FACTA UNIVERSITATIS
Series:**Mechanical Engineering**
https://doi.org/10.22190/FUME210728067G

Original scientific paper

IDENTIFICATION OF CHATTER VIBRATIONS AND ACTIVE VIBRATION CONTROL BY USING THE SLIDING MODE CONTROLLER ON DRY TURNING OF TITANIUM ALLOY (TI6AL4V)

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Abstract. *In recent years, with the development of sensor technologies, communication platforms, cyber-physical systems, storage technologies, internet applications and controller infrastructures, the way has been opened to produce competitive products with high quality and low cost. In turning, which is one of the important processes of machining, chatter vibrations are among the biggest problems affecting product quality, productivity and cost. There are many techniques proposed to reduce chatter vibrations for which the exact cause cannot be determined. In this study, an active vibration control based on the Sliding Mode Control (SMC) has been implemented in order to reduce and eliminate chatter vibration, which is undesirable for the turning process. In this context, three-axis acceleration data were collected from the cutting tool during the turning of Ti6Al4V. Finite Impulse Response (FIR) filtering, Fast Fourier Transform (FFT) analysis and integral process were carried out in order to use the raw acceleration data collected over the system in control. The system is modeled mathematically and an active control block diagram is created. It is observed that chattering decreased significantly after the application of active vibration control. The surface quality formed by the amplitude of the graph obtained after active control has been compared and verified with the data obtained from the actual manufacturing result.*

Key Words: *Chatter, Sliding Mode Controller, Active Vibration Control, Turning, Ti6Al4V*

1. INTRODUCTION

In recent years, smart manufacturing applications have found a wide range of uses in machining [1–3]. Increasing the quality in the machining process is possible by reducing

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Received July 28, 2021 / Accepted November 10, 2021
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and controlling the vibrations (chatter) that occur during production. Chatter vibrations in turning and milling, which are among the most widely used methods in machining, cause important problems and directly affect the cost and product quality [4–7].

Chatter vibrations occurring during machining may cause early completion of the life of the cutting tool, increase in surface roughness of the workpiece and damage to machine parts. Chattering is a classic problem that occurs frequently and reduces production efficiency. The operator often encounters it while its cause is not entirely clear. In a good quality turning process, it is desirable that the chip thickness should be standard at the beginning and end of production. However, chatter vibrations cause the thickness of the chip in turning to be variable. This negatively affects the roughness of the machined surface and causes noise during turning [8-10]. These chatter vibrations, which are constantly encountered in machining applications, should be avoided without sacrificing quality and efficiency [11]. For this reason, the identification of chatter vibration and chatter suppression has been a subject of interest to researchers working in the field of machining. To overcome these problems, various techniques have been developed by researchers to detect, reduce and control of chatter vibration. Techniques suggested in the literature include determining of the effects of machining parameters on product quality, prediction of machining parameters for the best product quality, optimization of machining parameters, tracking/monitoring of the machining process, identification/detection of chatter vibrations, real-time control of chatter during machining, and also providing suitable numerical tools for modeling those effects [12-15].

Passive control of the chatter vibrations during turning is an easy, applicable and efficient approach with correct element selection. The basis of the reduction of chatter vibration by passive control is the spring and damping element design suitable for the system frequency and amplitude [4]. However, the trend towards active control applications with different methods for a higher product quality has increased. In active vibration control applications in turning, there are stages of measuring the vibrations occurring during processing accurately, filtering/analyzing the measured data and creating an external impact force that can damp down the chatter vibration [16-18].

There are many studies in the literature on the determination, identification, prediction and control of chatter. Alternative techniques to reduce chatter have been studied by J. Munoa et al. They proposed progressive solutions to design and control approaches and examined the success of the existing methods used to improve the cutting process [4,16,19]. In the study in which passive control and active control applications and future expectations were discussed, it is argued that active vibration control promises hope for the future in reducing chattering [20].

The chatter vibration generated during turning has high frequency and low amplitude. Therefore, sensors, data acquisition devices and actuators used in active vibration control must have high speed and precision. In a study conducted to measure the vibration values that occur on the cutting tool and are constantly increasing, Jang and Tarng used piezo-electric sensors and measured and compared the controlled and uncontrolled vibration frequencies occurring in the cutting tool. They observed that the controlled vibration frequency values are 90% less than the uncontrolled vibration frequency values [21].

