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cutting condition, water, PEO
resonance, damping ratio, surface roughness

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DEVELOPMENT ON TECHNIQUE REGARDING CHANGE OF RESONANCE FREQUENCY ON MACHINE TOOL FOR OPTIMIZATION OF CUTTING CONDITION

Establishment and selection of proper cutting condition can improve tool life and final cutting result. Cutting speed, feed speed, depth of cut and selection of tools are conditions of cutting that determined the cutting accuracy. However, when the optimum cutting condition with selected cutting speed coincides with machine resonance frequency, large vibration will occur. Consequently, even small periodic of driving forces can produce large amplitude vibrations. The simple technique to lower resonant frequency of machine tool was developed in previous research by using mixture of water and polymer with 6wt% concentration. As it was difficult to obtain damping ratio when the concentration is larger than 6wt%, therefore, the aim of this paper is to change machine resonant frequency for optimizing cutting condition by improving mixture concentration of water and polymer. It is concluded from the results that (1) By controlling machine tool resonance frequency enable cutting speed to be used for processing at its optimum cutting condition (2) New damping value of polymer mixed with water was presented, (3) Machine vibration reduced as resonance of machine was successfully avoided and surface roughness was also improved.

1. INTRODUCTION

The selection of optimum cutting condition before machining is important to achieve optimum final cutting result [1],[2]. Determine proper spindle speed is important because the excessive of spindle speed can cause premature tool wear, breakages, and tool chatter, all of which can lead to potentially dangerous conditions. Using the correct spindle speed for the materials and tools will prolong tool life and enhance quality of the surface finish. However, when the selected optimum cutting condition with force frequency of spindle speed coincides with resonance of the machine, large vibration will occur. At this circumstance, changes in cutting condition is required to avoid vibration, consequently, geometrical accuracy, tool life and surface roughness may not be optimum. This condition is considered as a problem for productivity in manufacturing [3],[4],[5],[6]. Previous

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research [7] has presented new and simple technique to reduce resonant frequency by using water mix PEO polymer powder with concentration 6wt%. The maximum concentration used in that study was decided based on the difficulties in performing mixture water with polymer when the concentration is increased. Thus, the mixture concentration was limited to only 6wt%. Recently, the demand for the improvement of mixture concentration was requested as it was hypothesized that the improvement of the mixture concentration can improve damping ratio. Therefore, the study on this paper is aimed to change machine tool resonance frequency in order to maintain the use of optimum cutting condition and investigating the improvement of the mixture of water with polymer to higher damping ratio. Some techniques for changing machine tool resonance frequency by reinforce machine structure and changing position of supports are generally used, however they are not effective yet in changing machine resonance. Therefore, in this paper, the technique by adding water mix polymer was proposed to change machine tool density for changing resonance frequency. New result of damping value with concentration larger than 6wt% is presented. In optimizing our proposed technique, the combination usages with two existing techniques of reinforce machine structure and change of support position was performed and evaluated to define the optimum combination control.

2. STUDY ON TECHNIQUES FOR CHANGING MACHINE TOOL RESONANCE

2.1. DETERMINATION OF PROPOSED CONTROL METHOD

Every part in machine tool has its own resonant frequency which can vibrate any time when force frequencies coincide with resonant frequency of those parts. Therefore, finding the resonance of machine tool will help in avoiding operation in resonance zone and lower vibration amplitude. Here, in order to determine the method for changing machine resonance, the simulation study on bench lathe machine to define the resonance part was performed with the results shows in Fig. 1. The result shows that large vibration occurred at

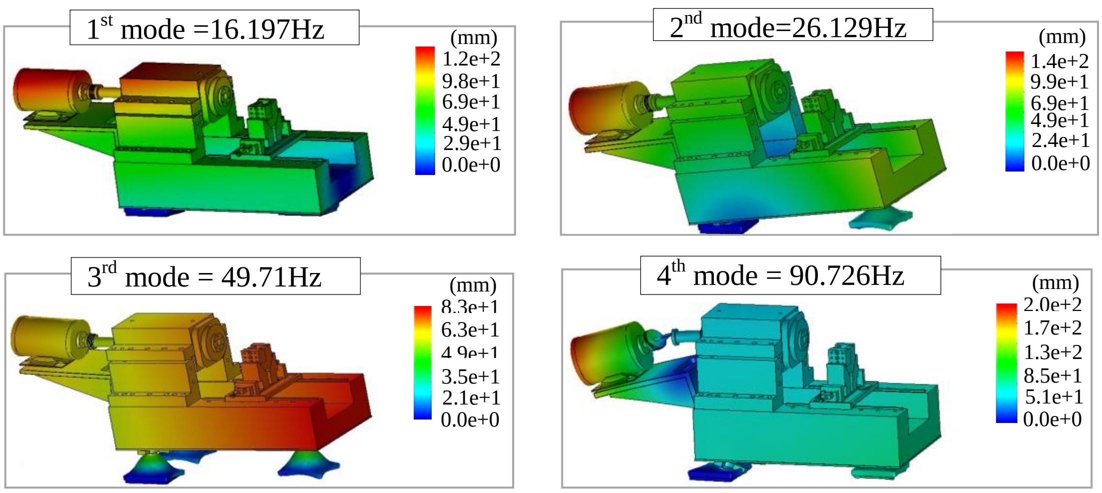


Fig. 1. Simulation results of mode shapes of bench lathe at free vibration studied using CosmosWorks software

