Identification and Active Control of the Chatter Phenomenon in the Milling Process Using a Pneumatic Actuator

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1 Introduction

Given the advances in metal cutting in recent years, the issue of metal machining with milling and turning machines is still in the spotlight, and these machines are progressing every day. In today's advanced industries, especially the aerospace, military and medical industries, components of high dimension precision and roughness, are needed. Reduction of production time is also one of the most important issues of concern to the industry. However, one of the problems making these demands fail is the chatter vibration phenomenon. This vibration causes poor surface quality, reduced dimensional accuracy, increased production time and damage to the machines and tools. Many studies have been conducted on this subject, and they all try to suppress or reduce the negative effects of this vibration using different methods.

Generally speaking, any phenomenon that alters the cutting forces in machining process periodically, can be candidate of the chatter source. There are two main different types of chatter vibrations. The first type is caused by the cutting process phenomena including: friction between the tool and the workpiece, effects of the elevated temperature on the cutting tool and the workpiece which increase the tool length and consequently, alters the tool length contact length with the workpiece, and the mode coupling effect; which occurs when relative vibration between the tool and the workpiece is present in at least two directions on the cutting plane. The second type, on the other hand, is due to the successive waves created on the surface

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of the workpiece which alternatively changes the cutting forces. The latter is called regenerative chatter and is the main cause of the chatter phenomenon.

In the literature, several methods have been employed to address the chatter phenomenon. Some researchers have worked on determination of the machining parameters (i.e., mainly the spindle speed and depth of cut) so that the chatter would not occur. In these strategies (Tyler et al. 2015; Dai et al. 2018; Grossi et al. 2017), the main objective is the stability lobes diagram, by which the stable chatter-free zones in machining are distinguished from the unstable zones. These methods, however, do not alter the dynamic behavior and the stable zones of the machine tool; it enables the machine tool user to carry out the machining process with the highest achievable material removal rate while avoiding the destructive chatter phenomenon.

Some other researchers have approached differently toward the chatter problem. They have devised methods by which the dynamic behavior of the machine could be altered. These methods are divided into two main categories: namely active and passive methods. The distinction criteria between these two methods are that in the active chatter control methods (Shi et al. 2018; Fallah et al. 2019), the vibration parameters of the machine are detected and measured precisely, and an excitation in accordance with the vibration parameters is applied to the machine system. While in the passive methods (Wang et al. 2019; Fujimaki et al. 2020), there is no feedback from the machine, the dynamic behavior of the machine is altered via some methods that are known to be helpful in all machining chatter conditions. Some examples of these methods are the redesign of the dynamically weak components of the machine, and the variable helix and pitch angles end mills.

The advantage of the active method is that in this case, the dynamic state of the machine is controlled at any moment and when the system malfunctions, the controller acts and changes the system to a more stable state. Such systems typically use a controller that is specifically designed for the vibration characteristics of the system, an accelerometer or strain gage as the vibration sensor, and an actuator, usually for damping the vibrations (Quintana and Ciurana 2011).

The study of the machine dynamic behavior would eventually lead to a diagram which is called stability lobes diagram (SLD). The horizontal axis of the diagram is the spindle speed, while the vertical axis is the depth of cut. The lobes of the machine tool stability are depicted in this diagram, below which the machining is stable or chatter-free, and over which the machining is unstable and chatter phenomenon occurs. The calculations of the SLD are, in fact, based on the dynamics of the machine and the tool giving the operator a graph for each particular material. This chart shows how much depth of cut at each selected spindle speed is accessible before occurring the chatter and reaching unstable state.

According to Fig. 1, it can be said that if, by any means, the diagram could be shifted upward, higher cutting depths can be selected for the cutting operation, which results in higher material removal rates and lower production time, which is economically more advantageous. Furthermore, due to the periodic nature of the diagram, shifting the diagram into right or left directions might, in some cases, stabilize an unstable point. The shifting of the SLD upward primarily, and to the

Fig. 1 Milling machine used with accelerometer

right and left directions secondarily, is the main objective of the research works in chatter suppression/control literature.

