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Chatter suppression techniques in metal cutting

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ABSTRACT

The self-excited vibration, called chatter, is one of the main limitations in metal removal processes. Chatter may spoil the surface of the part and can also cause large reduction in the life of the different components of the machine tool including the cutting tool itself. During the last 60 years, several techniques have been proposed to suppress chatter. This keynote paper presents a critical review of the different chatter suppression techniques. Process solutions with design and control approaches are compiled to provide a complete view of the available methods to stabilize the cutting process. The evolution of each technique is described remarking the most important milestones in research and the corresponding industrial application. The selection of the most appropriate technique for each specific chatter problem is also discussed considering various aspects of machining processes.

1. Introduction

Chatter in machining is a classic problem that limits the productivity. As early as 1907, Frederick Taylor stated that “chatter is the most obscure and delicate of all problems facing the machinist, and in the case of castings and forgings of miscellaneous shapes probably no rules or formulas can be devised which will accurately guide the machinist” [300].

The appearance of chatter on machine tools is disastrous since they prevent from obtaining the required surface finishes and decrease the life of tools and mechanical components. These vibration occurs in a wide range of machining operations (Fig. 1), and it is still one of the major limitations for productivity.

The recent advances in industry, especially aerospace, mould and automotive sectors, have encouraged a considerable evolution in machine tools, which became more powerful, precise, rigid and automatic. However, new limitations and challenges also showed up such as machine vibrations. After the first observations of Taylor [300], the regenerative effect was reported as the main reason of chatter by Tlusty and Polacek [310] and Tobias and Fishwick [313]. Since then, the suppression of these self-excited vibrations has become one of the major concerns and the current situation indicates that the prediction and suppression of chatter will remain as an essential problem also in the future. The main reasons are summarized below:

- *Increasing material removal rate (MRR)*

  The evolution in material technology allows increasing the cutting conditions and material removal rate (MRR). Developed around 1900, HSS tools cut four times faster than the carbon steels they replaced. Nowadays, carbide tools, which have replaced HSS tools in most applications, can cut about 3–5 times faster than HSS tools [257]. This higher capacity in

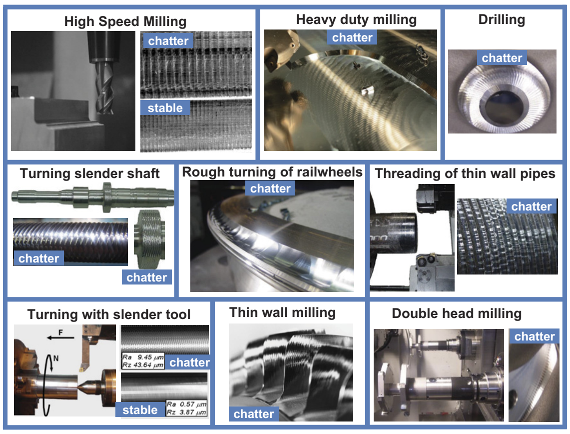

Fig. 1. Chatter problem in numerous machining applications.

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conjunction with the increase in rated power of new generation machines increases the risk of machining vibrations onset.

- *Limitations in the design procedure*

  Finite Element Method (FEM) can provide dynamic properties like natural frequencies and mode shapes in the design phase with reasonable accuracy. However, it is difficult to estimate damping which is one of the most important dynamic parameters to predict stability. This difficulty comes from the fact that joints are the main agents dissipating vibration energy, and their damping behaviour cannot be accurately predicted so far [52,163,251]. Consequently, machine designers mainly focus on increasing the static stiffness; and the result can lead to a rigid but poorly damped machine tool.

- *Low friction guiding systems*

  Rising needs in terms of accuracy have brought along an evolution in guiding systems. The first machine tools were guided through frictional guiding systems which provide relatively high damping via friction. In order to increase precision and speeds, roller bearing or aerostatic guiding systems are introduced. These guiding systems are weakly damped, and therefore, they also jeopardize machining stability.

- *Light weight design*

  Eco-efficiency is an increasing concern among machine tool builders. Machine tools manufacturers face the challenge of conceiving machines that are capable of maintaining the productivity, while consuming at the same time the least possible amount of material and energy [357]. The competition in achieving larger accelerations also leads to lighter machines which are more prone to the appearance of vibrations.

- *Manufacturing of flexible parts*

  Manufactured parts have also become lighter and less stiff, in order to minimize costs or fuel consumption in transports. Aerospace industry is the best example, where the parts must be as light as possible. The MRR requirement, together with the thin walls, makes these parts an important source of chatter (Fig. 2).

Due to the listed factors, chatter is and will be a crucial problem for the metal cutting industry.

