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Modeling of Vibration Behaviors of Turning Machining with the Constant Surface Speed Effect

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ABSTRACT
Turning machining is a complex process in which many variables can influence the desired results. Among those variables, cutting tool vibration and cutting force greatly affect the precision of the workpiece and the tool life. While the tool vibration and cutting force in feeding are primarily determined by cutting speed, feed rate, and depth of cut as well as the dynamic characteristics of machining system. This paper presents an analytical modeling approach to investigate the effects of machining conditions based on the governing equation of the machining system. The machining behaviors under different conditions were simulated by Simulink block diagram. Basically, the cutting speed is considered the parameter dominating the vibration behavior and hence is served as the primary input for the simulation. The effectiveness of constant surface speed (CSS mode) or function G96 in turning process was further examined through comparisons of the variations of vibration and cutting force generated in feeding with different conditions.

Keywords: constant surface speed, cutting force, machining vibration, turning process.

INTRODUCTION

One of the most significant factors affecting the performance of machining process is the tool vibration, which limits not only the surface quality of workpiece, material removal rate but also the wearing extent and tool life [1÷4]. Many researchers have conducted investigations on this phenomenon, trying to find better solution for improving the machining performance [5÷13].

Some studies have reported the influences of machining parameters and tool vibrations on surface roughness [13÷16]. For example, Chauhan and Dass [13] have shown the surface roughness increases with the increasing of the cutting speed and feed rate in machining. In the experimental study of dry turning operation, Izelu et al. showed that higher feed rate increases the surface roughness and induces vibration [14]. Kassab et al. [2] reported that the surface roughness was significantly affected by vibration of cutting tool, which can be controlled at lower level by appropriately selecting the cutting parameters. Das and Hazarika [15] worked on the study of the effects of cutting parameters on the too vibration and reported that both depth of cut and feed have more influence on peak acceleration of the cutting tool as compared to cutting speed. Okokpujie et al. [16] conducted experimental analysis to demonstrate the effects of cutting parameters on the machining vibration, in which the depth of cut has significant influences on machining vibration.

Besides, study of the Thomas and Beauchamp [17] demonstrated that the tool vibration was affected not only by the interactions of the cutting parameters, but also by modal parameters of cutting tool and workspace. Their results showed that a lower tool vibration can be expected in turning with low cutting depth and speed, which may implies that cutting tools with lower rigidity and higher damping are more useful for control the machining vibration at lower level. Also, the vibration level can be predicted based on the cutting parameters by artificial neural network and regression analysis [18÷20]. For example, Abouelatta and Madl [18] established a mathematical model for predicting the surface roughness based on the cutting parameters, tool geometry and tool vibration in radial and feed directions. Basically, the machining vibration was caused in the form of chatter or regenerative chatter due to inappropriate use of the cutting parameters in turning process [21, 22]. For this, the controller was also added to reduce the bad influence of the machining vibration phenomenon [23÷28]. The strategy for improving machining performance can be conducted by using featured function code G96 or constant surface speed (CSS) on the turning machine. The function G96 is a technique for controlling the speed of a spindle on a lathe which is determined by the diameter of the workpiece being processed and the desired cutting speed/surface velocity [29, 30]. For example, Pan et al. [25] reduced approximately 20 dB of chatter in machine tools through the modeling of the control system with Least Mean Square (LMS) adaptive filter and Albus's Cerebellar Model Articulation Controller (CMAC) neural network control algorithms. Albertelli et al. [26] presented an experimental study regarding the effects of spindle speed variation technique on tool wear in steel turning. The experimental tool wear tests were arranged and performed following the cutting speed, and the cutting speed modulation was the main factors investigated in study. Al-Regib et. al. [27] presented a novel method for programming spindle speed variation for machine tool chatter suppression which was verified experimentally.

As a featured function G96 (CSS mode), the determination of the appropriate cutting speed in machining is of importance and still worthy of investigation, in particular when considering the influence of tool vibration and cutting force caused by the interaction of the different cutting conditions. This study was therefore aimed to modelling the machining behaviors in turning process based on the governing equation of the machining system. The machining vibration and cutting force were simulated by simulink block diagram. The effectiveness of featured function G96 in turning process was further examined through comparisons of the variation of vibration and cutting force generated in feeding with different conditions.

ANALYTICAL APPROACH

The dynamic behavior of a machining system can be expressed in terms of the mechanical system with single degree of freedom, as shown in Figure 1. The system can be characterized by mass (m), spring (k), and damping (c) and the governing equation can be expressed as the following form.

$$m\ddot{x}(t) + c\dot{x}(t) + kx(t) = F(t) \tag{1}$$

where: $x(t)$ is the relative displacement of the system and m, k and c is the mass, stiffness and damping of the system, respectively. $F(t)$ is a dynamic cutting force.

Basically, the cutting force is related to the cutting resistance between the cutter and workpiece and is determined by the product of the cross section area of the chip and cutting resistance. Considering the variation of the cross section of the chip due to vibration of the cutter in feeding direction, the cutting force is therefore determined by the formula:

$$F_x(t) = K_f a[h_0 + x(t-\tau) - x(t)] \tag{2}$$

In above, $x(t)$ and $x(t\text{-}T)$ are the vibration generated during the current and previous revolution of the workpiece, K_f is the static cutting force coefficient in feed direction, a is the width of cut, h_0 is the feed per revolution, and τ is the time delay between the inner and outer vibration waves.

Furthermore, according to study of Das and Tobias [30], the vibration of the machining system could be reduced by the process damping effect under low cutting speed. The process damping force is linearly proportional to the vibration velocity and the cutting width and inversely proportional to the cutting speed [21, 22], which can be expressed by following equations.

$$F_{pd}(t) = C_{pd} a h_0 \frac{\dot{x}}{V_c} \tag{3}$$

The constant of proportionality C_{pd} is referred the process damping coefficient or the velocity-dependent cutting force coefficient, which also represents the contact characteristics between the wavy surface material and flank face of the tool and can only be identified from a set of dynamic cutting tests [31]. V_c is the cutting speed ($V_c = \pi Dn/60$), determined by spindle speed (n) and workpiece diameter (D).