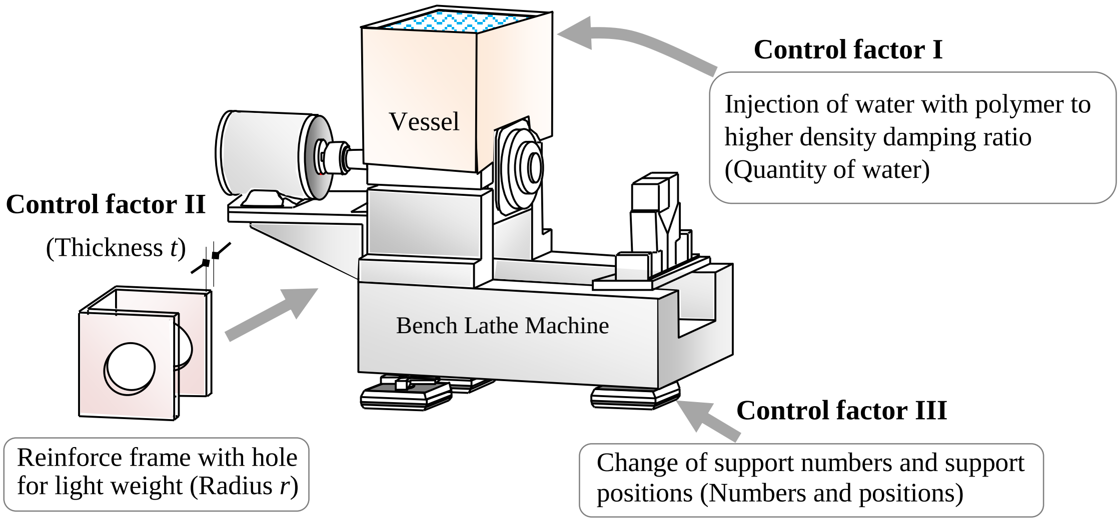


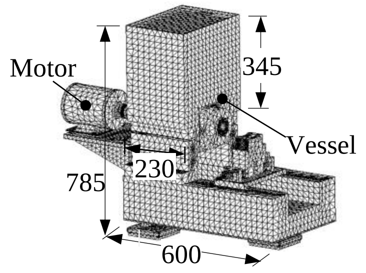
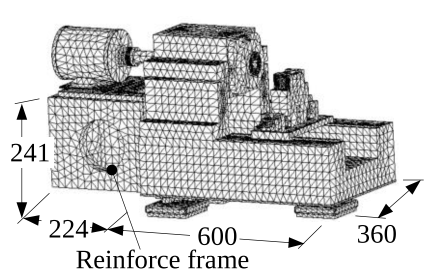
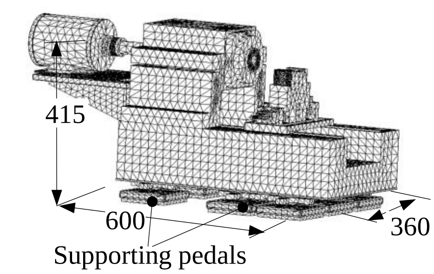
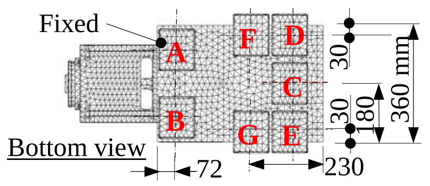
Fig. 2. Explanation of parameters and countermeasures for controlling resonance in a machine tool
※( ) is control parameter

the area near machine motor in all 4 modes and at machine support point. By considered this, the methods for control resonance were developed to reduce the magnification during operating in resonance zone. Changing apparent density, changing overall stiffness, and changing position of supports points were 3 factors that were considered. These methods were applied with different parameters and were determined from the view point of easier and faster approach. Specifically, the setup of parameters for changing resonant frequency on bench lathe machine is illustrated in Fig. 2. Firstly, to higher machine density for reducing resonant frequency, mass is added by injecting water into vessel in machine head which is defined as control factor I. Resonant frequency of bench lathe reduce when this method is applied. However, as water magnifies the vibration because of low damping factor, therefore for high effectiveness, mixture of polymer with water is proposed to be used. Next, in accordance to the mode shapes in Fig. 1 with large amplitude occurred near motor base, therefore reinforcing motor base to improve rigidity of machine tool is considered and defined as control factor II. Finally, changing positions and numbers of supporting pedal of machine tool is considered to change resonance frequency and its mode shape. This control method is defined as control factor III. Furthermore, in this paper, these control methods are considered for resonant frequency range below 100Hz where there exists large influence to the processing accuracy [3].

2.2. SIMULATION OF PROPOSED CONTROL METHODS BY CAE ANALYSIS

In order to improve the effectiveness of proposed control methods, CAE design and analysis was performed. This computer simulation helps the designs to be evaluated and refined rather than physical prototype testing which is saving money and time. Table 1 shows the condition and parameters for simulation using CAE based CosmosWorks. In this analysis, the original position of the supporting pedal (A-B-C) was used. Free vibration and forced vibration analysis were performed. To obtained vibration result with response to 1 Newton force, the impact of 1N force was applied to the upper part of machine headstock from vertical direction. This force was applied to all three control factors during performing simulation study. For study of control factor I, the analysis was done by adding 10, 16 and 22 liters of water to the vessel placed in machine headstock and analyzing their vibration responses. The analysis result of frequency response is shown in Fig. 3 with vertical axis is compliance which has very big influence for surface roughness. The result shows that machine frequencies reduce as the amount of filled water increased. When machine frequency shifts away from resonance source, the amplitude becomes smaller. It also observes that amplitude of vibration become larger when water is added. In this condition, we consider that the rise