Chatter, as a kind of self-excited vibration, depends on many factors, such as dynamic stiffness of the structure and/or the tool, cutting parameters, workpiece and tool characteristics. Mathematically, the most general case is described by a delay differential equation (DDE) with time dependent coefficients:

$$\mathbf{M}\ddot{\mathbf{r}}(t) + \mathbf{C}\dot{\mathbf{r}}(t) + \mathbf{K}\mathbf{r}(t) = \mathbf{F}_s(t) + K_t a \mathbf{A}(t)(\mathbf{r}(t) - \mathbf{r}(t-\tau)) + \mathbf{F}_{pd}(t, \dot{\mathbf{r}}(t)). \quad (1)$$

Here, $\mathbf{r}(t)$ denotes the displacement vector in Cartesian coordinates, while $\mathbf{M}$, $\mathbf{C}$ and $\mathbf{K}$ stand for the system mass, damping and stiffness matrices. Thus, the left-hand-side presents a multi-degree-of-freedom damped oscillator that models the system formed by the tool, tool holder, spindle, machine tool structure, fixture and workpiece. The cutting force on the right-hand-side is typically formed by three terms: the time periodic stationary part $\mathbf{F}_s$ causing forced vibrations, the second term is the dynamic part related to the regenerative effect, and the third term is the process damping force $\mathbf{F}_{pd}$. In addition, the dynamic force term involves further parameters like the cutting force coefficient K_t, the depth of cut a is, the regenerative delay τ and the Cartesian directional matrix $\mathbf{A}(t)$, which includes the projection of the vibration onto the chip direction and the projection of the cutting force onto the Cartesian directions.

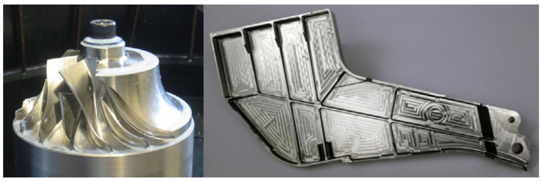

Fig. 2. Examples of machining of titanium impellers.

All these factors give rise to a complex problem but at the same time it allows tackling the problem from various perspectives according the different terms of Eq. (1):

- *Process parameter selection (a, τ)*

  Chatter problems can be avoided by selecting process parameter by means of Stability Lobe Diagrams (SLD) (Section 3).

- *Regeneration disturbance (τ)*

  The regeneration can be reduced by varying the delay with the help of special tool geometries (Section 4) or spindle speed variation techniques (Section 7).

- *Process damping maximization ($\mathbf{F_{pd}}$)*

  Process damping can be increased using special edge geometries (Section 4).

- *System stiffness enhancement (**K**)*

  Stiffness can be increased by different procedures (Section 5).

- *System damping enhancement (**C**)*

  The damping of the system can be increased using passive (Section 6) or active (Section 8) techniques.

2. Concepts for chatter suppression technique selection

One of the main goals is to define the best chatter suppression technique for each chatter case. The most suitable technique should be selected by considering different aspects of the chatter problems which are classified by the following criteria:

2.1. Machinability

Several chatter suppression methods are based on the variation of the cutting conditions, especially the cutting speed. Therefore, the machinability is an important factor when selecting the best chatter suppression technique. Materials with good machinability permit changes in the spindle speed to avoid chatter. With low machinability, however, the range of spindle speed is limited, and the objective is to move the most stable zone of SLD to the best machining conditions [16].

2.2. Relative location in the stability diagram

The qualitative location of the chatter process on the stability diagram is a key factor to select the optimal chatter suppression technique. The relative position of the unstable process is defined by the ratio k between the chatter frequency f_c and tooth passing frequency f_z which depends on the spindle speed N and the number of teeth Z on the tool (Eq. (2)). Physically, it defines the number of complete waves per period produced by the chatter. It is possible to identify four relative zones according to this ratio [282] (Fig. 3).

$$k = \frac{f_c}{f_z} = \frac{60 f_c}{Z N} \ (\text{with } N \text{ in rpm}). \quad (2)$$

- *Zone A: process damping zone ($k > 10$)*

  Process damping is important in this zone, and therefore a high increase in the stability is obtained due to the friction between the flank face with the wavy surface. In this zone, the lower the spindle speed is, the higher the stability boundary is.

- *Zone B: intermediate zone ($10 > k > 3$)*

  The stability limit is close to the absolute stability limit in the whole spindle speed range. This is especially true for high damping values.

- *Zone C: high speed zone ($3 > k > 0.5$)*

  In this zone, the stability can be drastically increased by means of the selection of the spindle speed coincident with one of the stability pockets.

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