Recent research efforts rely on the use of active and passive methods of chatter phenomenon control. Active methods are based on the measurement of the vibration parameters which enable the controller to detect the chatter occurrence and its parameters, and then excitation of the machine in accordance to the chatter parameters using an actuator. The most commonly used actuators include piezoelectric stacks and magnetostrictive actuators. Passive methods are designed based on changes in system structure and by changing the system natural frequencies by adding and deducting masses, changing machining parameters or redesigning machine tool accessories (Munoa et al. 2016).

Ahrens et al. (2016) used an electromagnetic actuator, tried to suppress the chatter in the grinding process using the active method. The idea of an active chatter damper is to estimate the shape of the waves on the tool and create a force against the forces on the workpiece that is the cause of the surface waves. Bort et al. (2016) attempted to control the chatter using a model-predictive-control (MPC). By using an MPC, the process time and roughness improved by 46% and 22%, respectively. Burtscher and Fleischer (2017) presented an adaptive tuned mass damper (ATMD) that its design and results are based on the genetic algorithm. When the machine's frequency values change through the working position, the ATMD reduces the chance of the chatter occurring by adjusting and dominating these frequency values. When the damper was activated, the vibrations were reduced by 36%.

As a conclusion of the review of previous studies, it is clear that none of the abovementioned studies, has used pneumatic actuators to control the chatter. These actuators, in addition to their many capabilities, are inexpensive and affordable and, as far as their operating frequency allows, can be used as a chatter control actuator. The compressed air for the actuator is available in almost all machining workshops, which enables the machine shop owners to use this system with minimum cost.

2 Materials and Methods

We need to obtain SLD for the milling machine to know chatter frequency occurs at what speed range. To obtain SLD, the basis for predicting chatter in theory, the machine's natural frequencies are required. For this purpose, an experimental modal analysis is carried out in order to obtain the dynamic behavior parameters of the machine.

2.1 Experimental Modal Analysis

Modal analysis is the process of determining the dynamic properties of a system in terms of natural frequencies, damping coefficients and mode shapes (He and Fu 2001). We apply them to create a mathematical model for the system dynamic behavior. The basis of this technique is based on the relationship between vibrational response at one point of the structure with the excitation at the same point or another. The equipment used in the experiments is an impact hammer (Bruel & Kjaer brand), which analyzes the input data using PULSE LabShop software Version 6.1. The accelerometer is made in DJB Instruments with part number of A/120/V, and the hammer used was type of RION PH-51. The milling machine is a DECKEL FP4M type, made in Tabriz Machinery Manufacturing Company. Since the structural chatter phenomenon occurs in collet and collet holder when the tool is involved with the workpiece, the accelerometer is directly installed beneath the collet holder. The hammer impact point is on the collet holder nut. The vibration bandwidth in structural chatter is between 0 and 200 Hz (Quintana and Ciurana 2011). Figure 1 shows the milling machine with the accelerometer attached to it.

At the beginning of the modal experiments, the force range applied by the operator to the object with the hammer is measured. The coherence diagram illustrates the relationship between the final response and the input impulse to stimulate the system. If the vertical value of the diagram is less than 0.8, the response obtained is considered as a noise signal. This indicates that the stimulus generated in the system has been caused by an external factor. The way to obtain natural frequencies from the obtained graphs is by simultaneously examining the coherence graph and the frequency response graph. When the number shown on the Y-axis of coherence graph is between 0.8 and 1. The corresponding peak in the frequency response diagram is the natural frequency. Finally, for the first and second modes, the values of 16 and 48 Hz were obtained.

In order to obtain the SLD, the cutting force coefficient is also needed. The force coefficients are mostly influenced by the workpiece material and the cutting tool parameters (i.e., geometry, size and material). The materials used in this study are Inconel 617 superalloy and austenitic stainless steel 316. The cutting forces are measured using a Kistler 9443B dynamometer. The end mill is a WC tool with the diameter of 12 mm manufactured in YG-1 company under the code number G9453912.