Magnetorheological (MR) and Electro-rheological (ER) fluids are among the systems commonly used in active vibration control applications. Mei et al. performed MR-based active vibration control for the boring process and achieved great success [22]. In addition to these, piezoelectric patches and actuators have expanded the application area thanks to their high operating frequencies and precision [23]. Harms et al. Designed and implemented a piezoelectric-based cutting tool for active control on the lathe [24]. Haifeng et al. implemented a piezo-based active vibration control to suppress chatter vibrations that occur during the turning process [25].

As seen from the studies given above and in literature, there are many studies on the identification, examination and control of chatter vibrations occurring during turning. However, it has been seen that there is not sufficient study on the determination of chatter vibrations during the turning of the Ti6Al4V alloy and the active control of these vibrations. It has been observed that the active chatter suppression studies in turning are generally carried out with classical control applications. By this paper, it is aimed at identification of chatter vibrations and active control of chatter by using SMC which is known robust, stable and optimal for Ti6Al4V.

In this study, an active vibration control application working with a Sliding Mode based has been implemented in order to reduce the chatter, which adversely affects product quality, tool life and productivity in turning, during production. In this context, three-axis acceleration data were collected on the tool during machining, the collected data is filtered, and the double integral is taken for the displacement data, and then chatter analysis was performed using the Fast Fourier Transform (FFT) method. Active force control is carried out with the help of the mathematical model created.

2. EXPERIMENTAL STUDY

In the experimental studies, a Quantum turning lathe and Ti6Al4V titanium alloy workpiece with dimensions of Ø28 mm x 250 mm are used. Experiments were carried out with the processing parameters determined for this alloy. The image of the experiment set is given in Fig. 1. The constant parameters used in the experiments are given in Table 1.

Table 1 The constant parameters used in experimental studies

Workpiece Material	Ti6Al4V
Cutting Tool	Tungsten Carbide
Depth of Cut, a (mm)	1
Cutting Speed, V (m/min)	50
Feed Rate, V_c(mm/rev)	0.3
Spindle Speed (rpm)	1200

Ti6Al4V (Titanium Grade 5) Ti alloy used as a workpiece has a wide range of uses such as military equipment, navy, protection, aerospace, medical technology, ultrasonic thanks to its low specific gravity and high mechanical properties [26–28]. Ti alloys are generally selected according to phase transformations and Ti6Al4V alloy is in the α/β group. This alloy is often seen in aircraft landing gear, gas turbines, and implant applications. It is possible to see that Ti6Al4V alloy is frequently produced by casting, forging and machining methods, as well as powder metallurgy [29,30]. The chemical composition and mechanical properties of Ti6Al4V alloy are given in Table 2 and Table 3, respectively.

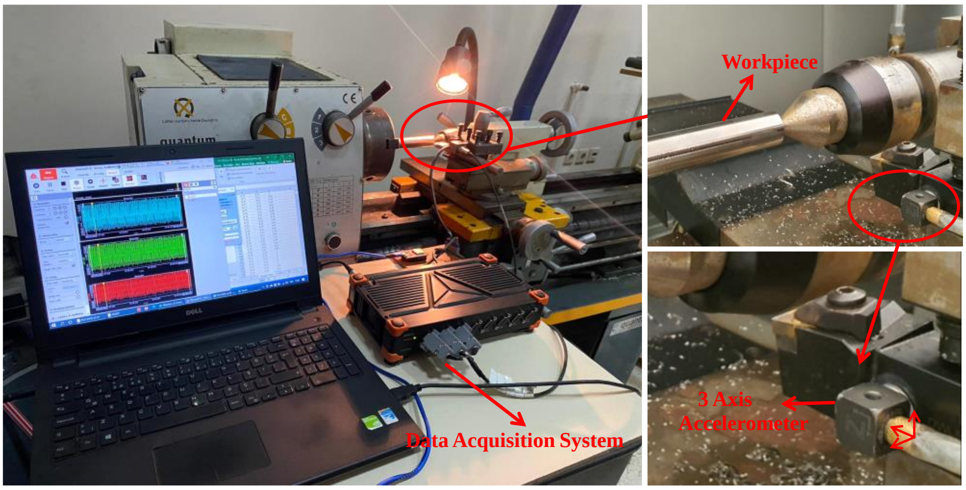

Fig. 1 Experimental setup for vibration measurement

Table 2 The chemical composition of Ti6Al4V (%)

Al	**V**	**C**	**Fe**	**O**	**N**	**H**	**Ti**
5,5-6,5	3,5-4,5	0,08	0,25	0,13	0,03	0,012	Rest

Table 3 Mechanical properties of Ti6Al4V

Mechanical properties	
Density (g/cm^3)	4,45
Specific heat (J/(g x K))	0,56
Thermal conductivity (W/(m x K))	7,1
Elasticity modulus (KN/mm^2)	114
Thermal elongation (10-6/K)	8,9
Tensile strength (MPa)	892
Yield limit (MPa)	828
Elongation (%)	10

2.1 Theoretical background

There are two types of vibration in machining: spontaneous and forced vibration. These vibrations cause deterioration of the surface quality. It also wears the cutting tool, shortening its life and damaging the components of the bench. Forced vibration is a vibration that occurs as a result of the mechanical movements of the machine. The spontaneous vibration, on the other hand, occurs separately from the machine and external factors due to chip removal. This vibration is also called chatter vibration [12,31].

