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Experimental Analysis of Vibration Reduction of Boring Bar with Tapered Mass-Rubber Dynamic Vibration Absorber (MR-DVA) †

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Abstract: One of the machining processes that can be performed on a lathe machine is the boring process, which is used to enlarge holes in a workpiece using a cutting tool called a boring bar. During the boring process, excessive vibration or chatter occurs, which can significantly degrade the surface quality of the workpiece. To reduce these vibrations, a system called the Mass-Rubber Dynamic Vibration Absorber (MR-DVA) is used. A tapered MR-DVA is used, and it is located on the cavity of the customized boring bar. The absorber mass is made of brass, and the absorber stiffness is made of natural rubber. The MR-DVA is designed with various dimension ratios: 10/21, 14/21, and 16/21. The boring bar designed consists of a regular boring bar and a customized boring bar (with MR-DVA) with a diameter of 32 mm and a length-to-diameter (L/D) ratio of 7. The experiment was carried out with variations in cutting parameters such as the cutting speed, feed rate, and depth of cut as well as the variations in the taper ratio of the MR-DVA. The experiment shows that a customized boring bar with a tapered MR-DVA can reduce vibration, and the combination of variation that is optimal to reduce vibration is a customized boring bar with a taper ratio of 14/21. With the obtained optimal parameters for reducing vibrations, the manufacturing efficiency and product quality will be enhanced.

Keywords: dynamic vibration absorber; taper ratio; tapered

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1. Introduction

The manufacturing industry is inseparable from machining processes, which create workpieces using machine tools to produce the desired finished products. A commonly used machine tool is the lathe with the machining process known as boring. The boring process is a machining process used to remove material from the inner surface of a rotating specimen, typically producing machine parts or finished products with cylindrical shapes [1]. During the boring process, the boring bar and the workpiece come into contact and generate vibrations [1,2]; vibrations from the driving motor are also transmitted. These vibrations can degrade the surface quality of the workpiece and reduce the productivity of the lathe [2]. Vibrations in the boring bar can be reduced by adding a dynamic vibration absorber (DVA) system [3]. The DVA is a mechanical device that is used to reduce unwanted vibration, which can be added to the main system [4].

One such type of DVA is the damped DVA, which consists of an additional system (absorber mass) attached to the main system, forming a two-degree-of-freedom system with two natural frequencies. The damped DVA reduces response further and broadens the damping range. Pachpute [5] found that vibration reduction is influenced by three main parameters: the mass ratio (μ), damping ratio (ζ) and frequency ratio (f). Suryandari

et al. [6] analyzed the vibration response and reduction of vibration in the milling process by adding a DVA with a mass-rubber system. Based on the simulation results, it was found that the addition of an MR-DVA could reduce vibration by up to 92%. The DVA has been used in various machining processes, especially in boring bars, under different conditions such as cutting parameters, dimensions, workpiece characteristics, and the system of DVA, to achieve the best vibration damping performance suitable for a wide range of working conditions [7–10]. This addition of DVA can expand the frequency range that the boring bar can operate stably, thereby enhancing the stability and performance of the boring bar. A simulation was conducted by designing the boring bars with a passive DVA mechanism with variable stiffness by varying the amount of rubber to minimize vibrations [11]. The results of this research identified the natural rubber effect, the dynamic response of boring bars with the proper placement and the amount to maintain stability under various cutting parameters.

In addition to changing the material, dimensions, and structure of the boring bar, the shape and dimension of the DVA have an impact on vibration reduction. Zhang et al. [12] analyzed the chatter stability and natural frequency of a tapered composite boring bar. Tapered boring bars show higher stiffness than uniform boring bars. The results of this study show that a smaller ratio taper and L/D will affect a higher natural frequency and chatter stability. The taper model is also analyzed in the modeling of the spindle-holder taper joint [13] to predict stiffness and stress distribution. It was found that the deformation is non-uniform and the surface stress is non-linear along the axial direction. Both simulation and experiments with variations in cutting parameters are commonly used to observe the effects on vibration response or chatter frequency. Obinna et al. [14] analyzed the mathematical model with an experiment to predict the chatter frequency's equation in the turning process. The experiment conducted showed that varying the feed rate, cutting speed, and depth of cut influence the chatter vibration frequency.