The force term in Eq. (1) can then be rewritten as the following form

$$F_x(t) = K_f a[h_0 + x(t-\tau) - x(t)] - C_{pd} a h_0 \frac{\dot{x}}{V_c} \tag{4}$$

which is composed of the cutting force in feeding direction and the force caused by process damping effect. The governing equations of the dynamic behavior of the machining system can be expressed as

$$m\ddot{x}(t) + \left(c + C_{pd}\frac{ah_0}{V_c}\right)\dot{x}(t) + kx(t) = K_f a[h_0 + x(t-\tau) - x(t)] \tag{5}$$

It is noted that the term ($C_{pd}\,ah_0/V_c$) representing the process damping increases the system damping ability at lower cutting speed. Also, the introduction of the process damping in dynamic cutting force model is expected to yield the higher cutting limit for stable machining without chattering. Such effects will be more significant and favorable to obtain better machining performance when the machining is conducted by activating the constant surface speed function with appropriately defined cutting speed.

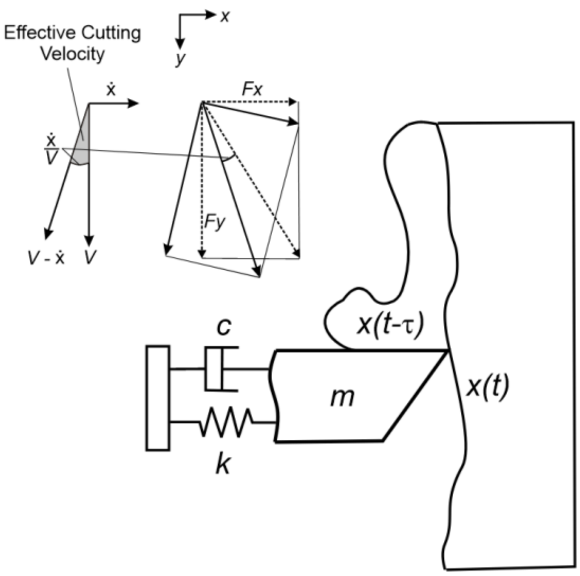

Fig. 1. Single degree of freedom system [22]

SIMULATION APPROACH

The workpiece with geometry illustrated in Figure 2 is used for facing and tapering process. In facing process, the diameter of workpiece is 60 mm. In tapering process, the diameter of the workpiece changes from 20 mm to 80 mm along the axial length of 60 mm.

The mechanical characteristics of the machining system including system mass, stiffness constant, and damping coefficient were defined as $m = 0.561$ kg, $k_x = 6.48\times10^6$ N/m, and $c_x = 145$ Ns/m, which were obtained from the study conducted by Atlintas [22]. In addition, the cutting force coefficients K_f and process damping coefficient C_{pd} were identified respectively as 1384 N/mm^2 and 1.16×10^6 N/m.

The machining parameters, also the input variables in simulation, are defined as below: feed rate $f = 0.2$ mm/rev; surface speed $V_c = 300$ m/min, maximum spindle speed $n_{max} = 5000$ rpm. The cutting depth a_p was defined as 0.1 mm and 0.4 mm, respectively, which is in the stable and unstable region based on the stability lobes of the system, respectively.

The simulation approach for analyzing the tool vibration on a turning machine was carried out on Simulink software in Matlab.

To demonstrate the effectiveness of the constant surface speed function, the simulations

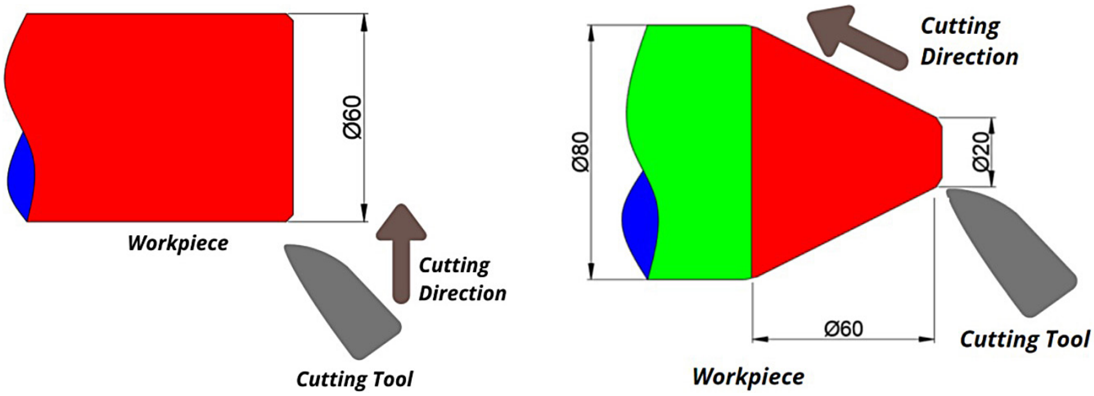

Fig. 2. Schematics of the turning machining with different geometry of the workpiece