After measurement of the machining forces, the cutting coefficients are derived from the following Eqs. 1 and 2:

$$K_{tc} = \frac{4\overline{F}_{yc}}{ac} \tag{1}$$

$$K_{rc} = \frac{-4\overline{F}_{xc}}{ac} \tag{2}$$

where $\overline{F}$ is the average of the force measured, a is the depth of cut and c is the feedrate per tooth.

Finally, the stability lobes are calculated as follows:

Selection of a chatter frequency from transfer functions around a dominant mode. Solution of the eigenvalue, by use of transfer function gotten in modal test, from

$$a_0\Lambda^2 + a_1\Lambda + 1 = 0 \tag{3}$$

Calculation of the critical depth of cut from

$$a_{\lim} = -\frac{2\pi\Lambda_R}{NK_t}\left(1+\kappa^2\right) \tag{4}$$

where Λ_R is the real part of the eigenvalue real part, κ is obtained by dividing the real and imaginary part of eigenvalue and N is the tool tooth flute. Calculation of the spindle speed from for each stability lobe $k = 0, 1, 2, \ldots$, from

$$n = \frac{60}{NT} \tag{5}$$

where T is tooth-passing period. Repeat the procedure by scanning the chatter frequencies around all dominant modes of the structure evident on the transfer functions.

Pneumatic Actuator

To damp the vibration of the machine actively, an actuator is required for excitation of the system in accordance to the chatter parameters.

In this study, after investigations, it was decided to use a pneumatic actuator. One advantage of this actuator is its cost-effectiveness compared to other actuators for its use in the first modes of the system. The compact cylinder, has force of 1000 N, made by SNS Company in model of SDA 63X40-S.

An air solenoid valve is required to command the cylinder to generate the signal sent to the valve. The VUVG-L14-M52-MT-G18-1P3 model solenoid valve made by FESTO Company is used for this purpose. The valve is able to withstand pressure up to 800 kPa and has an operating frequency of 16.5 Hz. To produce desired signal an AFG-2125, GW INSTEK arbitrary function generator is employed.

2.2 Equipment

Since the purpose of this study is to control the vibrations and motion of the machine tool, a sensor is required to measure the vibration amplitude during machining. In this research, a MicroSense 5810 non-contact capacitance displacement sensor precision made by MicroSense Inc. is used. This sensor, which is shown in Fig. 2, measures the spindle vibration amplitude by voltage variation and has the ability to measure vibrations in frequencies up to 100 kHz.

Due to the fact that this sensor shows the values in an analog way, it is necessary to connect it to a data acquisition card (DAC). The 12-bit POS-760 data card made by Advantech Company is used for this purpose.

The active controller constantly receives and processes the input signals online. Therefore, a host computer is needed to establish a connection between the input and output data. LabView 2018 software is employed to design the controller. Finally, the control cycle is depicted in Fig. 3. The spindle vibration is measured during machining using the displacement sensor. Whenever the chatter phenomenon occurs, the controller detects the chatter as the vibration amplitude increases, and it excites the pneumatic actuator in the chatter frequency.

3 Results and Discussion

The capacitance displacement sensor and the DAC are used to detect the chatter by checking the displacement versus time diagram of the device in the LabView software. The experiments are carried out in different spindle speeds with and without the controller to study the advantage of the active control. When the chatter occurs, the displacement vs. time diagram shows a peak, as it can be seen in Fig. 4.