Chatter vibrations, which are seen as spontaneous vibrations during turning, are caused by machining forces, chip cross-section and changes in tool geometry. Due to the complex nature of the chatter vibrations, the cutting forces that occur during turning activate one of the structural modes of the cutting tool and the workpiece system, causing a wavy surface on the workpiece. It is of great importance to recognize the system elements in order to identify and control the chatter vibrations.

Within the scope of this study, system modeling is carried out for the active vibration control application. The vibrations in the direction of the plunge axis with the highest vibration are taken into account and the mathematical model is created accordingly. The mechanism of chatter vibration is shown in Fig. 2. In this mechanism, *m*, *k*, *c* are the tool parameters and refer to mass, spring constant and damping coefficient, respectively.

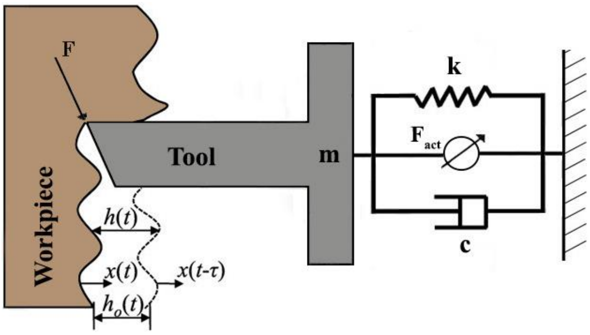

Fig. 2 System modeling in turning

Time dependent mathematical expression of sawdust is shown in Eq. (1). In the equation, the displacement of the cutting point over time with concern to the position in the previous cycle is expressed as $x(t)\text{-}x(t\text{-}\tau)$, where h_s(shown as $h_0(t)$ in Fig. 2) is the thickness of the uncut chip. In the equation, it is defined as $\tau = 60/N$, where N represents the rotation speed of the spindle in rev/m.

$$h(t) = h_s - x(t) + x(t-\tau) \tag{1}$$

The equation expressing the system behavior during turning is presented in Eq. (2). Here, F_c is the cutting force, *b* is the depth of cut, K_f is the specific cutting coefficient. Specific cutting coefficient varies depending on the physical and mechanical properties of the material.

$$m\ddot{x}(t) + c\dot{x}(t) + kx(t) = F_c(t) \equiv K_f b(h_s - x(t) + x(t-\tau)) \tag{2}$$

In active control applications, an external actuating force is required to keep the tool vibration at the desired level. As expressed in Fig. 2, the acting force has been designed to affect the tool. In the case that the actuator force is added to the system, the mathematical model will be as in Eq. (3). F_{act} represents the impact force generated by the actuator.

$$m\ddot{x}(t) + c\dot{x}(t) + kx(t) = K_f b(h_s - x(t) + x(t-\tau)) + F_{act}(t) \tag{3}$$

The process parameters used to ensure real situations are [25,32,33]: mass (*m*) = 2.5 kg, stiffness (*k*) = 2x10 N/m, damping (*c*) = 1340 N.s/m and cutting coefficient (K_f) = 2000 N/m^2. Eq.(4) is obtained if the transfer function between force and displacement for the cutting tool is defined as $\phi(s)$. With the addition of F_{act} to the system for Fig. 2, which is adapted for the closed-loop feedback control strategy, the general transfer function of our system is obtained as in Eq.(5) and the system transfer function in Eq.(6).

$$x(s) = \phi(s)(F_c(s) + F_{act}(s)) \tag{4}$$

$$x(s) = \phi(s)(K_f b(h_s + x(s)(e^{-s\tau} - 1)) + F_{act}(s)) \tag{5}$$

$$G(s) = \frac{X(s)}{F(s)} = \frac{1}{ms^2 + cs + k} = \frac{C}{s^2 + As + B} \tag{6}$$

2.2 Data acquisition

Within the scope of this study, the acquisition of vibration data generated during surface turning of Ti6V4Al alloy workpiece is performed with Dewesoft/Sirius, which provides a flexible, modular, expandable and safe working environment (Fig. 3a). The most important features of SIRIUS are that it prevents errors frequently encountered during the measurement process, is simple to use and has user-friendly data processing software.