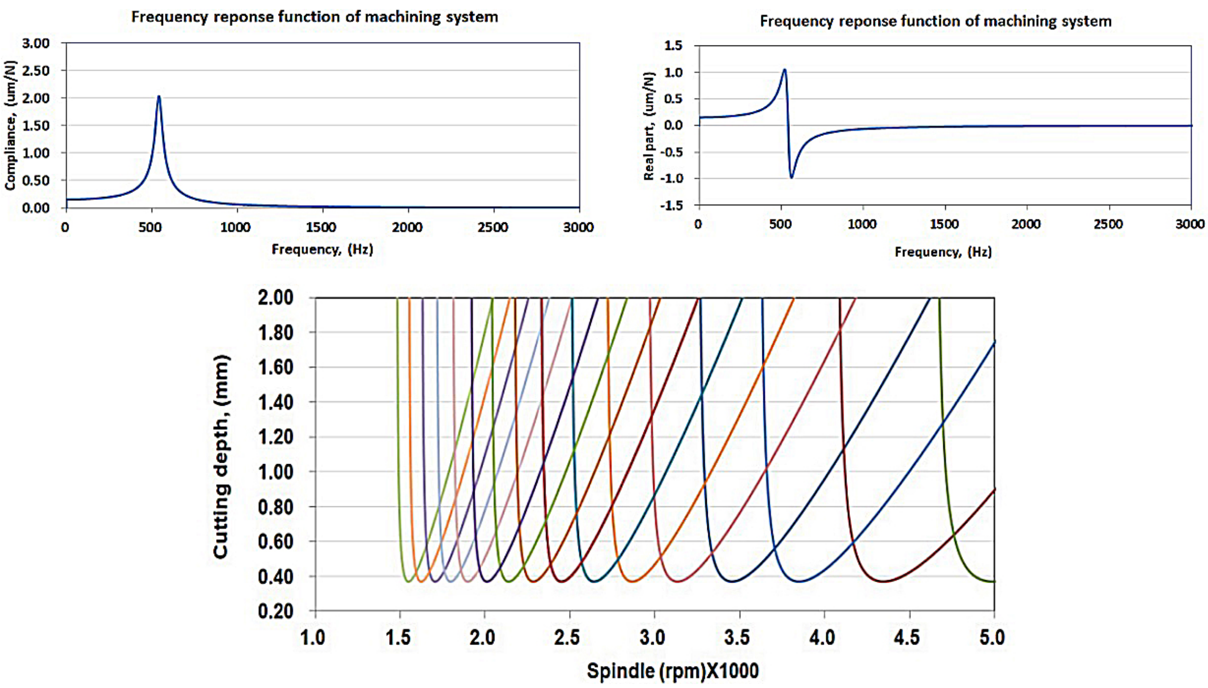

Fig. 3. Frequency response function and stability lobe diagram of machining system

of the two turning process, facing and tapering were performed with and without activation of G96 technique. For machining without activating function G96, a constant spindle speed was assumed at 1592 rpm throughout the machining of facing and tapering process, which gives a variable cutting speed, with maximum value of 300 m/min. For machining with function G96, a constant surface speed of 300 m/min was assumed throughout the machining of facing and tapering process, which yields a variable spindle speed, changing with the diameter of workpiece at the cutter position in machining. Variations of the spindle speed and surface speed with feeding time for different turning process with and without CSS are shown in Figures 4 and 5.

In case of facing process with activation of function G96, the spindle speed changes from 1592 to 5000 rpm at constant surface speed of 300 m/min. In case of tapering process without activation of function G96, the surface speed changes from 75 m/min to maximum speed of 300 m/min under constant spindle speed of 1193 rpm. In tapering process with function G96, the spindle speed changes from 4774 to 1193 rpm at constant surface speed of 300 m/min.

The simulink block is shown in Figure 6 and Figure 7. There are four simulation models with different input values and simulation times based on the machining process and featured function G96 or G97 function for activation of surface speed. The system blocks were built based

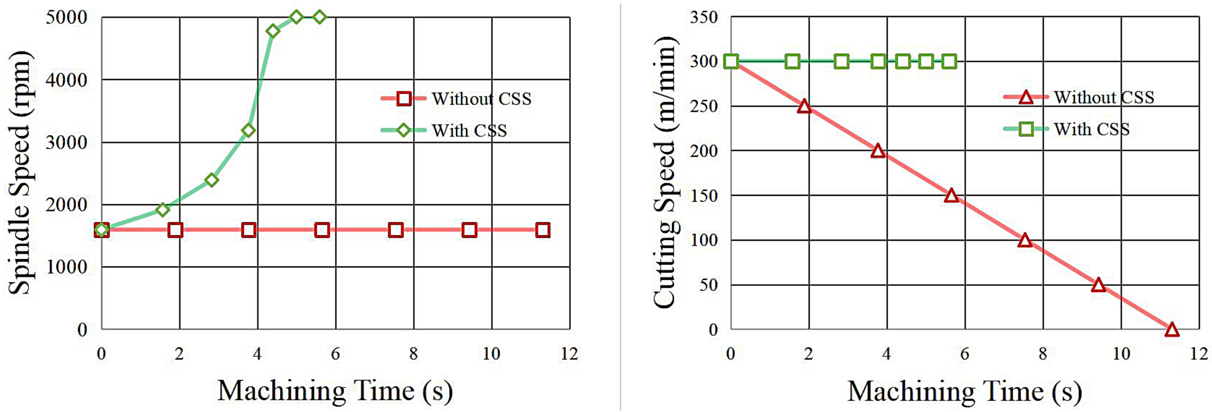

Fig. 4. Variation of the spindle speed and surface speed in facing process with and without CSS

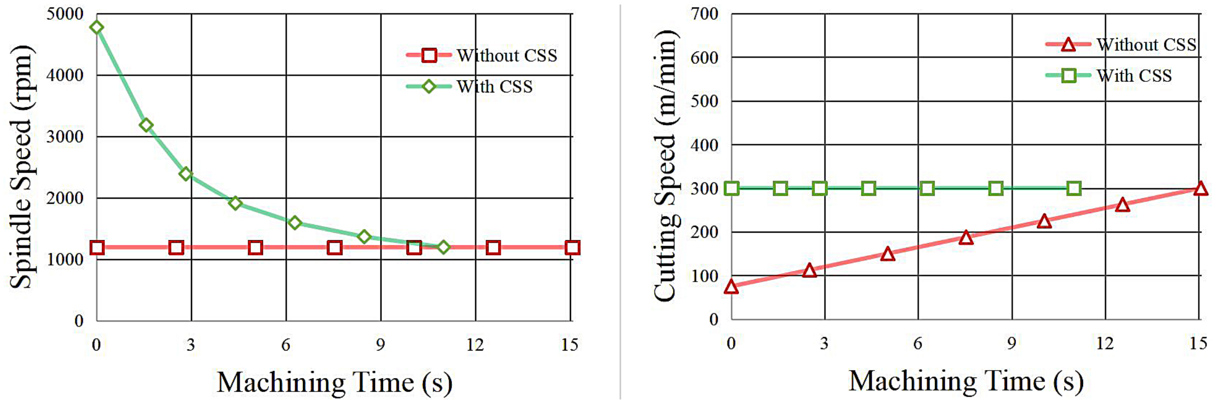

Fig. 5. Variation of the spindle speed and surface speed in tapering process with and without CSS