Table 1. Experimental parameters for the control factor I, II and III

Control factor I	**Control factor II**	**Control factor III**
		
Parameters: Amount of water (0, 10, 16, and 22 liter)	Parameters: Frame thickness (12, 24, and 32mm)	
Mesh properties: Body material : SS400 Steel Adding parts : water, polymer Element size : 22mm No. of Node : 161817 No. of element : 99602 Mesh type : Solid Jacobian : 4 points	Mesh properties: Body material : SS400 Steel Adding parts : SS400 plate Element size : 22mm No. of Node : 142202 No. of element : 84835 Mesh type : Solid Jacobian : 4 points	Mesh properties: Body material : SS400 Steel Adding parts : Pedal, rubber Element size : 22mm No. of Node : 148697 No. of element : 88181 Mesh type : Solid Jacobian : 4 points

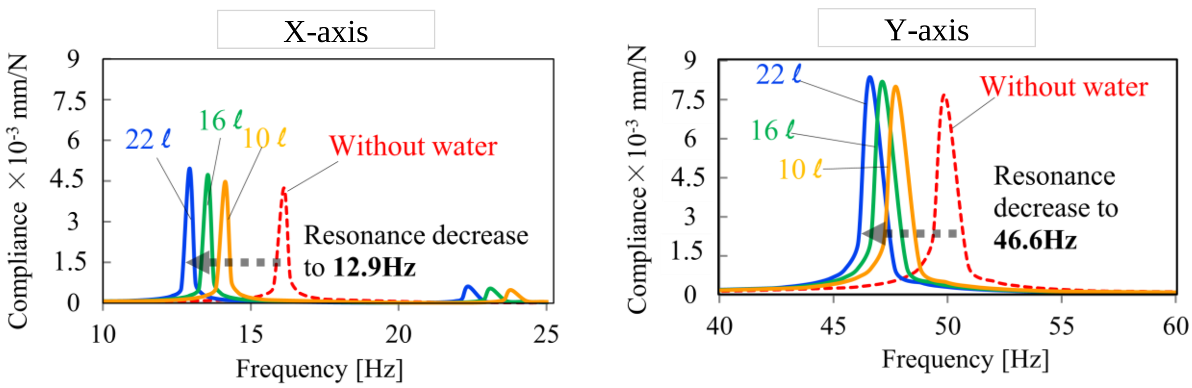


Fig. 3. Frequency response of the bench lathe from X-axis and Y-axis by injecting water

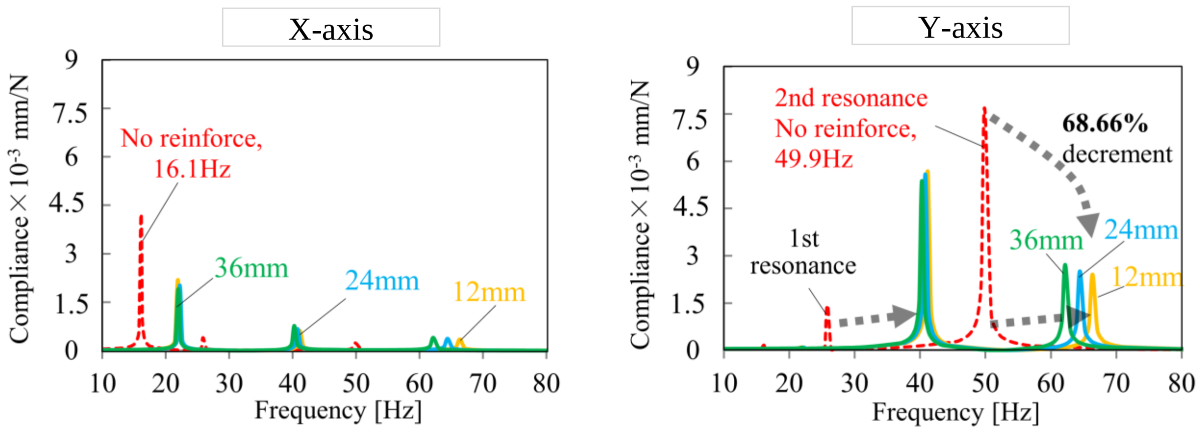


Fig. 4. Frequency response of the bench lathe from X-axis and Y-axis with reinforce motor base

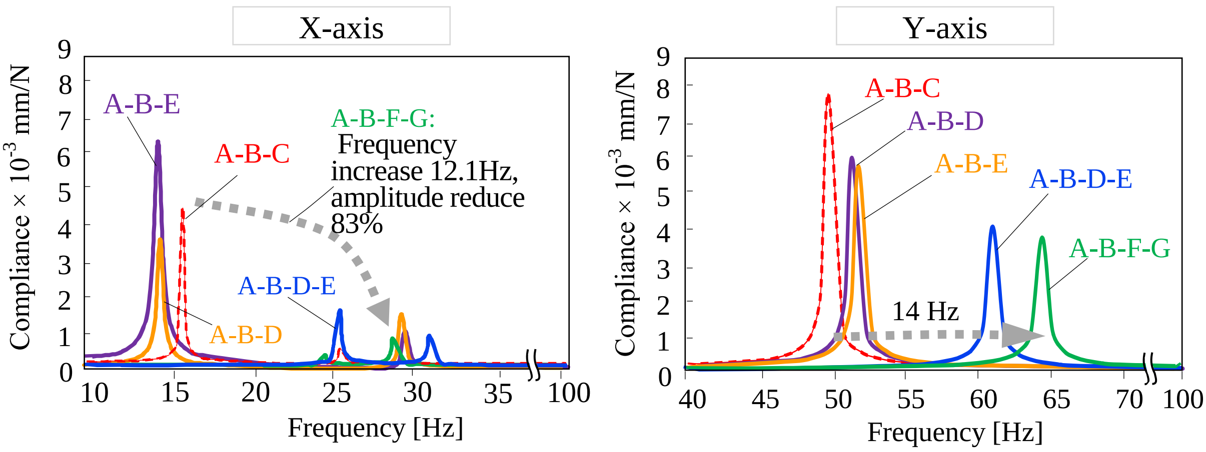


Fig. 5. Frequency response of the bench lathe from X-axis and Y-axis with different support positions

of amplitude is caused by addition of water which has low damping factor. Therefore, to suppress vibration amplitude caused by water, the research on improving damping characteristic of water was performed (will be explained later). In this research, the amount of water is limited to only 22 liters with consideration to the vessel size. Thus, the amount of 22 liters is considered sufficient to shift machine resonance along with 10 and 16 liters and will be used as one of control parameter throughout this research. Although the injection of water is an easy operation, very large effect can be achieved.

