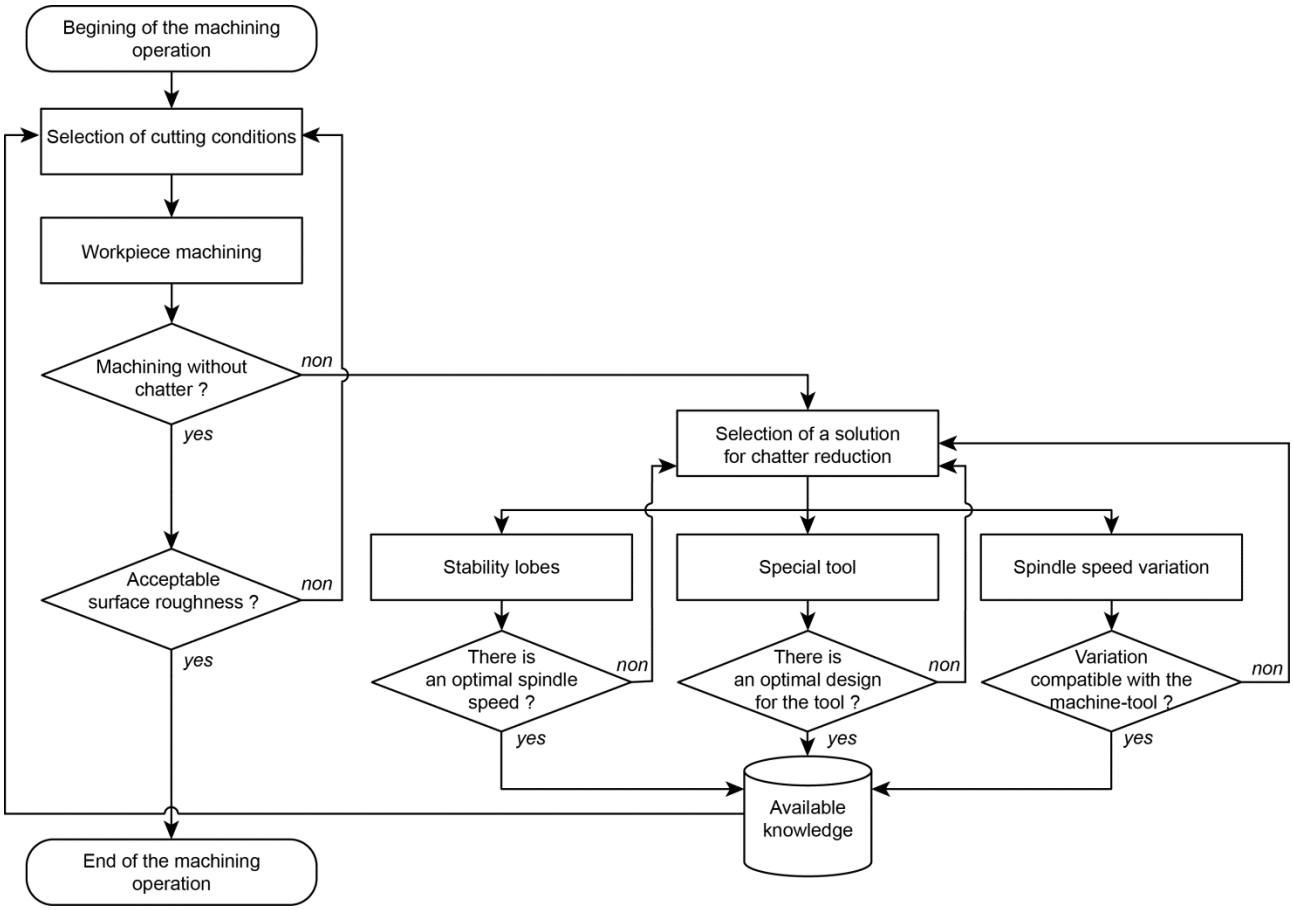

FIG. 2 – Methodology for decision support on the context of machining chatter

3 A solution for chatter reduction

In this Section, a solution of chatter reduction based on the stability lobes is proposed [2]. The main objective is to present the result of this approach. The main assumptions are:

- the tool is rigid compared to the workpiece, which is considered to be globally flexible, but rigid in the cutting zone,
- the workpiece moves along the x direction only (Fig. 3), like a single degree of freedom,

- the transfer function of the part in the *x* direction is:

$$G_x(i\omega_c) = \frac{\omega_0^2}{k(\omega_0^2-\omega_c^2+2\xi\omega_0\omega_c i)}, \quad (1)$$

where k, ξ and ω_0 are respectively the stiffness, damping ratio, and natural pulsation of the workpiece. Here, ω_c is the chatter frequency.

