Vibration control in boring process using a constrained viscoelastic layer damper

V.Vishal Krishna¹, S.Saravanamurugan², P. Sanjeev Kishore³, K.J.Yedhu⁴, Goutham K Iswar⁵, A.Shanmughasundaram⁶*

¹,³,⁴ & ⁵ Under Graduate Student, ² & ⁶ Assistant Professor
Department of Mechanical Engineering, Amrita School of Engineering, Coimbatore
Amrita Vishwa Vidyapeetham, India
E-mail: a_shanmugasundaram@cb.amrita.edu

Abstract A passive vibration control method is adopted to control vibrations of a boring bar. A viscoelastic layer sandwiched between main steel boring bar and aluminium tube, known to be constrained viscoelastic layer damper (CVLD), is designed and developed in order to reduce the vibration produced during the machining operations. The low density aluminium tube and natural rubber as viscoelastic layer are used in the boring bar to increase its natural frequency and damping property respectively. The finite element simulation of boring bar with and without CVLD are carried out using ANSYS and the results are used to develop a model to predict the influence of thickness of viscoelastic layer and aluminium tube on natural frequency of boring bar using full factorial design of experiments (DOE) and regression analysis. The DOE and regression analysis, carried using Minitab package, provides optimum thickness of viscoelastic layer and aluminium tube. These optimum thickness values are used to fabricate CVLD and its effectiveness to control boring bar vibration is tested by conducting machining experiments. The surface roughness of the machined components is also measured and the results show that the boring bar with CVLD is more efficient than conventional boring bar in controlling vibrations during machining. Moreover, stability lobes, which are plots of spindle speed vs. depth of cut of a machining process, are also constructed. Stability lobes indicate that the machining stability may be improved by 15 % by using boring bar with CVLD.

Nomenclature

| Symbol | Description |
|--------|-------------|
| δ      | Deflection  |
| K      | stiffness   |
| ωₙ    | Natural Frequency |
| ξ      | Damping ratio |
| I      | Area moment of inertia |
| E      | Young’s Modulus |
| L      | Length of the boring bar |
| F      | Force at the endpoint |
| ρ      | Density |
| FEM    | Finite Element Method |
| CLD    | Constrained Layer Damper |
| DOC    | Depth of Cut |
| FRF    | Frequency response function |
1 Introduction

The vibrations between the boring tool and work piece alter the magnitude of machining forces that lead to a self-excited vibration known as regenerative chatter. The regenerative chatter causes instability during boring process. This form of instability can damage the cutting tool and deteriorates the surface of the work piece [1]. Passive vibration control methods such as attachment of vibration absorbers and addition of damping using constrained layer dampers can be adopted to control regenerative chatter in boring process. The use of Constrained Viscoelastic Layer Damper (CVLD) is a passive method of controlling vibration. It involves a damping material, such as viscoelastic layer, placed between two elastic materials that normally have very low damping [2] & [3]. Tuned mass dampers, made of constrained viscoelastic dampers, were used to control regenerative chatter in machining processes [4] & [5]. Carbon fibre epoxy composite was used to fabricate a rotating boring bar and optimum geometry of the boring bar was found using experimental studies [6]. Damping coating using nano composite materials was applied to boring to improve chatter stability [7]. Constrained layer damping tool holder was developed to control chatter in end milling process by improving the dynamic stiffness of the end mill cutter [8]. Constrained layer damper was added to boring bar to improve machining stability of boring process. Beam theory and finite element simulations were used to optimize the constrained layer damper [9]. Finite element model of three layer composite bar consisting of viscoelastic layers was described to estimate the modal damping ratio [10]. Constrained layer damper was applied to thin walled member during milling process and the experimental results showed the improvement in surface finish [11]. The influence of chatter frequency on machining dynamics of boring bar with constrained layer damper was studied [12]. Chatter stability in boring process was analyzed by plotting stability lobes. Constrained layer damper was added with conventional boring bar to control regenerative chatter [13]. Chatter stability in deep hole boring process was analyzed. Constrained layer damper was used to improve the chatter resistance of a slender boring bar [14]. In this work, a ring type constrained viscoelastic damper is used to control machining vibrations in boring process.