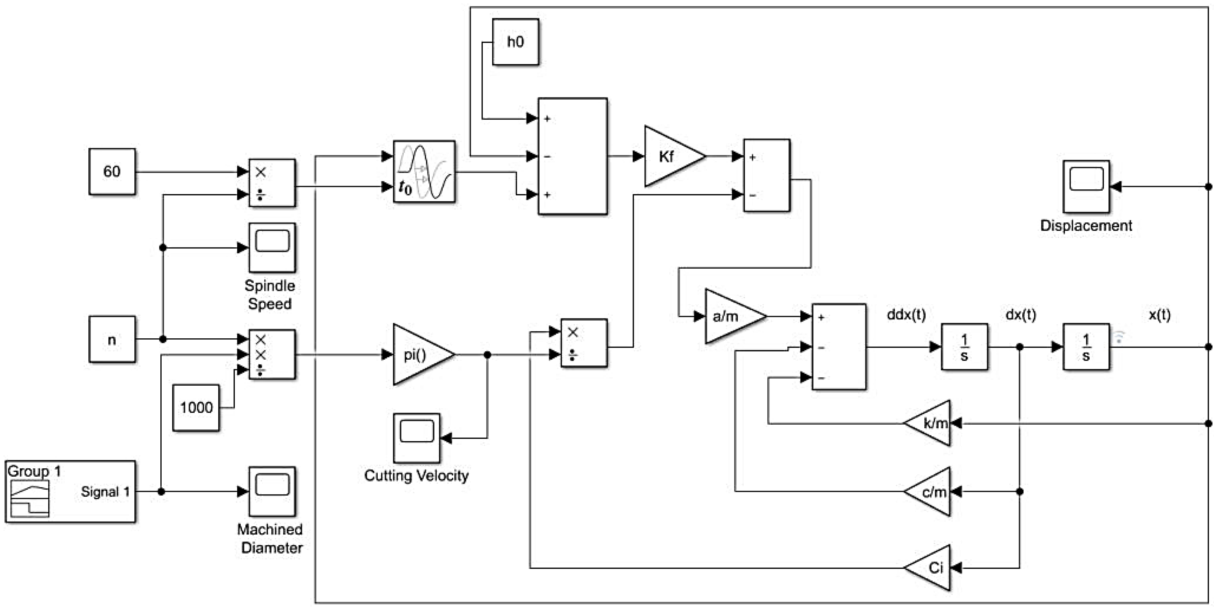

Fig. 6. Simulink block diagram of simulation for G97

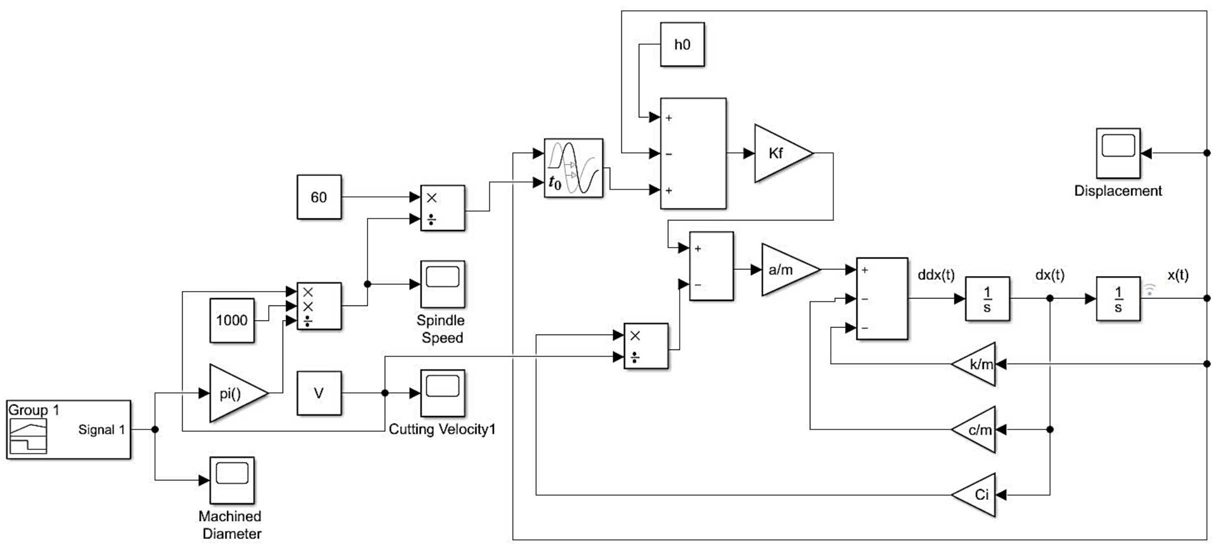

Fig. 7. Simulink block diagram of simulation for G96

on Equation (1) to (4). In a G97 simulation, the constant input value was spindle speed and the value of cutting velocity was calculated from the workpiece diameter and spindle speed. Whereas in the G96 simulation, the constant input value was cutting velocity, so that spindle speed was determined by workpiece diameter at cutting point.

RESULTS AND DISCUSSIONS

All the input variables for simulation of facing and tapering process conducted with and without activation of the constant surface speed (function G96) are listed in Table 1. For each machining, the simulated vibration and cutting forces of the machining system are presented as below.