The result of FEM study for control factor II is showed in Fig. 3. In this study, machine resonant frequency is expected to be increased by adding reinforce frame on the weak part of machine structure. Here, the reinforced frame with thickness 12, 24 and 36mm are used. The various diameters of hole were also applied on the frame with objection to lighter frame weight; however the inclusion of holes were not affecting much on the change in resonant frequency. Therefore, only plain steel frame without hole was used. Base on the result of mode shapes on previous Fig. 1, the reinforcement was applied under the base of bench lathe motor. The result from vibration response shows that machine resonance shifted up when reinforcement was applied. The frame with thickness 12mm shifts frequency better than both 24 and 36mm. It should be noted that the shifts of frequency (as shows Fig. 9 of vibration response in Y-axis) should not match the second frequency of machine resonance, otherwise larger vibration will occur. Therefore, we consider that it is sufficient to increase frequency only between 1st and 2nd resonance. As 12mm frame shifts resonance better, therefore it is used as one of control parameter throughout this research.

The result of FEM study for control factor III is showed in Fig. 5. In this study, changes in the numbers and positions of pedal supporting bench lathe are considered can change machine resonance. Others supporting pedal were added with combination of A-B-D, A-B-E, A-B-D-E, A-B-F-G together with the original support position A-B-C as parameters for simulation (Table 1). The result shows that the more number of supporting pedals are used, frequency of resonance shifted greatly. By using different combinations of support points, resonant frequency can be shifted about 10Hz to 20Hz. It is also observed that the supporting machine near to the center of mass of the machine (A-B-F-G) has higher frequency than supports that far for center of mass of machine (A-B-D-E). The vibration amplitude reduces about 80% when the position of support pedals set to (A-B-F-G). However, all pedals combinations are effective in controlling machine resonance.

2.3. IMPROVEMENT OF THE DAMPING RATIO OF WATER MIX POLYMER

The experimental evaluation for the improvement of the damping ratio of water was performed. As mentioned earlier that water magnifies amplitude of vibration, the viscosity of water was increased to higher damping ratio. Here, water was mixed with polymer PEO (Polyethylene Oxide) and the degree of improvement in damping ratio was investigated by experiment. The experimental setup for measuring damping characteristic of water shows in Fig. 6. The steel pipe is filled with water mixed polymer PEO and hanged with wire in 100 mm from both sides of pipe. The central part of pipe is excited with impact hammer and the vibration response is measured by accelerometer that attached on the opposite side of the impact point. The damping ratio value is calculated from the excitation response. As it is difficult to stir the mixture of polymer and water with concentration larger than 6wt% in

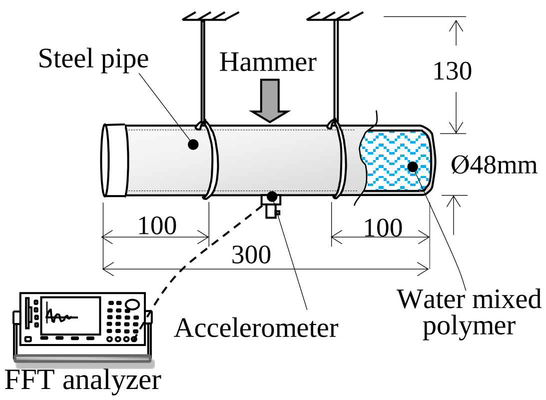


Fig. 6. Experimental setup for measuring damping ratio

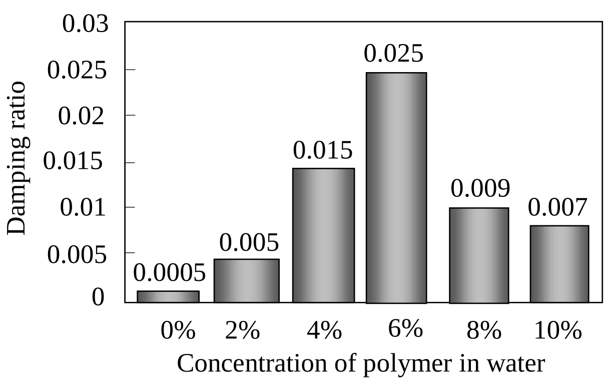


Fig. 7. The relationship between polymer percentage and the damping ratio

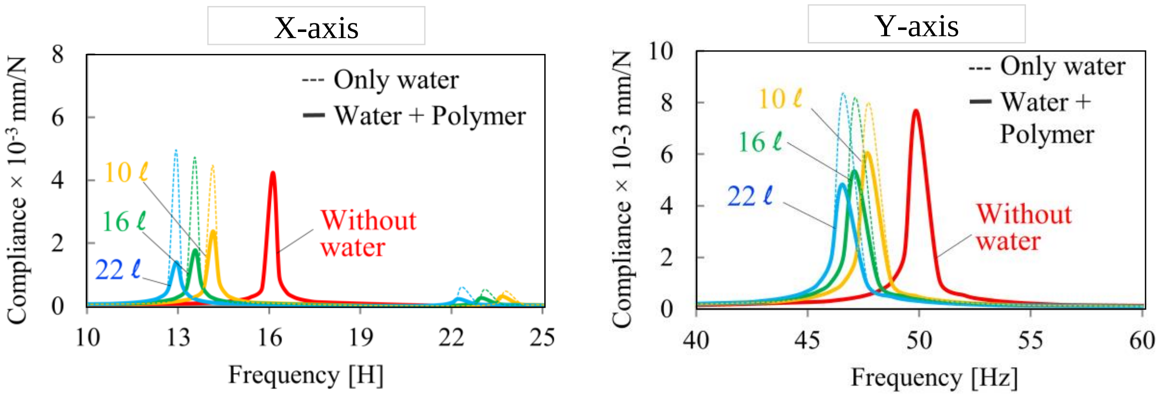


Fig. 8. Comparison of frequency response without polymer and with 6wt% polymer concentration