2 Hollowing of boring bar

In order to place a ring type CVLD, a hole is drilled in boring bar. The removal of material increases the natural frequency and deflection of the boring bar whereas the stiffness is reduced. The variations of stiffness, deflection and natural frequency with inner diameter of the hole of boring bar are plotted as shown in fig-1, 2 & 3. Stiffness is calculated theoretically from the formula [12]:

\[
K = \frac{2EI}{L^2}
\]

(1)

where \(K\) = Stiffness of bar, \(E\) = Young’s modulus of the bar, \(I\) = Moment of Inertia, \(L\) = overhang length of the bar.

\[
I = \frac{\pi(d_1^4 - d_2^4)}{64}
\]

(2)

where \(d_1\) = Outer diameter of boring bar, \(d_2\) = Inner diameter of boring bar.

Deflection is calculated theoretically using the formula [12]:

\[
\delta = \frac{FL^3}{3EI}
\]

(3)

where \(F\) = Force on the boring bar, \(E\) = Young’s modulus of the bar, \(I\) = Moment of Inertia, \(L\) = overhang length of the bar.
From the Fig 1, 2 & 3, it is inferred that natural frequency increases steadily due to the reduction in stiffness and mass where the latter plays a major role. Also, steady increase in deflection is found. The inner diameter and outer diameter of boring bar is fixed to be 20mm and 40mm respectively. The 10% reduction in stiffness is compensated by adding CVLD which also enhance the damping. The boring bar dimensions used in this study are given in the table-1.

**Table 1 Boring bar dimensions**

| Attribute | Quantity  |
|-----------|-----------|
| Diameter  | 40mm      |
| Length    | 300mm     |
| Material  | Hardened steel |

The bar was modelled in ANSYS APDL software with the above dimensions. The material properties of boring bar and CVLD are given in table 2:

**Table 2 Material properties**

| Properties       | Steel     | Rubber    | Aluminium |
|------------------|-----------|-----------|-----------|
| Young’s Modulus  | 210 GPa   | 0.001 GPa | 71.7 GPa  |
| Density          | 7850 kg/m^3 | 900 kg/m^3 | 2810 kg/m^3 |
| Poisson’s Ratio  | 0.3       | 0.47      | 0.33      |
Finite element Mesh of boring bar in ANSYS with loads and results

The meshed finite element model of the boring bar is shown in Fig-4. Static and modal analyses are used to find deflection and natural frequency of boring bar with CVLD respectively. For static analysis, the cutting force of magnitude 1350 N is used [14]. Finite element simulations are carried out by increasing the inner diameter of the boring bar from 0mm to 20mm with the step of 5mm. Two other combinations of material used to make CVLD are given in the table 3 and 4.

**Table 3** Materials used in finite element simulation

| Viscoelastic material      | Elastic Material |
|---------------------------|------------------|
| Rubber                    | Aluminium        |
| Foamed-Aluminium-material (FAM) | Carbide          |
|                           | YG20C            |

**Table 4** Material properties

| Material | Density | Young’s modulus | Poisson’s ratio |
|----------|---------|-----------------|-----------------|
| FAM      | 650 kg/m³ | 12 GPa          | 0.33            |
| YG20C    | 13400 kg/m³ | 400 GPa        | 0.3             |
| Carbide  | 12180 kg/m³ | 606.7 GPa      | 0.3             |

Using ANSYS APDL, three hollow cylinders are constructed and they are glued together in the order of boring bar material as outer layer, viscoelastic layer as middle layer and elastic material as inner layer. The results of natural frequency and deflection for different thickness values of rubber and metal layer are used in Design of Experiments (DOE) to find the optimum geometry of CVLD to control regenerative chatter in boring process.