In this research, a tapered MR-DVA system is added at the front part of the customized boring bar to reduce vibration in the boring process in the y, z, and x-axis directions. The stiffness of the tapered MR-DVA was made of brass and then covered with the stiffness of the MR-DVA made of natural rubber. Experiments were conducted to determine the significant effect of the cutting parameters, the variation in the MR-DVA taper ratio and the combination of both variations in reducing vibration in boring processes.

2. Research Method

In this experiment, two types of boring bars were used: a regular boring bar and a customized boring bar with a tapered MR-DVA mounted at the cavity in the front of the boring bar. The boring bar that is used mainly consists of (1) a boring bar and (2) a tapered MR-DVA, as shown in Figure 1. Regular and customized boring bars have a diameter of 32 mm and an overall length of 256 mm, so the L/D ratio is 7. Boring bars are made of AISI 1045 material, which is commonly used in components that frequently experience friction or pressure, requiring good wear resistance. The insert made of carbide TCMT 16 was used, which has high hardness considering the workpiece material being used. The tapered MR-DVA consists of two components: (1) stiffness made of natural rubber and (2) mass made of brass. The MR-DVA had an overall larger diameter of 21 mm and variations in the overall smaller diameters of 10, 14, and 16 mm. The lengths of the MR-DVA were also varied, namely 18, 24, and 30 mm, so the taper ratios of the MR-DVA are 10/21, 14/21, and 16/21. The mass of the MR-DVA will be covered by natural rubber with a thickness of 2.5 mm, and the shape of the tapered MR-DVA is shown in Figure 2. The workpiece material is AISI 4340, the length of the workpiece is 60 mm, the outer diameter is 60 mm, and the inner diameter is 40 mm.

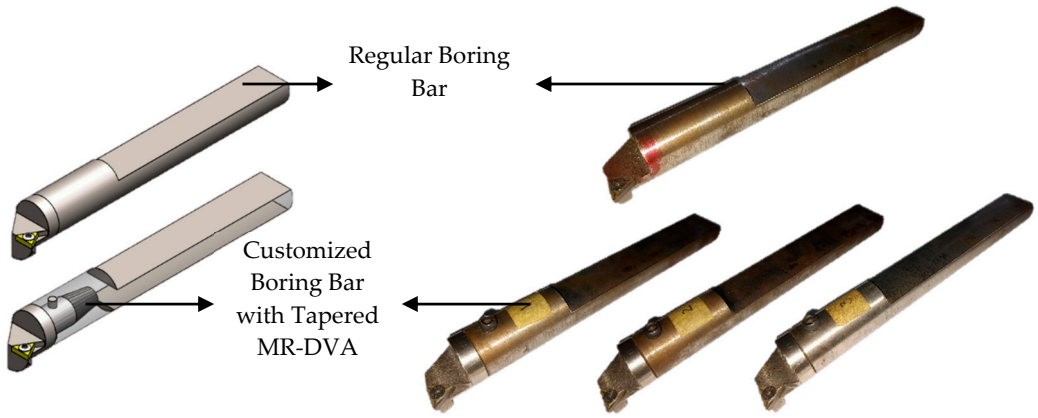


Figure 1. (**a**) Structure of the regular and customized boring bar; (**b**) Regular and customized boring bar for experiment.



Figure 2. Tapered MR-DVA with taper ratio of (**a**) 10/21; (**b**) 14/21; (**c**) 16/21; and (**d**) thickness of rubber.

In the main system, a customized boring bar can be modeled as a 2 degree-of-freedom system. In the boring process, when the excitation force was delivered, the edge of the insert boring bar was analyzed with three forces: namely, tangential or cutting force F_c, radial force F_r, and thrust force F_t, as shown in Figure 3. In the experiment, 6 variations of cutting parameters were tested. The spindle speed was varied at 3 levels, the feed rate was varied at 2 levels, and the depth of cut was constant. From the discussion [14], a higher value of feed rate (f) and depth of cut (d) causes an increase in vibration response, while a higher spindle speed (N) causes a decrease in vibration response. This study aims to analyze the effect of cutting parameters, the variation in the taper ratio of the MR-DVA, and the combination of both variations in reducing vibration in boring bars. The cutting parameters used for the experiment are shown in Table 1.