Facing process

Figure 8 illustrates the simulated vibrations and cutting force of the machining system in facing process with and without activated function G96. In this simulation, the cutting parameters are in stable region of stability lobes diagram. It is found from Figure 8 that both of the vibration and cutting forces induced in facing process with function G96 are stable with feeding of cutter from outer surface to center of the workpiece. However, in facing machining with function G97, the vibration gradually decreases in feeding period, in which higher amplitude occurs at high cutting velocity and lower amplitude at lower velocity, but there is a significant variation in vibration level when the cutter feeds near the center point where the cutting speed approaches to zero. At the same time, the cutting force also gradually increases with the decreasing of the cutting speed when the cutter feeds in radial direction. The highest force occurs at the cutting point with lowest speed.

The simulation results of facing process indicate the variation of the cutting speed in feeding induces an unstable changes of cutting forces and an abnormal vibration, especially at the cutting point near the center of workpiece with extremely lower cutting speed. Contrarily, the activation of constant cutting speed in machining can stabilize the cutting force and vibration.

Table 1. Input variables for simulation of facing and tapering process

Specification	Facing process		Tapering process	
	Without CSS (with G97)	With CSS (with G96)	Without CSS (with G97)	With CSS (with G96)
Spindle speed (rpm)	1592	1592 ~ 5000	1193	4774 ~ 1193
Cutting speed (m/min)	300 ~ 0.0	300	75 ~ 300	300
Feed rate (mm/rev)	0.2	0.2	0.2	0.2
Cutting depth (mm)	0.1/0.4	0.1/0.4	0.1/0.4	0.1/0.4
Machining time (sec)	11.3	5.6	15.1	10.9

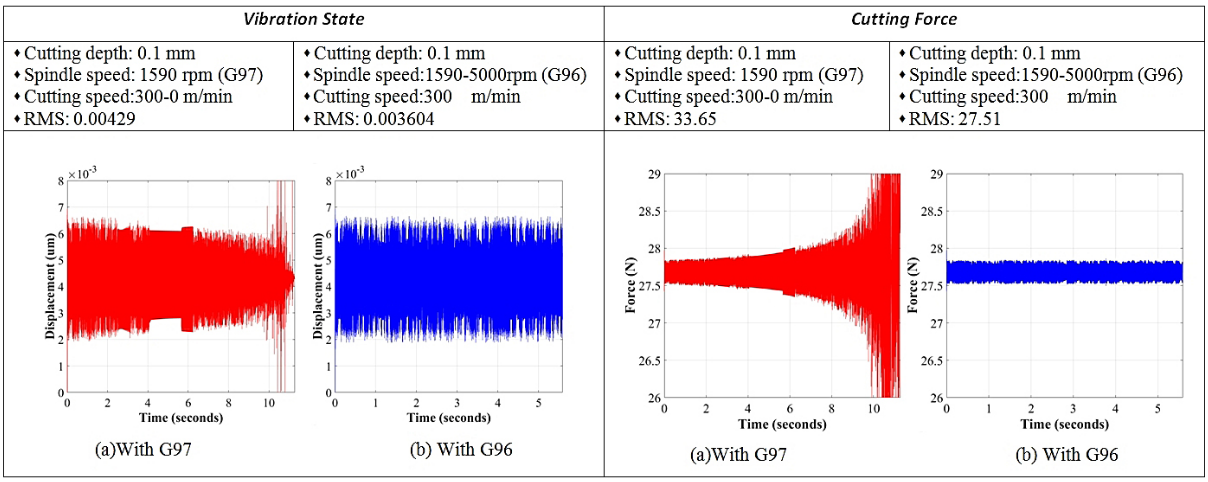

Fig. 8. Simulated vibration and cutting force in facing process at cutting depth of 0.1 mm without and with activation of function of constant surface speed

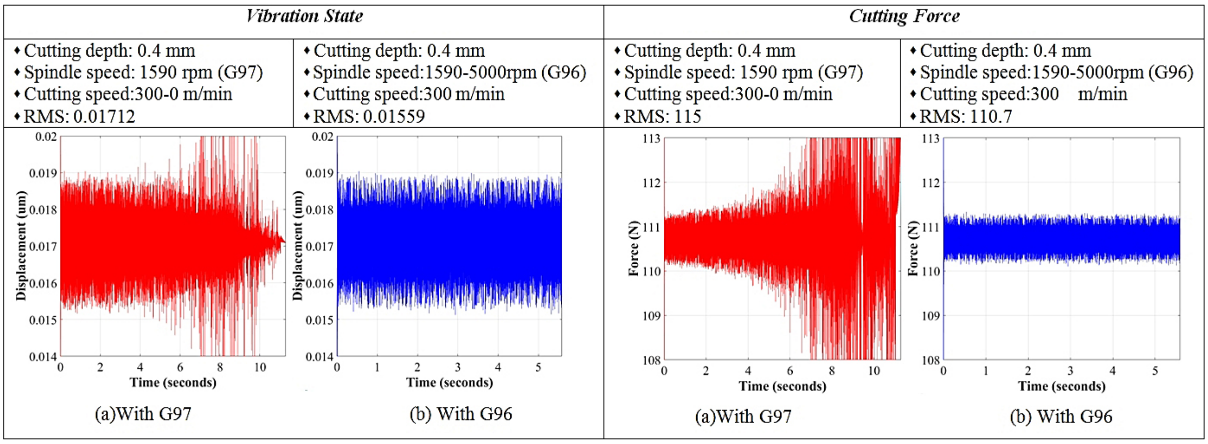

Fig. 9. Simulated vibration and cutting force in facing process at cutting depth of 0.4 mm without and with activation of function of constant surface speed

Similar phenomenon was also observed in the facing process with cutting depth of 0.4 mm. The vibration and cutting forces induced in machining are illustrated in Figure 9, which show similar scenario appeared in Figure 8 for cutting depth of 0.1 mm. According to Figure 9, we can find that without activation of function G96, the facing process with the unstable cutting parameter indeed generates more rigorous vibration and higher cutting forces when compared with the facing machining with lower depth of cut. The significant variations of the vibration and cutting forces at lower cutting speed probably can be caused by chatter. As shown in Figure 3, the cutting conditions, spindle speed of 1593 rpm and the cutting depth of 0.4 mm fall at the boundary of stability lobes, which may initiate the occurrence of chatter in machining. But, the activation of constant cutting speed can stabilize the cutting force and vibration even if the machining is defined in the unstable region with higher cutting depth.