previous research [7], in this research, warm water was used. Warm water keeps the jelly staying soft for several minute before its viscosity increase, which make it easy for stirring. Therefore, the mixture for concentration of 8wt% and 10wt% were performed. Fig. 7 shows the relationship between percentage of polymer and damping ratio from measurement result. The measurement result shows that when the apparent density of the water is increased by mixing with polymer, the damping ratio increase. Therefore it is considered sufficient to lower resonant frequency and vibration amplitude. By increase polymer concentration, its effectiveness also increases however, since viscosity becomes higher, the injection and extraction becomes difficult and damping value also reduces when the polymer concentration is more than 6wt%. Thus, the concentration of 6wt% is used for further experiment in this research. Fig. 8 shows the comparison result of frequency response from FEM simulation study without using polymer and by using 6wt% polymer concentration. The result shows that by adding 6wt% polymer to the water, vibration amplitude can be reduced about 50% and considered effective to be used as machine resonance controller.

3. THE EXPERIMENTAL EVALUATION FOR CONTROL METHODS

The experiment was performed for evaluation of the control method. Fig. 9 shows the experimental setup of bench lathe machine. The bench lathe with specification shown in Table 2 was used for the application of proposed control methods and their effectiveness was evaluated. The accelerometers are placed on the headstock in X and Y directions with the output of accelerometers are connected to FFT analyzer for analyzing amplitude of vibration. Control parameters to control resonant frequency are shown in Table 3. Firstly, in control factor I, the vessel is installed on the headstock regarding to the previous FEM analysis results for injection of water into machine structure. The relationship between amplitude of vibration at headstock and spindle speed are measured by taking parameters of empty vessel, injecting water to the vessel with amount 10 liters, 16 liters, and 22 liters in headstock, and then injecting water mixed with 6wt% polymer PEO, respectively. Next, in the method to increase resonant frequency using control factor II by reinforcement to

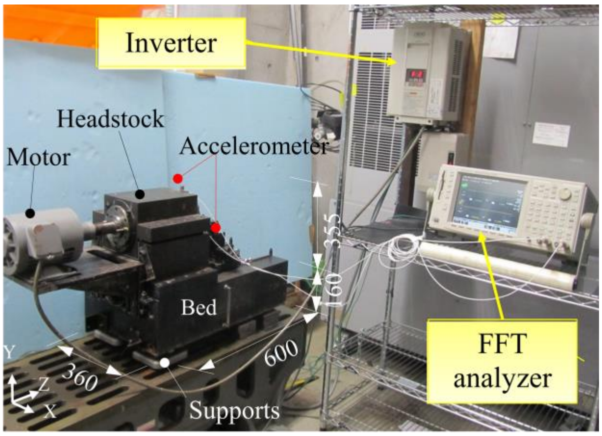
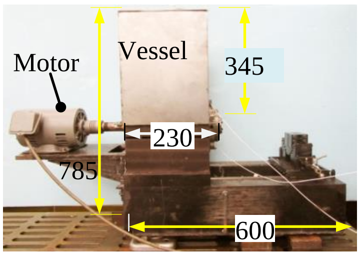
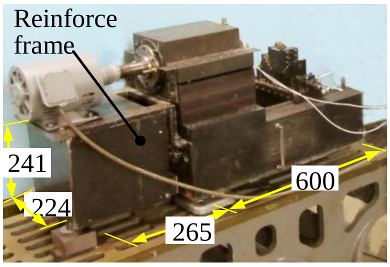
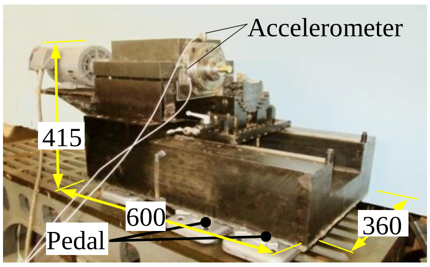
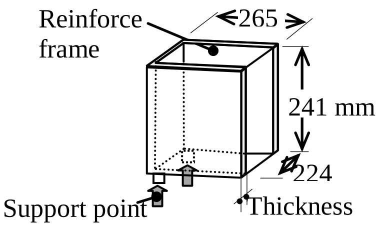
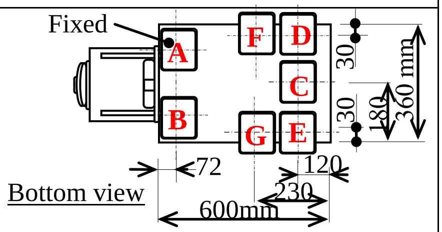


Fig. 9. Experimental set up and the model of bench lathe

Table 2. Specification of the bench lathe for experiment evaluation of proposed method