Fig. 3 a) Dewesoft Data acquisition device b) MEMS triaxle accelerometer

MEMS type PCB/3713B1130G brand accelerometer has been used to collect 3-axis acceleration data on the machine tool (Fig. 3b). The accelerometer has a measurement range of ±30 g and is produced with a titanium coating to prevent damage to interference data and external effects. The accelerometer has a measurement frequency of up to 1 kHz.

During turning, cutting force and tool vibration occur in three axes: rotation axis (radial), feed axis and plunge (depth) axis. Reducing vibration in any direction increases turning reliability and product quality. However, in this study, the vibrations in the direction of the plunge axis with the highest vibration were taken into account and a mathematical model was created accordingly. When choosing the location of the sensor, a point where the vibration will occur the most and where active control can be applied is selected. For this reason, the acceleration sensor is placed on the cutting tool and in the area close to the cutting point.

2.3 Data processing

The collected raw data may be insufficient to reach the desired result or use in control applications. Data processing is an important step in recalculating and filtering of signals, revealing signal statistics and ultimately achieving the desired result.

2.3.1 Filtering of acceleration data

It is of great importance to clean and analyze the signals in order to use the raw data collected from the system. Filtering, one of the most basic applications of signal processing studies can be used for different purposes such as decreasing or increasing certain frequencies, decreasing or increasing the signal amplitude, cleaning and analyzing unwanted signals.

Filters can also be used to condition a time history signal by reducing unwanted frequency content. In active control applications, filtering processes are often used to eliminate a disturbance or model the response of a physical system. It is possible to see both IIR (Infinite Impulse Response) and FIR (Finite Impulse Response) applications in active control applications. The formulas for FIR and IIR are detailed in Eqs. (7) and (8).

$$y(n)=\sum_{k=0}^{N}a(k)x(n-k) \tag{7}$$

$$y(n)=\sum_{k=0}^{N}a(k)x(n-k)+\sum_{j=0}^{P}b(j)y(n-j) \tag{8}$$

In these equations, *x(n)* is the input series in time, *y(n)* is the time series at the output, n is the total number of data points of the input signal in the time domain, with the series called *a(k)* filter *a*, *N* and *P* are the numbers of terms in the filters, also referred to as rank and number of links, respectively. For example, FIR filter is implemented between $k=0$ and $k=N$.

2.3.2 Integral of acceleration data

It is often impossible to use the raw data collected from the system directly. Especially, in order to use the acceleration data from the system in sensitive active control applications, the acceleration data must be converted into displacement data. Thus, more accurate results can be obtained. The most important method used to convert acceleration data into position data is integrating [33,34].

The triaxial acceleration data collected during machining are arranged in the DewesoftX software interface and converted into displacement data to be input in active control applications. Then, the displacement data were input to the control model from the same point as the point where data was collected under real conditions.

2.3.3 Fast Fourier transform (FFT)

The Fourier transform, developed by the French mathematician Jean-Baptiste Joseph Fourier, argues that any function can be written as the sum of sine and cosine functions, and the amplitude of the sine and cosine waves can be determined using the integral. The basic equation used for the Fourier transform is given in Eq. (9). In this equation; $S_x(f)$ is the output of the Fourier transform in the frequency domain, *x(t),* the function due to time and the frequency in radians $2\pi f$ [35].

$$S_x(f)=\int_{-\infty}^{+\infty}x(t)e^{-j2\pi ft}dt \tag{9}$$

FFT can be used to determine the high-frequency values in any signal. These frequencies can cause unwanted noise or vibration. FFT analysis is also widely used in the monitoring and fault detection of the vibration state of machine elements in constant motion such as bearings and gears. FFT analyses, which have an important place in the space, aviation and automotive industry, are performed by using multiples of two (512, 1024, 2048) samples in the time block [36].

The general equation for FFT is given in detail in Eqs. (10) and (11), and k row represents the frequency element, *N* number of samples, *i* square root (-1) value, *x(i)* sampled signal data, *n* represents the index of the sample waiting to be processed.

$$\sum_{n=0}^{N-1} x(n)e^{-jn}\omega_k \left(k = 0,1,2,\ldots\ldots,N-1\right) \tag{10}$$

$$Xk = \sum_{n=0}^{N-1} x[n]*e^{-i*(2\pi*k*n/N)} \tag{11}$$

Within the scope of this study, in order to obtain information about the vibration that occurs during the turning process, FFT analysis has been carried out and examined for the acceleration data collected. Thus, information was obtained about what the operating frequency of the system was during processing, what the natural frequency range was and what the sampling number should be in data collection.