Tapering process

Figures 10 and 11 illustrate the simulated vibrations and cutting forces in tapering process with and without activated function G96. In this simulation, the cutting depth was set at 0.1 and 0.4 mm respectively. In tapering process, the cutter was fed from the part of small diameter to larger diameter along longitudinal axis of workpiece. For the machining with constant spindle speed at 1597 rpm and G97 function, the vibration gradually increase with the increasing of the cutting speed from 75 m/min to 300 m/min at larger diameter, but the cutting force decreases with from a maximum to a lower value. Besides, for cutting depth of 0.4 mm, the vibration and cutting force show extremely abnormal phenomena, which occurs at point with cutting speed below 120 m/min, as shown in Figure 12.

In the case of tapering machining with constant surface cutting speed of 300 m/min (G96 function), the machining vibration and cutting force remain in stable variations during feeding. Such phenomena are found appearing in machining at cutting depth of 0.1 and 0.4 mm, which is referred as stable and unstable region in stability lobes diagram of the milling system. The simulated results clearly show the machining with activation of G96 function can stabilizes the cutting force and hence appropriately suppresses the vibration level even if the unstable cutting parameter is selected.

Again, simulations of tapering process verify the influence of cutting depth on the vibration behavior and the force generated in machining. In the case of tapering machining with constant cutting speed, the RMS value of vibration amplitude is about 0.002518 and 0.0160 um for cutting depth of 0.1 and 0.4 mm, respectively. the RMS value of cutting force at cutting depth of 0.1 and 0.4 mm is about 27.76 N and 110.8 N, respectively. This clearly indicates the cutting depth greatly affects the vibration and forces in machining.

Regarding the influence of the cutting speed on the machining states, it has been clearly demonstrated in the simulation of facing and tapering process under activation of function G96 or G97. As shown in Figure 13, cutting speed varies from 300 to 0.0 mm/min in facing and from 75 to 300 m/min in tapering. Both of the vibration and cutting forces increased more significantly after certain time.

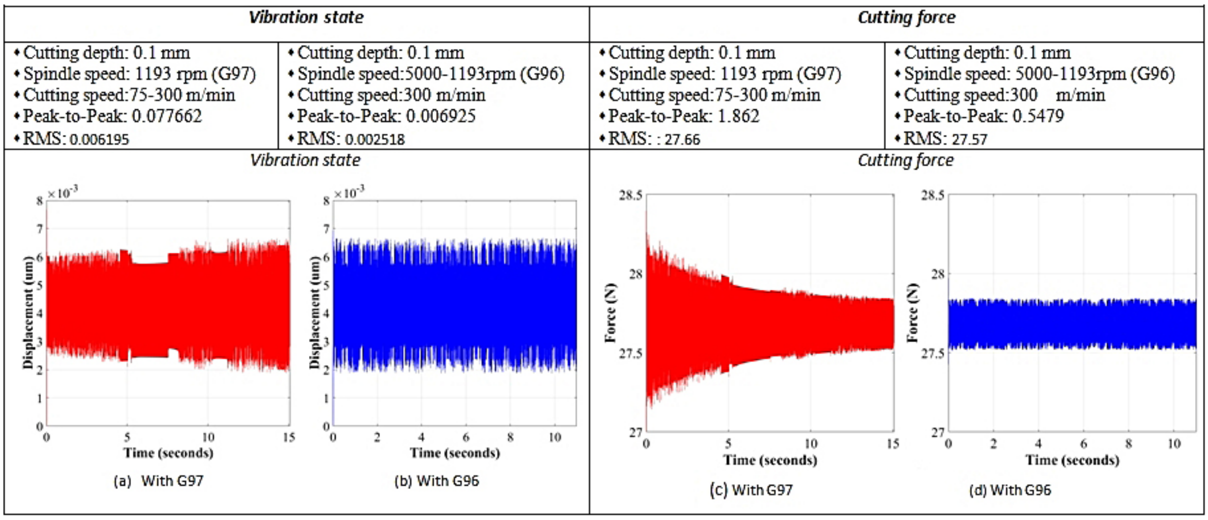

Fig. 10. Simulated vibration and cutting force in tapering process at cutting depth of 0.1 mm without and with activation of function of constant surface speed

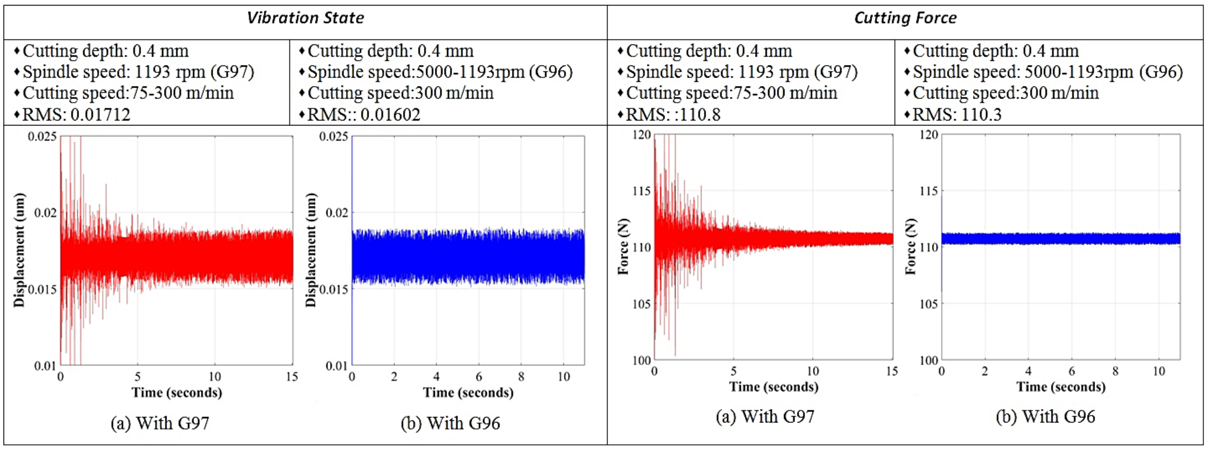

Fig. 11. Simulated vibration and cutting force in tapering process at cutting depth of 0.4 mm without and with activation of function of constant surface speed