### 3 Design of experiments

Design of experiments is performed to determine the variation of natural frequency and static deflection with thickness of both the viscoelastic and elastic layers. Minitab software is used to perform DOE and it basically works on statistical background. Each factor has 4 levels and there are totally 16 experiments. The Minitab randomizes these experiments and provides the thickness to be varied. The combinations obtained through full factorial method are given in the table 5. ANSYS results are exported to Minitab to carry out the statistical analysis and the results are plotted as shown in fig 5. With regression analysis, the optimum thickness of viscoelastic layer and elastic layer are found.

**Figure 5** Interaction Plots of the natural frequency and deflection of MS-rubber –Aluminium combination.
The interaction plots, obtained from regression analysis, represent the variation of natural frequency and deflection trends with thickness of rubber and aluminium. It is found that there is a steady decrease in natural frequency with increase in thickness and marginal change in deflection exists with changes in thicknesses.

**Table 5** Design using full factorial Method

| t1 (mm) | t2 (mm) | Natural Frequency (Hz) | Deflection (m) |
|---------|---------|------------------------|----------------|
| 0.4     | 1.2     | 523.425248             | 0.000271       |
| 0.4     | 2.4     | 518.948288             | 0.000268       |
| 0.4     | 3.6     | 515.133728             | 0.000266       |
| 0.4     | 4.8     | 511.981568             | 0.000263       |
| 0.4     | 6       | 509.491808             | 0.000261       |
| 0.8     | 1.2     | 522.597312             | 0.000271       |
| 0.8     | 2.4     | 518.272992             | 0.000268       |
| 0.8     | 3.6     | 514.611072             | 0.000266       |
| 0.8     | 4.8     | 511.611552             | 0.000263       |
| 0.8     | 6       | 509.274432             | 0.000261       |
| 1.2     | 1.2     | 521.840192             | 0.000271       |
| 1.2     | 2.4     | 517.668512             | 0.000268       |
| 1.2     | 3.6     | 514.159232             | 0.000266       |
| 1.2     | 4.8     | 511.312352             | 0.000263       |
| 1.2     | 6       | 509.127872             | 0.000261       |
| 1.6     | 1.2     | 521.153888             | 0.000271       |
| 1.6     | 2.4     | 517.134848             | 0.000268       |
| 1.6     | 3.6     | 513.778208             | 0.000266       |
| 1.6     | 4.8     | 511.083968             | 0.000263       |
| 1.6     | 6       | 509.052128             | 0.000261       |
| 2       | 1.2     | 520.5384               | 0.000271       |
| 2       | 2.4     | 516.672                | 0.000268       |
| 2       | 3.6     | 513.468                | 0.000266       |
| 2       | 4.8     | 510.9264               | 0.000263       |
| 2       | 6       | 509.0472               | 0.000261       |

![Surface plot of natural frequency](image1)

**Figure 6** Surface plot of the natural frequency and deflection of MS-rubber – Aluminium combination.
Figures 6, 7 & 8 show the surface plots depict the variation of natural frequency and deflection. The surface plots reveal that there is a steady decrease in natural frequency over the gradual increase in thickness of viscoelastic and elastic layers whereas the deflections of the boring bar increases with decrease in thickness of two layers. By choosing mean deflection and mean natural frequency as basis, the thicknesses of both viscoelastic and elastic layers are chosen to fabricate the CVLD.

4 Experimental Method

In order to assess the effectiveness of CVLD in improving damping, two hollow boring bars with and without CVLD were fabricated. The CVLD was press fitted into one of the hollow boring bars and machining experiments were conducted. The surface roughness of the machined surface was also measured. It was also ensured that the both the boring bars have the same specification for the comparison purpose.