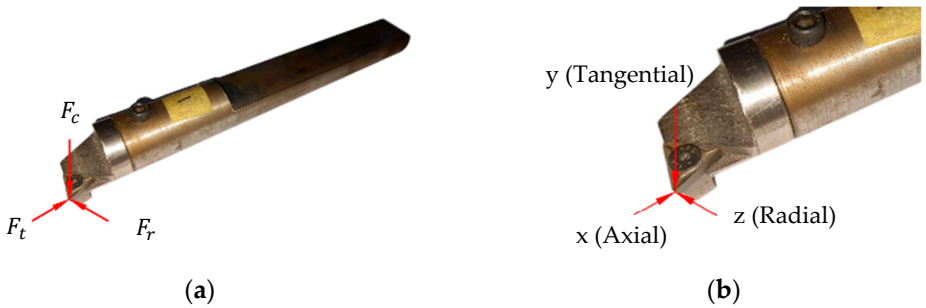


Figure 3. (**a**) Forces on the tip insert of boring bars; (**b**) axes on the tip insert boring bars.

Table 1. Cutting parameters.

Cutting Parameter	Level 1	Level 2	Level 3
Spindle speed N (rpm)	320	450	720
Feed rate f (mm/rev)	0.06	0.10	
Depth of cut d (mm)	0.20		

For the boring experiment, the Horizontal Lathe Machine CDL 6241 was used. The experimental setup is shown in Figure 4: (**a**): 1. Spindle (with a chuck), 2. Workpiece, 3. Boring bar, 4. Accelerometer vibration probe (x), 5. Accelerometer vibration probe (z), 6. Accelerometer vibration probe (y), 7. Tool post; and for (**b**): 8. Oscilloscope, 9. Oscilloscope cable connecting, 10. Cable accelerometer vibration probe, and 11. Accelerometer power supply. During the experimental conditions, the boring bar was clamped to the tool post and the workpiece was clamped to the spindle (with a chuck). Furthermore, in order to measure the time and voltage values of boring bars, the oscilloscope (Tektronix TBS1104 C011376, TEKTRONIX INC, Beaverton, OR, USA) was used. After the experiment, the vibration reduction of boring bars was observed by changing the cutting parameter and taper ratio of the MR-DVA.



(**a**) (**b**)

Figure 4. Experimental setup for boring bars: (**a**) experimental equipment; (**b**) experimental equipment for measurement.

3. Results and Discussion

The experiment is run with the output of reduction vibration and RMS value of the boring bar in the direction of the y-axis (tangential), z-axis (radial), and x-axis (axial).

3.1. Vibration Response of Regular Boring Bar

Figure 5 shows the dynamic vibration response of a regular boring bar with variations of cutting parameters for the y, z, and x-axis directions. It shows that for all variations of cutting parameters, the y-axis has the highest acceleration response value, which was followed by the z-axis and then the x-axis. This phenomenon is aligned with the discussion that cutting force F_c and radial force F_r have a greater effect compared to the thrust force F_t so that the response of the boring bar does not cause significant deflection. Furthermore, the RMS value that represents the vibration response on each axis has different values, as shown in Table 2, with the y-axis having the highest value. The highest vibration response on the y-axis was obtained at the cutting parameter with a spindle speed of 450 rpm, which decreased at the spindle speeds of 320 and 720 rpm. Based on these values, it can be concluded that the vibration response on the y-axis decreases as the spindle speed (N) increases. Likewise, for the z and x-axis, the vibration response follows the same trend as the y-axis, decreasing with the increase in spindle speed (N). The variation in feed rate

(*f*) also generates a different vibration response. The vibration response with a feed rate of 0.10 mm is higher than the vibration response for a feed rate of 0.06 mm. On the z and x-axes, the vibration response follows the same pattern as the y-axis. This vibration response trend is affected by variations in the cutting parameters, such that higher values of feed rate (*f*) and depth of cut (*d*) cause an increase in the vibration response, while a higher spindle speed (*N*) causes a decrease in the vibration response.

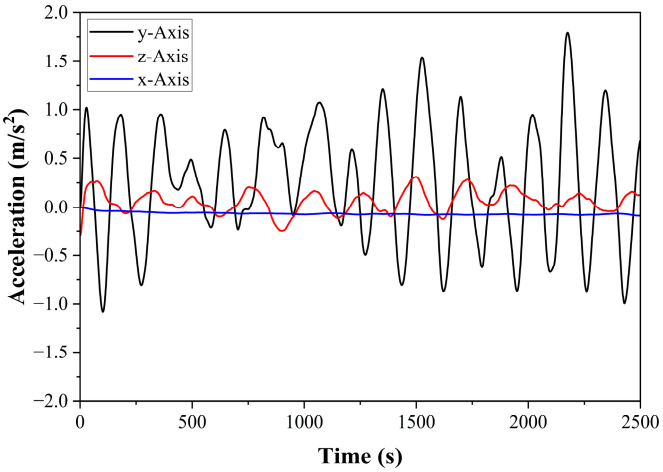


Figure 5. Vibration response of regular boring bar on cutting parameter A32012.