It is noted that the time for abrupt change in vibration and cutting force can be related to the changing of cutting speed. Referring to Figure 12 (a), stable variation in vibration and force are generated when the cutting speed reached the value between 120–300 m/min, which is regarded as stationary condition region; while vibration and force enter unstable states with abnormally high amplitude when cutting speed reduces below the critical value of 120 m/min, which is regarded as non-stationary condition region. Similar phenomena appear in the case of tapering process, Figure 13 (b), in which cutting speed increases from 75 to 300 m/min during feeding. The vibration and force induced in machining behaves abnormally with higher amplitude during low cutting speed (<120 m/min), but they become more stable when speed increases above the critical value.

It can be concluded from these simulations that the machining with constant spindle speed easily provokes unstable vibration and generates inconsistent cutting force. But, stationary condition of machining vibration can also be obtained by setting the cutting speed in the appropriate range in this machining process, such as 120–300 m/min. To the contrary, activation of constant surface speed or G96 function produces stable and consistent vibration and force, which are favorable for longer tool life and better surface finish. Therefore, the use of CSS feature could suppress the chattering phenomenon, even the machining conditions are in unstable region.

Besides, according to study by Das and Tobias [22], cutting velocity plays an important role on the vibration behavior of the machining system. As revealed in governing Equation (1), such

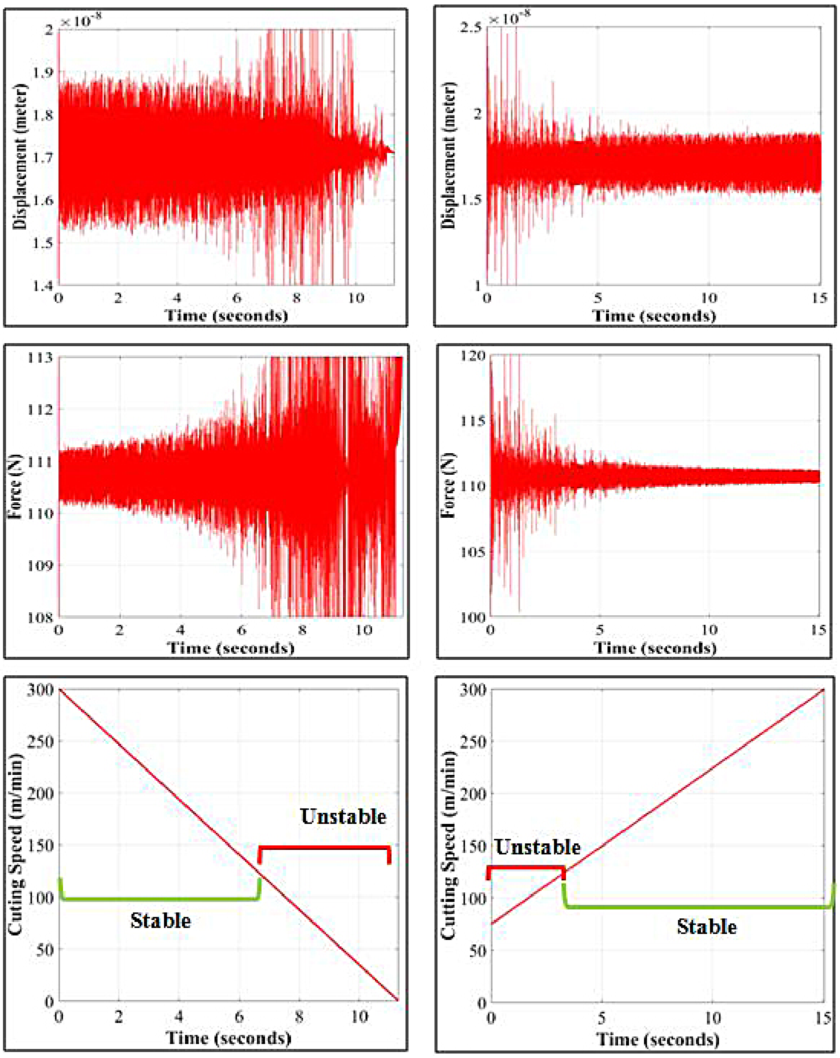

Fig. 12. Variation of vibration and force with changing of cutting speed in (left) facing process and (right) tapering process, respectively

effects have been incorporated with the process damping properties caused by the interaction of the workpiece and cutting tool and the damping effects are more profound at low speed cutting. To quantify the influence of the cutting speed on the vibration behaviors in turning process, more simulations were carried out at different cutting speed with activated function G96. The cutting speed was assumed at 100, 200, and 300 m/min, respectively, and cutting depth was set at 0.1 mm.

Finally, previous simulations have shown that machining under constant cutting speed with activated function G96 can stabilize the vibration and cutting forces. Besides, according to study by Das and Tobias [22], cutting velocity plays an important role on the vibration behavior of the machining system. As revealed in governing Equation (5), such effects have been incorporated with the process damping properties caused by the interaction of the workpiece and cutting tool. The damping effects are more profound at low speed cutting. To quantify the influence of the cutting speed on the vibration behaviors in turning process, more simulations were carried out at different cutting speed with activated function G96. The cutting speed was assumed at 100, 200, and 300 m/min, respectively, and cutting depth was set at 0.1 and 0.4 mm, respectively.