4.1 Selection of boring bar

The important parameter to be considered while selecting boring bar is the diameter to length ratio. Generally, Steel boring bars have a diameter to length ratio of 4:1. Choosing an appropriate boring bar material is also needed for an efficient vibration resistant operation. Some of the common materials used to make boring bar are steel, heavy metal or carbide. The specification of the boring bar S40TDCNR12F3 is given in the following table. The density and Young’s modulus of the boring bar is taken as 7800 kg/m³ and 210 GPa respectively. To increase the natural frequency of boring bar, boring bar is hollowed inside the conventional bar so that the decrease in mass results in increase the
natural frequency. The conventional boring bar is bored with inner radius of 18.7 mm. Tool description of the boring bar is elaborated below in table 6.

| Symbol | Description                      |
|--------|----------------------------------|
| S      | Shank material (steel)           |
| 40     | Diameter(mm)                     |
| T      | Shank Length (300 mm)            |
| D      | Double clamp                     |
| C      | 80 deg. Apex angle diamond type  |
| L      | Major cutting edge angle (95 deg.)|
| N      | Insert relief angle (0 deg.)      |
| R      | Feed direction right hand        |

4.2 Fabrication of CVLD
Boring bar with CVLD was fabricated by die casting. The composite bar of natural rubber and aluminium was press fitting inside the hollow boring bar. Aluminium 6xxx series was used in fabrication. It contains magnesium silicate which makes it heat treatable and it has medium strength and weld ability and machinability properties. Aluminium rod of 19mm diameter is turned to 14.7mm outer diameter and drilled to 6.5mm inner diameter. Length of the rod is 240mm. Natural rubber is die casted upto 2mm thickness over the hollow aluminium rod. Then the aluminum rod with natural rubber was press fitted into the pre-drilled boring bar using hydraulic press.

![Figure 9 Boring bar fitted with CLD](image)

The boring bar with CVLD is shown in figure 9. The second part of experiment, which was machining, was done to assess the vibration control capabilities of CVLD by determining the surface roughness. The two hollow pipes were machined by conventional boring bar and boring bar with CVLD. The spindle speed of 280 rpm, feed of 0.2 mm, depth of cut of 0.25 mm and boring bar overhang length of 200 mm were chosen for machining experiments. Experimental setup of the machining experiments is shown in figure 10.

![Figure 10 Experimental setup -Machining process using boring bar without and with CVLD](image)

4.3 Harmonic analysis
Harmonic analysis is done by using ANSYS. ANSYS offers different solution methods among which the full method was used to obtain the harmonic response of the boring bar with and without CVLD. The frequency range was chosen from 200-800 Hz with 1 Hz as sub step. The harmonic analysis gives the plot of frequency response function (FRF) of Y-component displacement vs frequency. The mode shapes are defined as a specific pattern of vibration occurring at a specific natural frequency of the structure. They are determined by defining the stiffness and mass and also the boundary conditions of the structure. The harmonic analysis is used to predict the steady-state response of the structure by applying external harmonic force over a specified frequency range based on results of modal analysis. In order to include damping to the system, the structural beta damping is applied. The damping factor value 0.02 is applied for conventional boring bar whereas 0.05 is used for boring bar with CVLD. Using the equation 4[13], the beta damping value is calculated and used in the harmonic analysis.

\[ \beta = \frac{2\xi}{\omega} \]  

The FRF of the boring bar with and without CVLD is shown in Fig 11(a) and 11(b).

Figure 11 Harmonic response of boring bar without and with CVLD

The peak amplitude of FRF of boring bar with CVLD is lower than that of with CVLD. Hence the results of harmonics analysis establishes the effectiveness of CVLD in controlling vibration.

Figure 12(a) Stability lobes of boring bar without CVLD  Figure 12(b) Stability lobes of boring bar with CVLD

Figures 12a & 12b represent the Stability lobe diagrams of boring bar without and with CVLD respectively. Stability lobes are plots of spindle speed vs depth of cut [14]. The frequency response function, which is required for construction of stability lobes, is obtained from harmonic analysis carried out in ANSYS. From the stability lobe diagrams, it may be inferred that the one with the damper has higher stability when compared to that of conventional boring bar without damper.