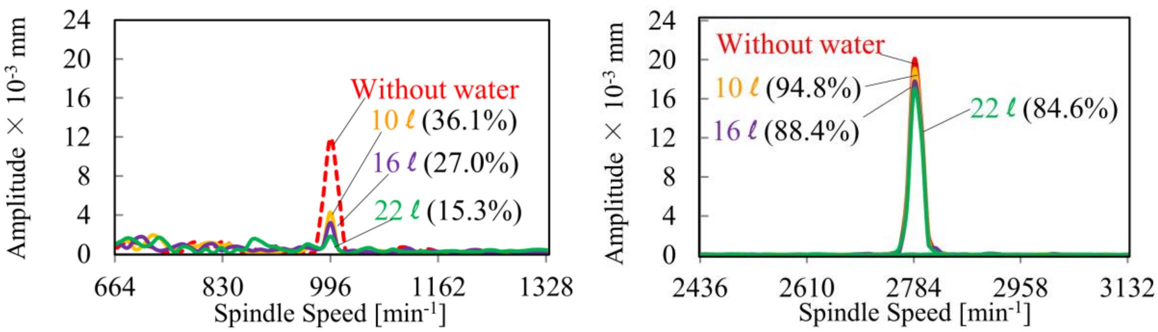
Head stock	Height of center from bed	177mm
	Height of center from floor	337mm
	Spindle speed	Max.3600min^{-1}
Bed	Size	600×360×160mm
Tool post	Stroke of Y axis	30mm
Table	Stroke of Z axis	200mm
Motor	Power	0.75kW
	Speed control	Inverter
Weight		200kg

Table 3. Experimental parameters for control factor I, II and III

Control factor I	Control factor II	Control factor III
		
Filled with water mix polymer with concentration 6wt% Countermeasures: Amount of water; (0, 10, 16, and 22 liters)	 Countermeasures: Thickness (12, 36mm)	 Countermeasures: Support position A-B-C, A-B-D, A-B-E, A-B-D-E, A-B-F-G

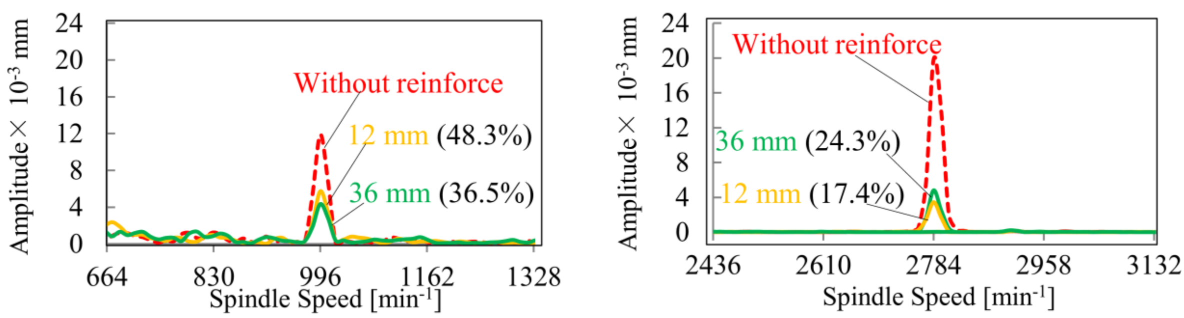
higher machine rigidity, parameters are taken using reinforce frame from steel plates with thickness 12mm and 36mm based on optimum result of FEM analysis. The frame is fitted and tightens with bolts under the table of bench lathe motor. The relationship between spindle speed and amplitude of vibration at the tip of headstock were measured. Lastly, in the method of changing pedal positions in machine to control resonant frequency and mode shapes in control factor III, the parameters are also decided based on result of FEM analysis. For this evaluation, 5 types of support combination are used as parameters. The measurement was done by evaluate vibration amplitude of spindle speed at headstock.

The evaluation result of controlling resonant frequency by injecting water mixed with polymer is shown in Fig. 10. The result shows that the amplitude of vibration without applying any countermeasure is higher at spindle speeds 996min^{-1} and 2784min^{-1}, respectively. However, after water mixed 6wt% polymer was injected, machine density increased and the resonant frequency becomes lower. With the increment of damping ratio, the amplitude of vibration at spindle speeds 996min^{-1} and 2784min^{-1} are suppressed to very small. Fig. 11 shows the evaluation result of resonant frequency control by reinforced machine structure. Here also, without applying any countermeasure, the result of vibration measurement of bench lathe shows that resonance is considered to be around 996min^{-1} and 2784min^{-1}. By reinforcing machine structure, the resonant frequency becomes higher. In addition, with high rigidity, amplitude of vibration near spindle speed 2784min^{-1} is suppressed to become extremely small. Moreover, amplitude of vibration in whole part is also small therefore this evaluation technique is very effective. Fig. 12 shows the evaluation result of resonant frequency control by changing position of supporting pedal. Here too, using main support combination A-B-C, large vibration occurs at bench lathe resonance around spindle speed 996min^{-1} and 2784min^{-1}. The measurement result shows that by changing supporting point, resonant frequency can be controlled and amplitude of vibration become extremely small which has big impact for machining accuracy.



(a) Vibration at X direction (b) Vibration at Y direction

Fig. 10. Relationship between the spindle speeds at machine resonance with the amplitude of vibration by injecting polymer



(a) Vibration at X direction (b) Vibration at Y direction

Fig. 11. Relationship between the spindle speeds at machine resonance with the amplitude of vibration by using reinforce frame