A linear cutting law was used: $F_T = K_T A_P h(t)$ and $F_R = k_r F_T$ where F_T and F_R are respectively the tangential and radial cutting forces, $K_T$and k_r are the corresponding tangential milling force coefficient and radial force coefficient ratio, A_P is the axial depth of cut, and $h(t)$ is the chip thickness.

Our goal is to choose spindle speeds easily for the system to be stable or unstable, the results using the stability lobes theory will be given directly. According to [2] the axial depth of cut limit is expressed in the form:

$$A_{Plim} = \frac{1}{\frac{z}{2\pi}\alpha_{xx}K_T\Re e[G_x(i\omega_c)]}, \quad (2)$$

where *z* is the number of teeth and α_{xx} the directional milling coefficient:

$$\alpha_{xx} = \frac{1}{2}[-cos(2\theta) - 2\theta k_r - k_r sin(2\theta)]_{\phi_{st}}^{\phi_{ex}}\ ;\ \begin{cases}\phi_{st} = arcos\left(\frac{2A_E}{D} - 1\right) \\ \phi_{ex} = \pi\end{cases}, \quad (3)$$

where θ is the tool angle engagement, *D* the tool diameter, A_E the radial immersion, ϕ_{ex} and ϕ_{st} the down-milling exit and start angle. $\Re e[G_x(i\omega_c)]$ is the real part of the structural transfer function of a system with one degree of freedom:

$$\Re e[G_x(i\omega_c)] = \frac{1}{k}\frac{1-d^2}{(1-d^2)^2-4\xi^2d^2}\ ;\ d = \frac{\omega_c}{\omega_0}. \quad (4)$$

The link between the chatter frequency ω_c and the spindle speed *N* is:

$$N = \frac{60\omega_c}{z\left[2m\pi+2\pi-2arctan\left(\frac{d^2-1}{2\xi d}\right)\right]}. \quad (5)$$

Eq. (2) and Eq. (5) constitute a system of parameterized equations $\{A_P(\omega_c), N(\omega_c)\}_m$, with *m* an integer corresponding to the number of full vibration cycles between the two teeth.

4 Application on a representative industrial case

This Section presents an industrial application of the methodology developed in this work. The context of the study is detailed and the results of the proposed methodology are highlighted.

4.1 Context

In aeronautical industry, airframes are composed of monolithic parts made of thin walls, which confer high stiffness to the entire part due to the spatial distribution of nerves. They are often presented in the form of thin wall clamped in one side (Fig. 3). Vibration problems – chatter – may appear in the finishing in flank milling. For this, each thin wall is machined in finishing with an axial depth of cut of 10 mm, a radial engagement of 0.2 mm and a feed per tooth of 0.05 mm/tooth.

The chatter problems are often observed during the part manufacturing. To reduce the additional costs at the manufacturing step, it is very difficult to change many settings. The spindle speed remains the most important parameters and the most effective for chatter reduction. All other parameters like geometry of the workpiece, cutting tool, etc… have been fixed.

In the industrial context, the cutting conditions are given by the tool manufacturer. During machining, if chatter appears, the operator is alone in front of the machine to solve the problem. A solution, widely used, is to reduce the spindle speed. For this, the operator will do many tests by gradually decreasing the spindle speed. The good spindle speed is selected by this iterative approach, intuitive and widely used in mechanical manufacturing workshops.