3. ACTIVE VIBRATION CONTROL

3.1 Sliding mode control theory

In recent years, Sliding Mode Control (SMC), which has been used in many areas with increasing acceleration and is among nonlinear control methods, is preferred especially for meeting high-speed control needs. Among the biggest advantages of SMC is the ability to change the dynamic behavior of the system, to reduce the degree of the system and to minimize disruptive effects. SMC is preferred as an effective control approach against systems that cannot be modeled dynamically, variable parameters and distorting effects [37].

In the sliding mode control consisting of sliding and reaching stages, equivalent and switching rules must be realized, respectively [38]. So many functions such as *tanh, sgn* etc. are used to overcome the chatter problem, which is one of the biggest disadvantages of the sliding mode control [39, 40]. The transfer function given in Eq.(6) is written as a differential equation, as in Eq. (12).

$$\ddot{x}(t)=\mathrm{A}\dot{x}+\mathrm{Bx} - \mathrm{Cu} \tag{12}$$

Tracking error *e(t)* to find control input *u(t)* in the sliding mode control can be defined as follows,

$$e(t) = r(t) - x(t) \tag{13}$$

In the Eq. (13), *e(t)* is the tracking error, *r(t)* is the command signal, and *x(t)* is the measured signal. Sliding surface function can be expressed as Eq. (14).

$$s(t) = \left(\lambda + \frac{d}{dt}\right)^{n-1} e(t) \tag{14}$$

Assuming $n = 2$, Eq. (15) is obtained.

$$s(t) = \lambda e(t) + \dot{e}(t) \tag{15}$$

In this equation, λ is a positive constant and if this equation is derivative, Eq. (16) is obtained.

$$\dot{s}(t) = \lambda \dot{e}(t) + \ddot{e}(t) \tag{16}$$

Substituting *r-x* for e in this equation, Eq. (17) is obtained.

$$\dot{s} = \lambda\dot{e} + \ddot{r} - A\dot{x} - Bx + Cu \tag{17}$$

The control input *u(t)*, which is the sum of equivalent control (u_{eq}) and switching control (u_{sw}), is given in Eq. (17).

$$u(t) = u_{eq}(t) + u_{sw}(t) \tag{18}$$

Due to the nature of the sliding mode controller, $\dot{s} = 0$ is expected. If Eq. (18) is arranged for $\dot{s} = 0$, u_{eq} can be expressed as Eq. (19).

$$u_{eq} = \frac{1}{C}\left(-\lambda\dot{e}(t) - \ddot{r}(t) + A\dot{x}(t) + Bx(t)\right) \tag{19}$$

With k_{sw}=0.5 and Ω= 0.1, λ=2. Switching function, u_{sw} can be expressed as in Eq. (20).

$$u_{sw}(t) = k_{sw} \tanh(s(t)\Omega) \tag{20}$$

Acceleration data received from the cutting tool was used as feedback information in the turning process. With the help of the acceleration data, the necessary reaction force for the actuator is calculated. The closed-loop used for control is shown in Fig. 4.

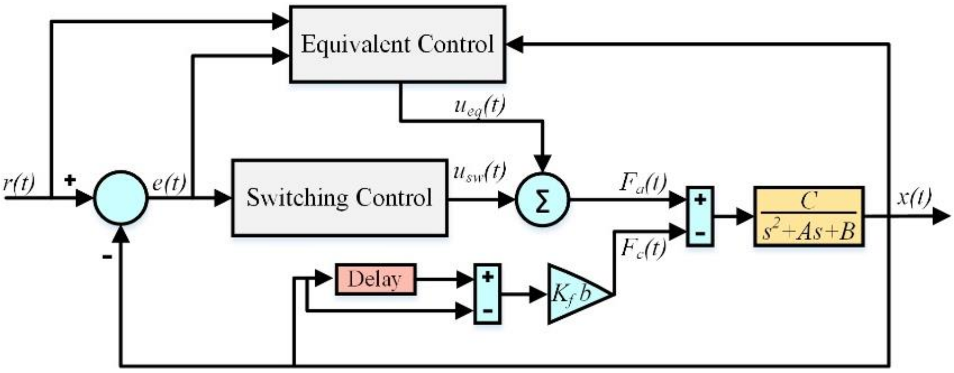

Fig. 4 SMC system block scheme

4. RESULTS AND DISCUSSION

Within the scope of the experiments, chatter vibrations generated on the tool holder were collected and evaluated for three different cutting axes with the help of a triaxial PCB brand industrial accelerometer and Dewesoft/Sirius data collection device. The accelerometer is rigidly fixed on the tool holder without using any damping element.