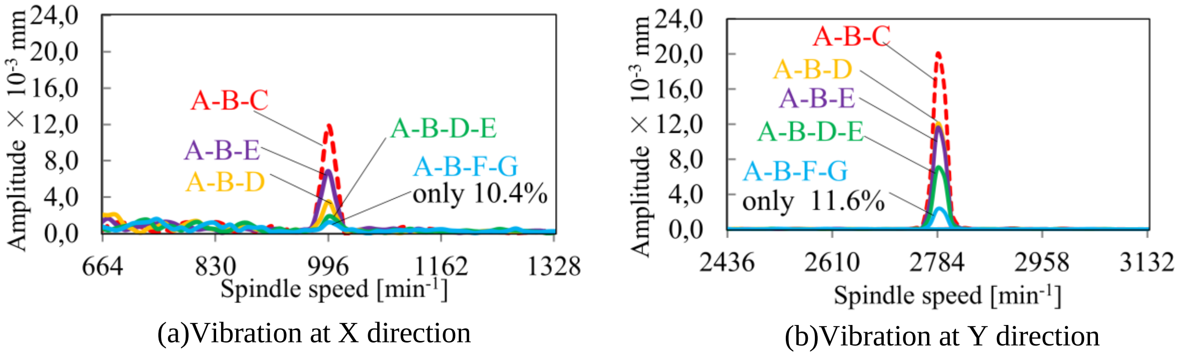


Fig. 12. Relationship between the spindle speeds at machine resonance with the amplitude of vibration by control of support positions

From the above experimental results, the optimum combinations between 3 control methods were evaluated and the results are shown in Table 4 with the measurement result of vibration amplitude on each spindle speed is shown in Fig. 13. The results show that amplitude of vibration became smaller compared to without control. Therefore, by using optimum combination of 3 control methods, resonance of the bench lathe can be effectively avoided.

Table 4. Optimum combination for three countermeasures

Spindle speed (min^{-1})	Control factor I	Control factor II	Control factor III
600	-	-	A-B-C
800	-	12mm	A-B-F-G
996	22 liters	-	A-B-C
1200	10 liters	-	A-B-D
1500	-	12mm	A-B-E
2000	10 liters	-	A-B-E
2500	22 liters	-	A-B-F-G
2784	16 liters	-	A-B-F-G
3000	-	12mm	A-B-D-E
3600	10 liters	-	A-B-C

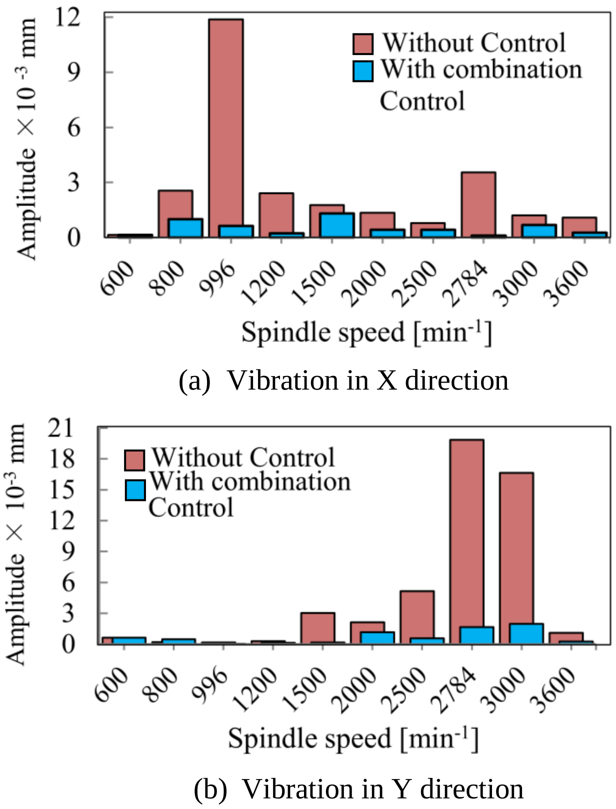


Fig. 13. Amplitude of vibration using three combination control (Experimental results)

4. EVALUATION OF PROPOSED METHODS BY REAL CUTTING

Finally, real cutting experiment was conducted using bench lathe to evaluate the effectiveness of proposed method. Cutting condition used in this experiment is shown in Table 5. The spindle speed 2784min^{-1} was selected to be used based on the calculation of optimum cutting condition. The control method used for cutting process based on Table 4 is by filled 16 liters of water mixed polymer and used support combination A-B-F-G. In addition, for the comparison, the same experiment is also performed using conventional setup without control method. The results of frequency response of bench lathe without control and with control are shown in Fig. 15. The results show machine resonance is shifted from 16.6Hz to 14.2Hz and vibration amplitude reduce about 96.9% in X-axis, while resonance shifts from 46.4Hz to 51.2Hz and amplitude reduces to about 91.6 % in Y axis. Generally, when spindle speed coincides with machine resonance, operation with this cutting speed is difficult to perform because of the large vibration. However, by controlling resonant frequency using our proposed controlling method, resonance phenomenon can be avoided and large oscillation can be suppressed. Moreover, the result of surface roughness measured after cutting (Fig. 16) shows the surface roughness improve about 80% when applying our proposed method of controlling machine resonant frequency. Although a conventional small bench lathe was used, the surface roughness was improved and the smoothness of surface finishing was obtained. Thus, it can be summarized that our proposed control techniques are effective in changing machine resonance and maintained the used of optimum cutting condition. In addition, high quality processing becomes much easier to achieve without further machining.