5 Results and discussion
From the modal analysis of the boring bars, it is found that the natural frequency of boring bar with damper is 504 Hz whereas the natural frequency of conventional boring bar is 477 Hz. Increase in the natural frequency leads to better machining stability. Furthermore, the results from harmonic analysis also prove that the CVLD minimizes the amplitude of FRF of boring bar. Machining experiments were also conducted and surface roughness values were measured. The machined components are shown in figure 13 (a) and (b). Surface roughness centreline average (Rₐ) was measured using CARL ZEISS (E-35A) portable surface measuring equipment. The surface profile of the component machined without and with damper are shown in the figure 14 and 15 respectively.

![Component machined without damper](image1)

![Component machined with damper](image2)

![Surface profile of component machined without damper.](image3)

![Surface profile of component machined with damper.](image4)

From the two profiles, it is inferred that the boring bar with CVLD provides a smooth surface finish. The component which was machined without the damper has Ra value of 5.36 μm and with damper has Ra value of 1.86 μm.
6 Conclusions
In this work, a constrained layer damper was designed, fabricated and tested for a boring bar to control vibrations during boring operations. The optimum thickness of natural rubber and aluminum tube were obtained using design of experiments and regression analysis. The finite element simulation results of boring bar with CVLD were used to develop a statistical model which was analyzed for maximization of natural frequency. The CVLD was press fitted into the hollow boring bar and the hollowing of boring bar and addition of CVLD leads to increase in natural frequency and damping of the boring bar. Machining experiments were conducted to assess the effectiveness of boring bar with and without CVLD. The surface profile of the component machined without damper depicts that there was a large variation in the surface roughness ($R_a$) with reference to mean centre line, whereas the surface profile of the component machined with damper shows very small variations. It may be inferred that there was an improvement of 65% in the surface roughness of the machined component with damper.

References
[1] Tobias S.A 1965 Machine-tool vibration J. Wiley.
[2] Jones, David IG. 2001 Handbook of viscoelastic vibration damping. John Wiley & Sons.
[3] Zhou X Q, DY Yu, XY Shao, SQ Zhang, and S. Wang 2016 Composite Structures 136, 460-480.
[4] Saravanamurugan S, Thirunarayanaswamy A, and Devarajan K 2015 Journal of Vibration and Control 21, 5, 949-958.
[5] Ram, Ganapathy HV, and Saravanamurugan S 2019 In IOP Conference Series: Materials Science and Engineering 577, 1, 012152.
[6] Hwang HY and Kim JK 2003 Composite Structures, 60(1), 115-124.
[7] Fu Q, Lundin D and Nicolescu CM 2014 Journal of materials engineering and performance 23(2), 506-517.
[8] Liu Yang, Liu Z, Song Q, and Wang B 2016 International Journal of Mechanical Sciences 117, 299-308.
[9] Song Q, Jiahao Shi J, Liu. Z, Wan Yi and Xia. F 2016 The International Journal of Advanced Manufacturing Technology 83, 9-12, 1951-1966.
[10] Johnson Conor D, and David A Kienholz 1982 AIAA journal 20, 9, 1284-1290.
[11] Shi Jiahao, Song Q, Liu. Z and Wan. Yi 2017 International Journal of Mechanical Sciences 128, 294-311.
[12] Liu, Yang, Liu Z, Song Q, and Wang B 2019 Journal of Materials Processing Technology 266, 687-695.
[13] Yuhuan, Zhang, Yongsheng R, Jishuang T, and Jingmin Ma 2019 Journal of Vibration and Control 25, 16, 2204-2214.
[14] Zhang, Jinfeng, Wang H, Yongsheng Ren, Chao Feng, and Chunjin Zhang 2020 Applied Sciences 10, 13, 4537.
[15] Young, Clarence W, Budynas R.G and Ali M. Sadegh 2002 Roark's formulas for stress and strain. Vol. 7. New York: McGraw-Hill.
[16] Altintas Yusuf and A. A. Ber. 2001 Manufacturing automation: metal cutting mechanics, machine tool vibrations, and CNC design. Appl. Mech. Rev. 54, no. 5 : B84-B84.
[17] Manual, ANSYS User’S 1994 Swanson analysis systems. Inc., Volumes I, II, III, IV, Revision 5.