Table 2. RMS of regular boring bar.

Variation	*N* (rpm)	*f* (mm/rev)	*d* (mm)	Vibration Response ($\frac{m}{s^2}$)		
				y-Axis	z-Axis	x-Axis
A32062	320	0.06	0.20	0.46104	0.13511	0.17131
A32012	320	0.10	0.20	0.65511	0.12561	0.06847
A45062	450	0.06	0.20	0.47596	0.12245	0.06013
A45012	450	0.10	0.20	0.79046	0.16587	0.0134
A72062	720	0.06	0.20	0.38225	0.07774	0.03163
A72012	720	0.10	0.20	0.61882	0.07325	0.00879

3.2. Vibration Response of Customized Boring Bar

The dynamic vibration response of a customized boring bar with variations in the cutting parameter and taper ratio for the y, z, and x-axis direction is shown in Figure 6. For both variations, the y-axis has the highest value, which is followed by the z and x-axis. The RMS value, for variations in the cutting parameter and vibration response on the y, z, and x-axes, decreases as the spindle speed (*N*) increases. The variation in feed rate (*f*) causes the vibration response to decrease as the feed rate (*f*) decreases. This vibration response trend aligns with the discussion that higher values of feed rate (*f*) and depth of cut (*d*) cause an increase in the vibration response, while the higher spindle speed (*N*) causes a decrease in the vibration response. The vibration response resulting from variations in the taper ratio causes different trendlines for the y, z, and x-axes in each variation. Based on the RMS values on the y-axis, the lowest vibration response occurs at the cutting parameter of spindle speed = 720 rpm, feed rate = 0.06 mm/rev, and depth of cut = 0.20 mm with a taper ratio of 16/21. The RMS value of the customized boring bar on various taper ratios is shown in Table 3.

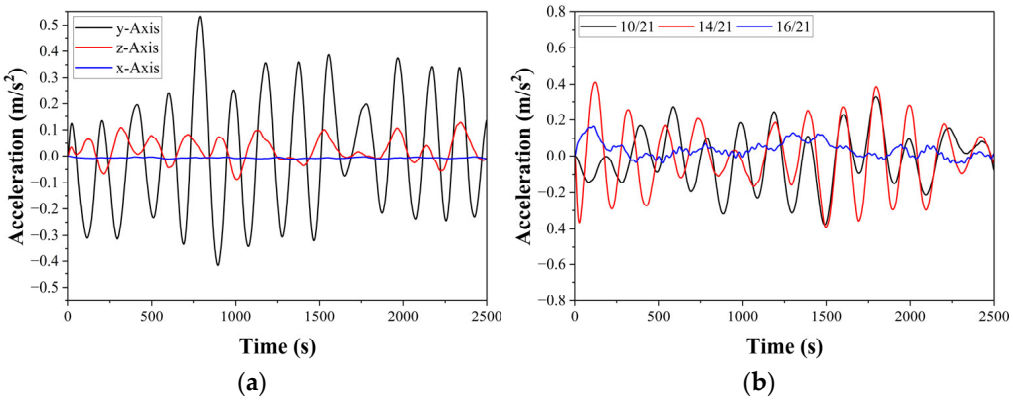


Figure 6. Vibration response of customized boring bars to variation in (**a**) the cutting parameter in a taper ratio of 10/21; (**b**) taper ratio in cutting parameter A72062 on the y-axis.

Table 3. RMS of customized boring bar.