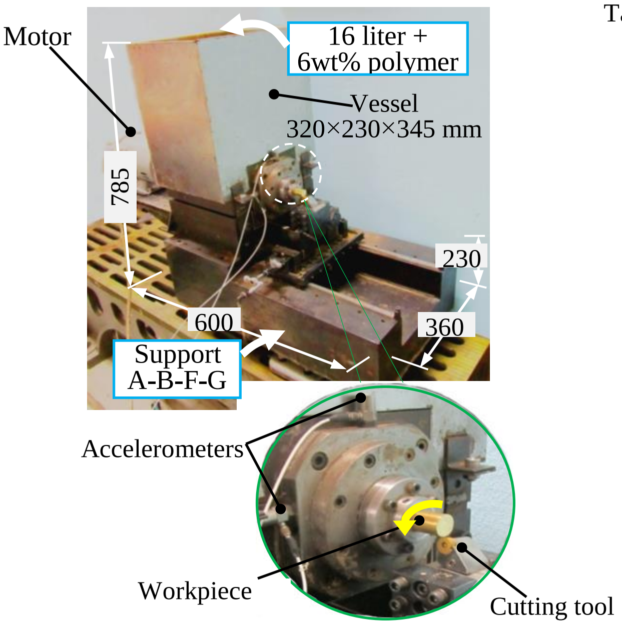
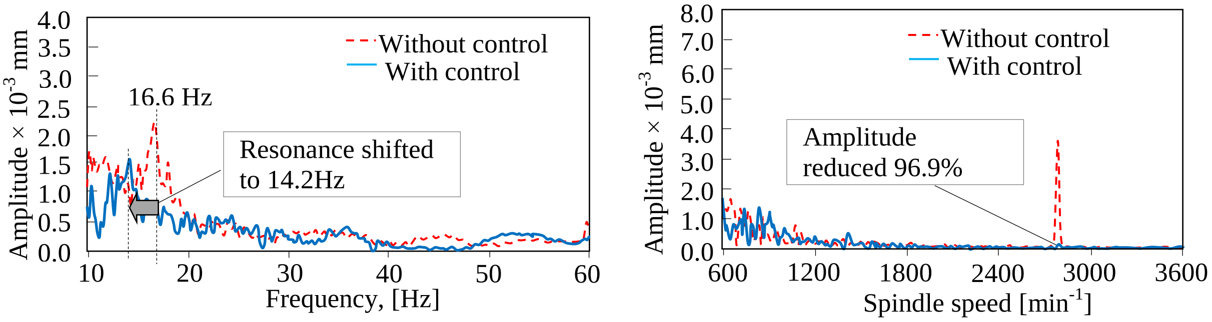


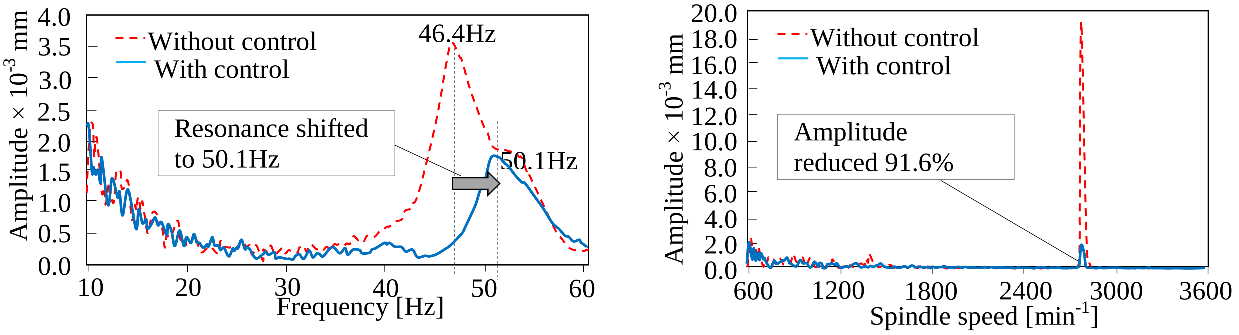
Fig. 14. Photograph of experimental setup for real cutting

Table 5. Cutting condition for evaluation of proposed method

Cutting speed		158m/min
Feed speed		0.1mm/rev
Spindle speed		2784min^{-1}
Cutting depth		0.2mm
Tool	Material	Carbide, T725X
	Type	Round
	Nose radius	6mm
Workpiece		Brass, Ø18 ×40mm
Control of resonance frequency	Density	16 liter
	Stiffness	-
	Support	A-B-F-G



(a). Frequency response by impact test (Right) and vibration amplitude operated at 2784min^{-1} (Left) in X-axis



(b). Frequency response by impact test (Right) and vibration amplitude operated at 2784min^{-1} (Left) in Y-axis

Fig. 15. Measurement result of frequency response of the bench lathe with control of machine resonance

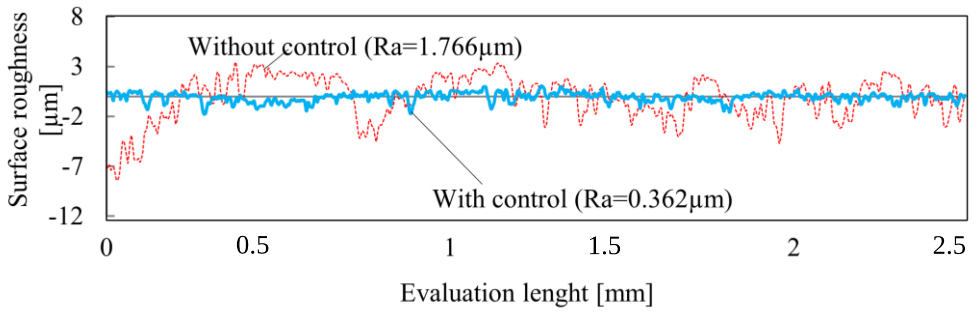


Fig. 16. Comparison of surface roughness after cutting using proposed control technique

5. CONCLUSION

From the above results, it is confirmed that the developed technique regarding changing machine tool resonance is capable to maintain and optimize the used of cutting condition during machining in resonance zone. The new results for damping ratio of water mixed polymer with concentration 8wt% and 10wt% are presented. Although both mixing concentration have lower damping value than the existing 6wt%, it is proven that 6wt% mixing concentration is the optimum concentration for vibration suppression. By injecting jelly-like water at concentration of 6wt%, amplitude of vibration suppressed about 96.9% and 91.6% in horizontal and vertical direction, respectively. By controlling machine tool resonance frequency enable cutting speed to be used for processing at its optimum cutting condition which improves final surface roughness.

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