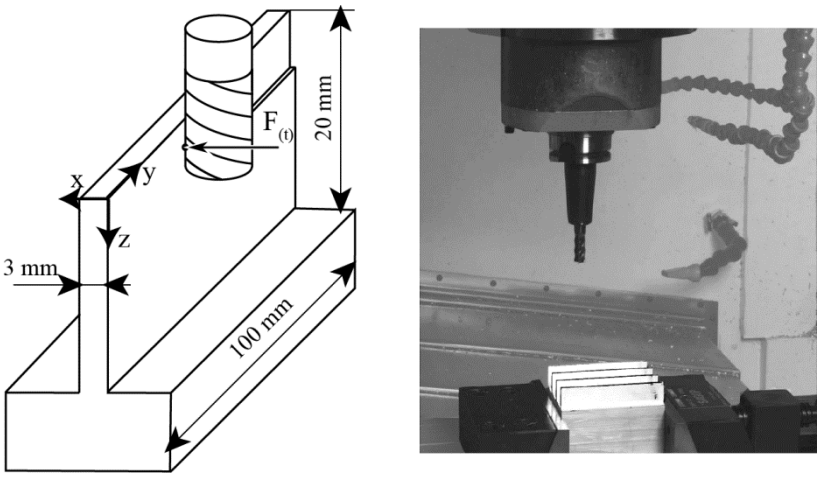

FIG. 3 – Thin wall milling. Left: workpiece. Right: experimental set up

For the machining of this part (Fig. 3), the first spindle speed of 24000 rpm was recommended by the tool manufacturer. These cutting conditions induce very strong vibrations which significantly damaged the part. Classically, the operator reduces the spindle speed by increments of 500 rpm. After the machining of 17 parts, a spindle speed of 16000 rpm was select because it does not generate vibrations.

4.2 Application of the decision support methodology

Using the methodology presented in Section 2.2, the operator is now guided through the process decision when dealing with a vibration problem. In this case, it will no longer apply an iterative solution allowing it to find optimum cutting conditions.

The first test conducted, as recommended by the tool manufacturer at 24000 rpm, generate chatter. Now the operator will use a solution for chatter reduction. In this case, the stability lobe method (see Section 3) is used in the company. The diagram obtained is presented in Fig. 4. The cutting condition of the test at 24000 rpm are above the stability lobe (see the cross), and chatter is present during machining, with a bad surface roughness and Ra = 7 µm.

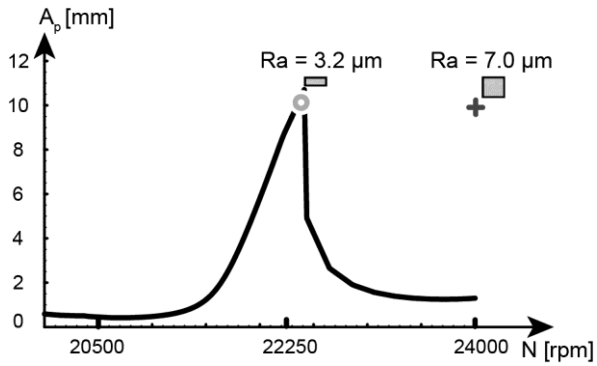

FIG. 4 – Stability lobe

At 22250 rpm, an optimal spindle speed is available on the graph. In front of the machine, the operator changes the spindle speed to this exact value, practically impossible to find without lobes. This test without chatter (see the circle), generate an acceptable surface roughness with Ra = 3.2µm (Fig. 4). In this case only two tests are necessary to find optimal cutting conditions. In addition, for the next machining operations, the operator has informed a database to capitalize knowledge. This knowledge can then be re-used on subsequent machining.

In this industrial case, the use of the decision support methodology reduces the number of machining to only two, when a vibration problem is detected. This represents a real saving time compared to the conventional method.

At first, the use of lobes can be done in collaboration with an expert in this method of chatter reduction. Then, the operator can reuse this method alone.

5 Conclusions

In this paper we have combined an operational approach and a decision making approach to propose a methodology of decision support for solving a problem of machining chatter.

An original decision model was developed. It takes into account several steps to guide an operator in a decision process. This new model also incorporates knowledge capitalization. The stability lobes method has been used to propose a reduction of chatter by optimizing cutting conditions. The detailed calculations for using this solution have been developed.

This methodology has been successfully applied on an industrial case. Using this approach reduces significantly the number of machining test in order to have a good surface finishing. The cost of problem solving is therefore reduced in the same proportions, despite the additional use of the stability lobes.

This work could be improved in order to generalize our approach to others decision making processes. A deepening of diagnostic mechanisms will also be considered to improve our methodological approach.

A more operational perspective is also considered with the definition of working procedures for operators. These procedures could help operators in their decision making activities.

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