No	Taper Ratio	Variation	Vibration Response ($\frac{m}{s^2}$)		
			y-Axis	z-Axis	x-Axis
1	10/21	A32012	0.21603	0.05154	0.00768
2		A32062	0.12115	0.04424	0.00903
3		A45012	0.09078	0.02150	0.00978
4		A45062	0.08737	0.02950	0.00825
5		A72012	0.11836	0.07039	0.00428
6		A72062	0.08857	0.03451	0.00746
7	14/21	A32012	0.14270	0.07448	0.00674
8		A32062	0.15620	0.07252	0.00014
9		A45012	0.11063	0.02305	0.00509
10		A45062	0.08962	0.02758	0.00353
11		A72012	0.13315	0.03038	0.00834
12		A72062	0.10986	0.02518	0.00652
13	16/21	A32012	0.30014	0.03054	0.05032
14		A32062	0.15024	0.02717	0.01128
15		A45012	0.10338	0.04719	0.02177
16		A45062	0.18024	0.03156	0.03266
17		A72012	0.14110	0.05091	0.00887
18		A72062	0.05605	0.01689	0.04782

3.3. Vibration Reduction of Boring Bar with Variations of Taper Ratio

The vibration reduction is performed by comparing the RMS values of the regular boring bar with the customized boring bar. In Figure 7, it can be seen that the green line represents the vibration response of a regular boring bar, while the black, red, and blue lines represent the vibration responses of the customized boring bar with variations in the taper ratio. The graph shows that the regular boring bar had a large amplitude during the experiment, which then decreased when the MR-DVA was added. Table 4 shows that all three taper ratios can reduce vibration at the same cutting parameters and across the three axes. For example, at the cutting parameter A45062, all axes successfully reduced the vibration with an average reduction of 84.26%. The highest reduction of 99.92% occurred in variation A32062 with a taper ratio of 14/21 on the x-axis, while the lowest reduction was seen with the taper ratio of 16/21 on the x-axis.

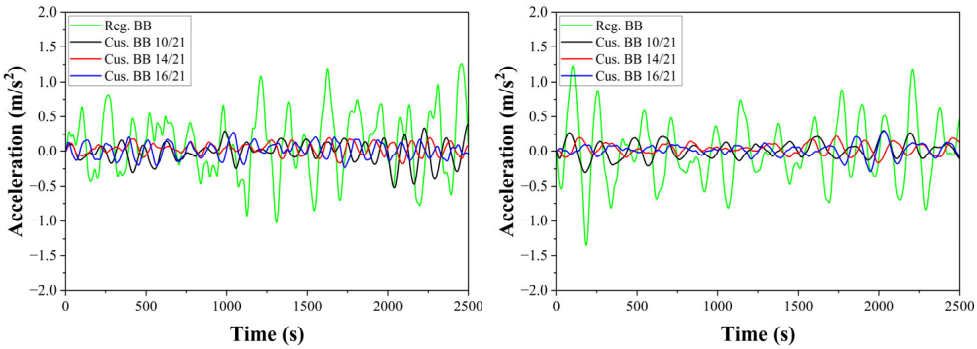


Figure 7. Reduction vibration of boring bar with variations of taper ratio in the lowest and highest reduction.

Table 4. Reduction vibration.

No	Taper Ratio	Variation	Reduction (%)		
			y-Axis	z-Axis	x-Axis
1	10/21	A32012	67.02	58.97	88.78
2		A32062	73.72	67.26	94.73
3		A45012	88.52	87.04	27.06
4		A45062	81.64	75.91	86.27
5		A72012	80.87	3.89	51.29
6		A72062	76.83	55.61	76.43
7	14/21	A32012	78.22	40.71	90.16
8		A32062	66.12	46.32	99.92
9		A45012	86.00	86.10	62.06
10		A45062	81.17	77.48	94.13
11		A72012	78.48	58.52	5.06
12		A72062	71.26	67.61	79.38
13	16/21	A32012	54.18	75.69	26.50
14		A32062	67.41	79.89	93.41
15		A45012	86.92	71.55	−62.42
16		A45062	62.13	74.22	45.68
17		A72012	77.20	30.50	−0.96
18		A72062	85.34	78.27	−51.15

4. Conclusions

In this study, the significant influence of the cutting parameters and taper ratio of the MR-DVA on the vibration response and vibration reduction was observed. The effect of cutting parameters was analyzed under various machining conditions with different spindle speeds, feed rates, depths of cut, and taper ratios. The vibration responses are affected by variations in the cutting parameters, which show that a higher feed rate (f) and depth of cut (d) cause an increase in the vibration response, while a higher spindle speed (N) decreases it. The optimal reduction occurred at the taper ratio of 14/21 with cutting parameter A45062, as it evenly reduced vibrations across all three axes. The highest reduction was observed at a taper ratio of 14/21 with cutting parameters of A32062 on the x-axis, while the lowest reduction occurred at a taper ratio of 16/21 with cutting parameters of A45012 on the x-axis.

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