For the active control application, a data set of 20 s was chosen from the data collected during turning. Selected data is filtered, integrated and FFT analysis is applied. The amplitude values of the collected data ranged between 110 m/s^2 in the positive direction and -132 m/s^2 in the negative direction, and the data collection rate was realized as 2000 (2000 samples/s) per second. In order to determine the operating frequencies of the system, the vibration data collected was first subjected to FFT and critical frequency values were determined. After FFT analysis, it is observed that 110 Hz is the critical frequency value. This value is in the range of chatter vibration seen in the literature and confirms the study by Munoa in 2016, where he also mentioned the range of chatter vibrations (20-200 Hz) [1]. The FFT analysis results are given in detail in Fig. 5.

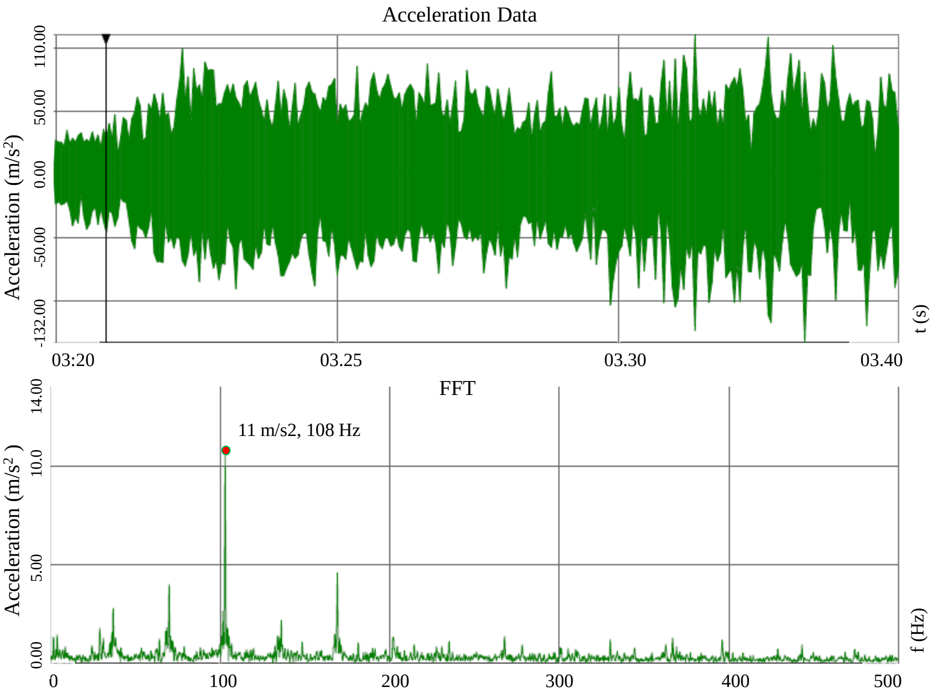

Fig. 5 FFT analysis results

In order to use the raw data collected from the system, it is of great importance to analyze the signals and to clean the unwanted signals. IIR or FIR filters are generally used in active control applications [2]. FIR filtering method was used to clean the parasitic data contained in the acceleration data and to obtain a clean data set that can be used in active control.

The triaxial acceleration data collected during turning are arranged in the DewesoftX software interface and converted into displacement data by taking its integral so that it can be input in active control applications. The 20-second data randomly selected from the raw data for the SMC application is given in Fig. 6.

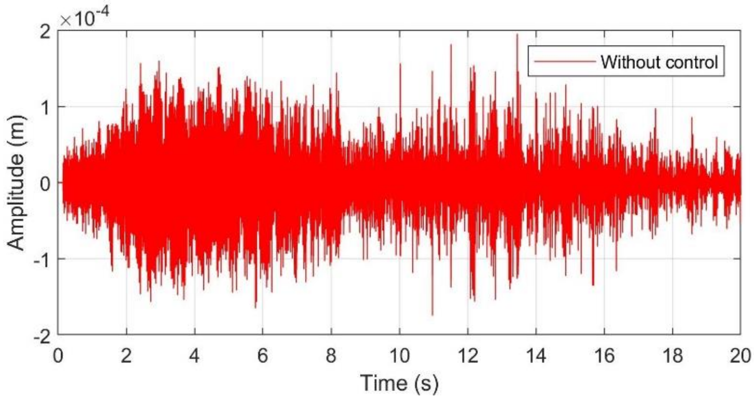

Fig. 6 Uncontrolled 20 seconds displacement data

Then, the displacement data were input to our SMC model from the same point as the point where the data was collected under real conditions, and the control of the model during processing was provided for 20 seconds. The displacement graph obtained after active control is given in Fig. 7.