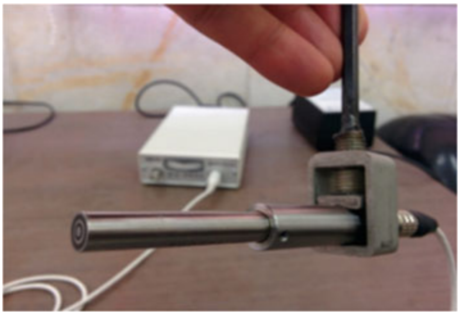

Fig. 2 Capacitance displacement sensor

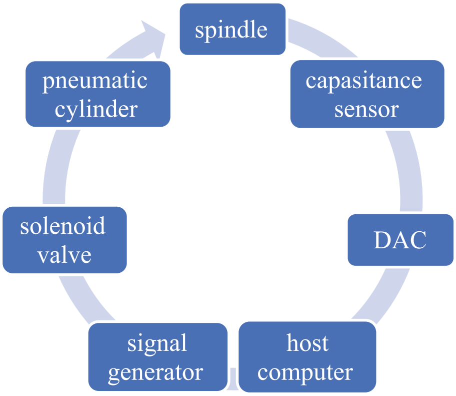

Fig. 3 Active control cycle

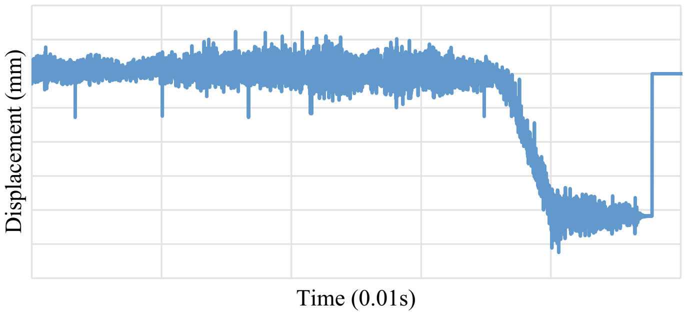

Fig. 4 Displacement versus time diagram

This is the method of detecting the chatter by a displacement–time diagram. The horizontal axis of the graph represents the time with a resolution of 0.01 s, and the vertical axis represents the spindle housing displacement by monitoring this diagram online during the machining, operator can stop the operation when the chatter phenomenon is started.

According to the experiments performed when the controller was switched off, the average voltage range was 0.3 V. As a result, this value was defined as a condition for the controller to send a signal via the signal generator to the solenoid valve if the amount of change has been exceeded during operation. The signal sent through the generator to the solenoid valve was 16 Hz square wave, with 75% duty cycle and a voltage of 5. The force applied to the spindle by the actuator was 154 N. Figure 5 illustrates the displacement sensor and cylinder installed on machine tool.

Workpieces require machining on each to determine the depth of cut at different speeds. For this purpose, the workpieces are designed with an inclined surface. Thus, depth of cut will be increasing during the machining. Since the feedrate did not affect the chatter, it was considered constant in all experiments with value of 12 mm/min.

Fig. 5 Installed capacitance sensor and cylinder

The results of the experiments on the austenitic stainless steel 316.

The machining experiments are carried out without the controller at the spindle speeds of 315, 400, 500, 1250, 1600 and 2000 rpm with a feedrate of 12 mm/min to reach critical depth of cut before occurring chatter. The above-mentioned experiments are performed once again with the presence of the controller.

Figure 6 is the final workpieces obtained from tests. It can be seen that when the actuator is exciting the system at the spindle speeds in the first mode in the SLD, the critical depth of cut increases. At the covering speeds of second mode, excitation of the machine in the first mode frequency has a negative effect and decreases the critical depth of cut.

Table 1 contains the final values obtained for the critical depth of cut at different speeds. The last column shows the percentage increase or decrease of the cutting depth in the presence of the operator, with a positive and a negative sign, respectively. At spindle speeds 315, 400 and 500 rpm, which lie in the first mode of the machine in the SLD, the amount of the critical of depth, in the presence of the actuator is increased up to 47%. The higher spindle speeds, which lie in the second mode of the machine, show a sharp decrease in critical depth of cut. The reason for such a decrease is that the excitation with the frequencies far from the mode frequency