The machining vibrations in tapering process with the CSS feature were simulated and illustrated in Figure 13. As seen in figure, machining with lower cutting speed of 100 m/min generates a more stable vibration as compared with that induced under higher cutting speed. The RMS value of machining vibration under cutting depth of 0.1 mm is 0.0044, 0.0045 and 0.0048um for cutting speeds of 100, 200 and 300 m/min, respectively. For cutting depth of 0.4

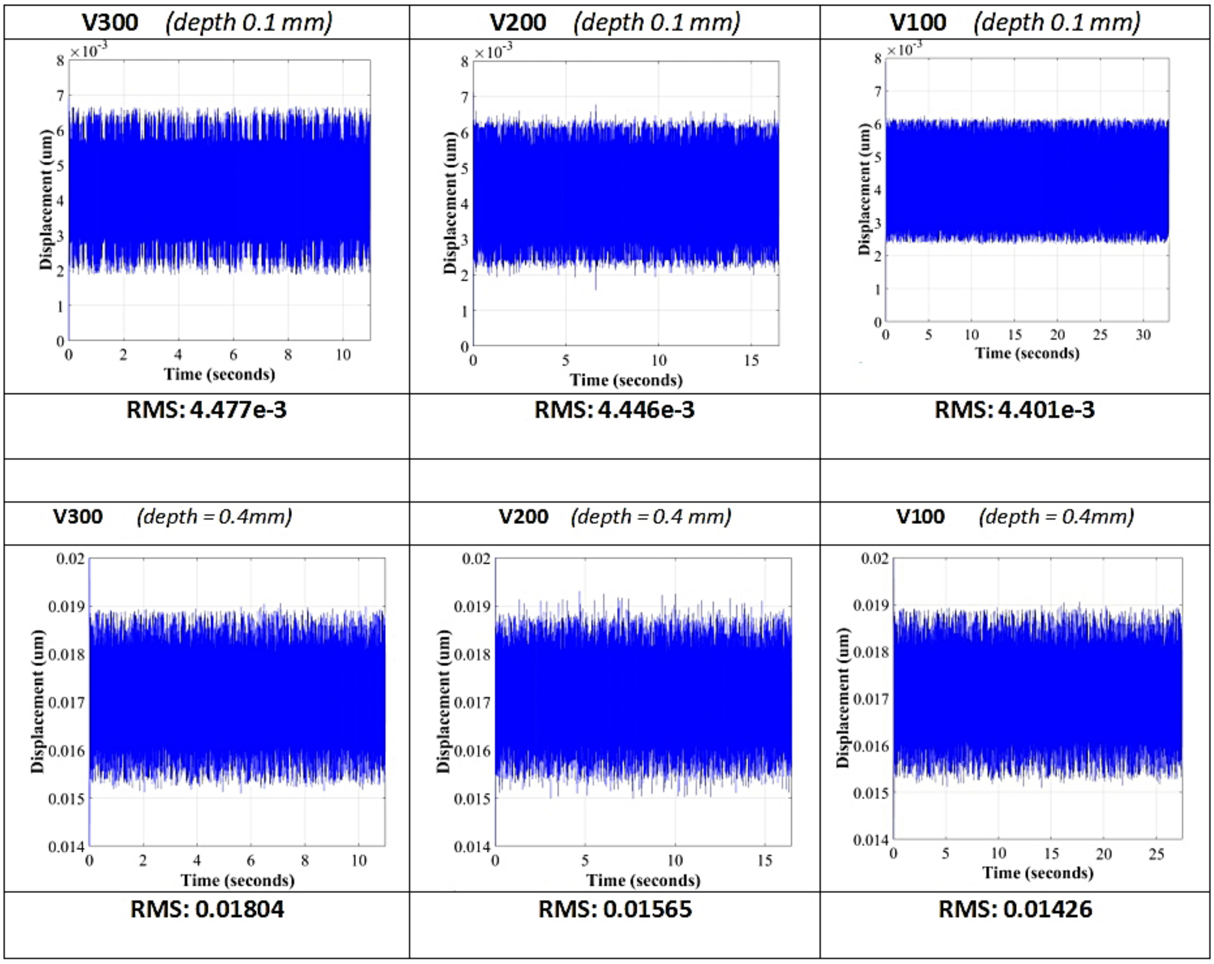

Fig. 13. Vibration of tapering process with CSS at cutting speed of 100, 200 and 300 m/min, respectively

mm, the RMS value assessed at cutting speed of 100, 200 and 300 m/min is 0.01084, 0.01565, and 0.01426 for respectively. It is again demonstrated from this simulation that higher level of vibration can be caused when the machining was conducted with higher cutting speed. Also, the vibration was significantly increased in magnitude when higher cutting depth was used in machining, and it was still kept in stable state under constant cutting speed.

Moreover, there are other discussions that can be taken from the phenomenon of non-stationary vibration that occurs, which can also affect other parameters in the lathe machine. Siddhpura et. al [5] did a review regarding the vibration in lathe machine, and concluded that regenerative chatter is the most detrimental to any process as it creates excessive vibration between the tool and the workpiece, resulting in a poor surface finish, high-pitch noise, and accelerated tool wear which in turn reduces machine tool life, reliability, and safety of the machining operation. Amin et al. [3], showed that vibration amplitude has a dominant effect on surface roughness generated in end milling operation. From those researches, it can be seen that the behavior and amplitude of the vibration phenomenon that occurs in the machining process also affect the surface finish, high-pitch noise, and tool wear. Therefore, the machining process using CSS techniques in the lathe machine gives a better impact on the other parameters in the machining process when compared to the machining process on the lathe without using CSS techniques. Because this CSS technique has a more stable vibration behavior tendency and some lower vibration parameter values.

CONCLUSIONS

This study proposed an analytical modelling approach to investigate the effectiveness with activation of constant surface speed or function G96 in facing and tapering process. Current results clearly show that the machining with function G96 induced stable vibration and cutting force with less variations in amplitude during turning machining although the machining conditions was selected from unstable region of the cutting system. While the use of constant spindle speed in turning was found to induce extremely abnormal vibration during feeding with changing cutting speed, which further generated a significant increment in cutting force at points with lower speed. The simulation also verifies that the cutting speed is an important parameter affecting the vibration level. Basically, a lower cutting speed is favourable to suppress the vibration level due to the process damping effects as compared the machining with higher speed. Overall, the results associated with analytical modelling approach provide a reference to select appropriate machining conditions for stabilizing the vibration behaviors.

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