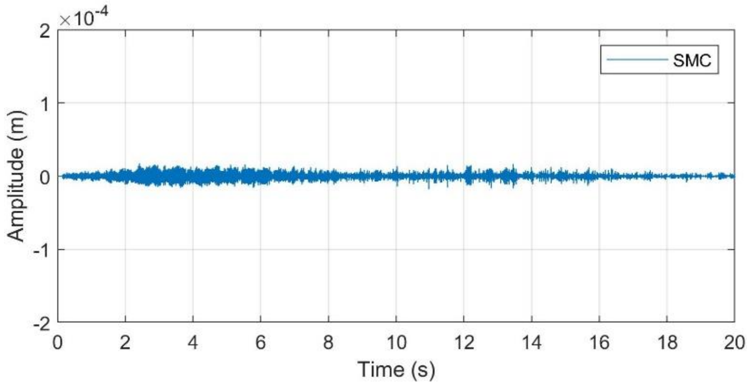

Fig. 7 Displacement data after active SMC

While the displacement data were between 300-500 µm before control, it was observed to be between 50-100 µm after the control. This significant difference will allow us to obtain a high-quality product during turning. According to the information obtained from previous studies, chatter vibrations occur with average displacement amplitude of 200-300 µm. In Fig. 8, there is a visual of the surface roughness after normal turning and chatter vibration [1,3–5].

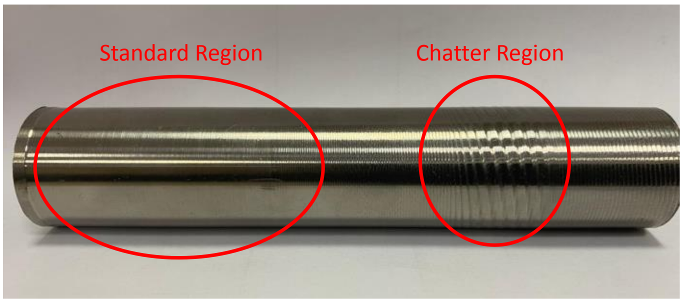

Fig. 8 Surface roughness after turning for Ti6Al4V workpiece

In Fig. 9, there is a visual where the data obtained as a result of the active control is compared with the chatter data received from the system. As can be deduced from the visual, there has been a serious improvement in the quality of the surface roughness due to the decrease in the vibration amplitudes that occur during turning as a result of the active SMC of the cutting tool.

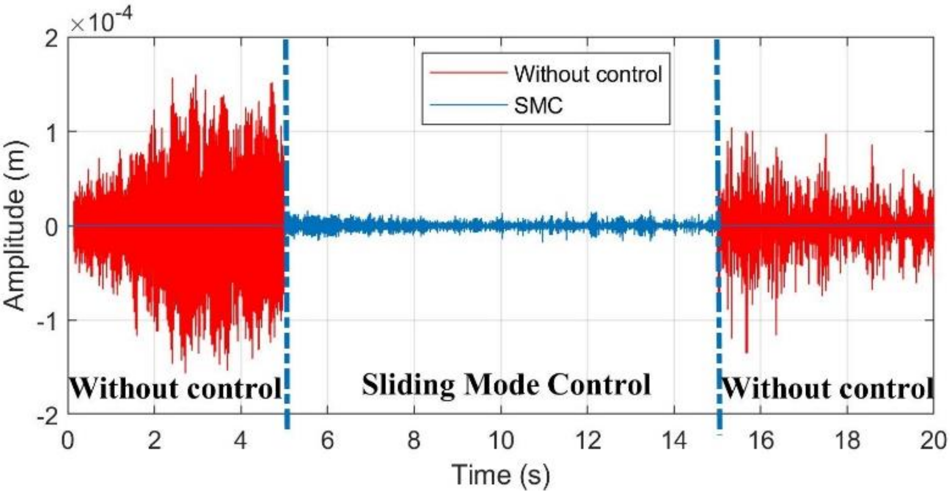

Fig. 9 Data from controlled and uncontrolled situations

It has been determined that the actuator generates a force of up to 25 N in order to decrease the amplitude during active control. As a result of the literature studies, it was seen that an actuator force of 18 N is required for active control of AA6025 aluminum alloy during turning, and 45 N for turning of C45 quality steel [6,7]. It is advocated that the force required by the actuator in active control applications varies depending on the mechanical properties of the workpiece, the properties of the cutting tool and the turning parameters. The information obtained from the literature confirms the results we have obtained [41-45]. The actuator force graph is given in the Fig. 10 for active control application.