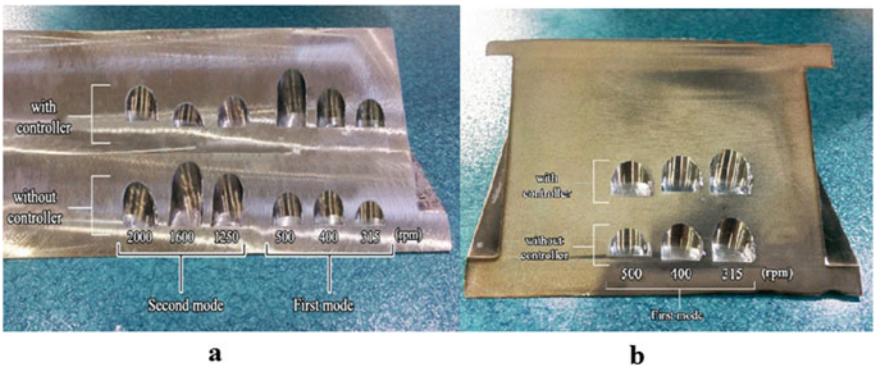

Fig. 6 **a** Final austenitic stainless steel 316 and **b** Inconel 617 workpieces

Table 1 Obtained values for austenitic stainless steel 316

Spindle speed (rpm)	Depth of cut (mm) without controller	Depth of cut (mm) with controller	Increase or decrease depth-of-cut percentage
315	4.85	6.15	+ 21
400	6.9	8.45	+ 18
500	6.65	12.7	+ 47
1250	10.25	6.6	− 55
1600	12.75	4.45	− 186
2000	8.95	6.8	− 31

would only add extra energy to the system, which eventually makes the system more prone to the chatter.

3.1 *The Results of the Experiments on the Inconel 617 Super Alloy*

Inconel 617 tests conducted at speeds of 315, 400 and 500 rpm with and without the presence of the controller. When the actuator is on, at the covering speeds of the first mode in the SLD, the critical depth of cut is increased.

In Table 2, the final values obtained for the Inconel 617 super alloy are shown when the controller is on and off. The three tests for Inconel were all in the first mode. In the first mode, critical depth of cut increases.

Note that the chatter phenomenon is mainly occurring in the roughing operations, where the depth-of-cut values are high enough. The roughing operations, specifically, in hard-to-cut materials such as austenitic stainless steels and super alloys, are usually carried out in low cutting speeds. Therefore, although the pneumatic actuator is unable to suppress the chatter phenomenon in higher spindle speeds due to the limitation of the actuator bandwidth, the excitation of the machine in the first mode is adequate, and the excitation of the machine in the second mode sounds redundant.

Table 2 Obtained values for Inconel 617 super alloy

Spindle speed (rpm)	Depth of cut (mm) without controller	Depth of cut (mm) with controller	Increase or decrease depth-of-cut percentage
315	6.95	7.5	+ 7
400	5.65	6.3	+ 10
500	4.75	5.3	+ 10

4 Conclusions

The main purpose of this study was to identify the chatter phenomenon and control it using the active method. As explained in previous chapters, an active control system requires data online to identify the chatter. An actuator is also used to actively control the vibrations. So, it can receive the signal and apply it to the desired area using the host computer and the controller defined for it.

After reviewing the final results, it is found that the pneumatic actuator is capable of increasing the critical depth of cut and mitigating the chatter in the first mode. But at speeds related to the second mode, the presence of the actuator reduces the cutting depth compared to the absence of it. The reason for this is due to the operating frequency of the solenoid valve. The frequency of the solenoid valve is 16 Hz, which corresponds to the frequency of the device first mode (16 Hz). The frequency value of the device second mode is 48 Hz. As a result, at the speeds of the second mode, the presence of the actuator stimulates the vibration more and helps the chatter to occur faster. Using this actuator in the first mode of the device increases the average cutting depth for austenitic stainless steel 316 and Inconel 617 super alloy by 28 and 10 percent, respectively. Therefore, due to the low price of this type of actuator, it can be said that the pneumatic actuator can be more economical than other actuators in order to damp the first modes of the device.

The employed pneumatic actuator bandwidth is limited to the first mode frequency due to the limitation in operating frequency of the valve. Although this is one of the disadvantages of the pneumatic system, since the chatter occurs mostly in roughing operations, and the roughing operations of the hard-to-cut materials are mainly carried out in the low cutting speeds, the first mode speeds are high enough in economic machining of these materials.

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