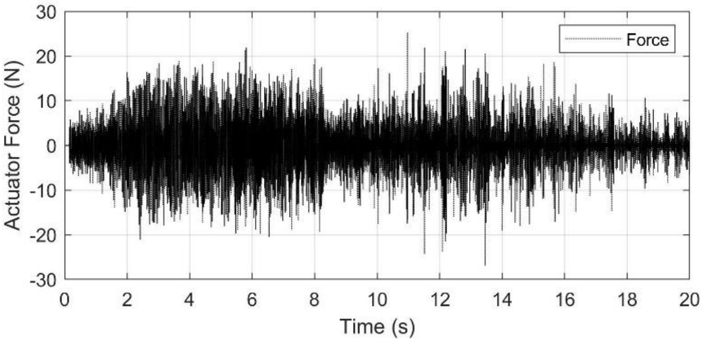

Fig. 10 Reaction force of the actuator

FFT analysis of displacement data is given for uncontrolled and controlled situations, respectively, in Figs. 11 and 12. According to the FFT results, there has been a significant decrease in the critical frequency amplitude. This situation has revealed that the amplitude and frequency of the vibration that occurs after the control are too small to affect the product quality and system elements negatively.

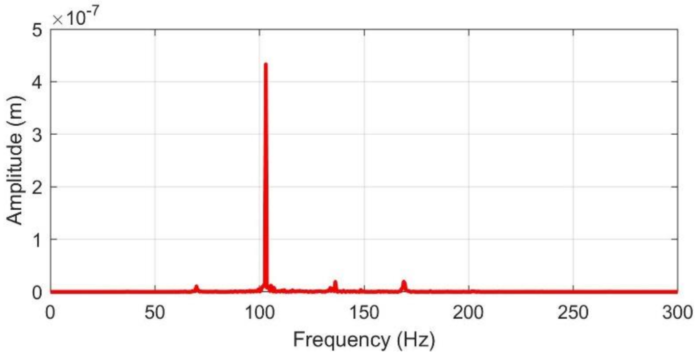

Fig. 11 FFT results for displacement data without active control

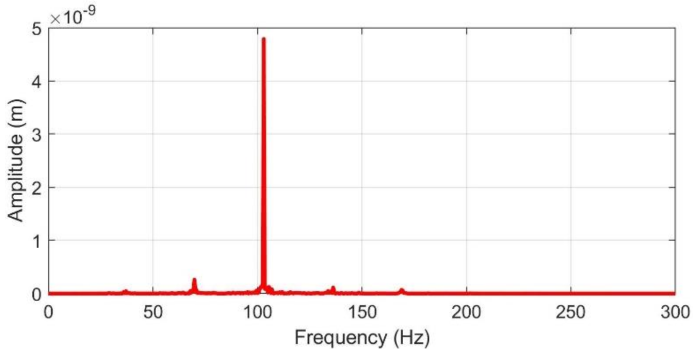

Fig. 12FFT results for displacement data after SMC

5. CONCLUSIONS

In this study, it is aimed to define chatter vibrations that negatively affect product quality and productivity in turning and to reduce them with active control application. Within the scope of the study, acceleration data in three axes were collected from the cutting tool during dry turning of titanium alloy Ti6Al4V quality material. The collected data is processed and then made available in active control applications. According to the results obtained from the study:

- It has been observed that the amplitude values of the acceleration data collected on the tool during the dry turning of Ti6Al4V alloy vary between 110 m/s^2 in the positive direction and -132 m/s^2 in the negative direction.
- According to the FFT result of the acceleration data, it is observed that the critical frequency values were 110 Hz.
- It is observed that the displacement values before the control were in the range of 250-350 µm.
- After the active SMC application, it has occurred that the displacement data decreased to the range of 50-100 µm.
- It is concluded that the FIR digital filtering method is an important step in active control applications.
- It is concluded that the chatter problem, which is one of the major problems of machining, can be solved with active vibration control applications, a correct data acquisition mechanism, controller, system recognition processes and correct actuator selection.
- It is concluded that the SMC works with high accuracy for active vibration control in turning.
- It can be said that SMC is promising with its high accuracy and robustness for future studies.

In line with the information obtained within the scope of the study, it is predicted that piezo and MR-based actuators will be of great importance for active vibration control in turning.

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