APPENDIX 1

CHATTER SUPPRESSION WITH PASSIVE DAMPER

During machining, the material deformation process induces a broad-band excitation of the machine tool as a result, relative dynamic motion between the boring bar and the workpiece frequently occurs, commonly referred to as chatter. This phenomenon is characterized by violent vibration, poor quality of surface finish and it causes a reduction of the life of the tool. In all cutting operations like turning, boring vibrations are induced due to the deformation of the workpiece. In boring operations, the boring bar is subjected to forces from both the cutting speed and the cutting depth direction. A boring bar can usually be characterized as a slender beam and is generally the weakest link in a machine tool system. This implies economical disadvantages during machining. The main objective of the proposed work is to design a damped tool for existing machine tool with low cost. In this investigation, improvement of the damping capability of boring tool and suppression of chatter vibration using dampers are analyzed. The inertia mass of the dampers have been increased to suppress the chatter vibration. The materials selected for the dampers are nitinol, tungsten carbide and tungsten-nickel-copper alloy. Finite elements analysis has been performed to study the dynamic behavior of tool using the selected damping materials.

The main contributions of the current study are observed that the natural frequency of the boring tool has been enhanced with dampers. From harmonic and transient analysis, it is observed that there is reduction in amplitude of vibration with respect to the frequency and time taken to decay
the amplitude of boring tool with dampers. Hence the result of finite element analysis of tungsten-nickel-copper alloy damper shows that there is a significant improvement in dynamic behavior when compared with other damping materials.

A1.1 INTRODUCTION

A schematic picture of a cutting operation using a boring bar can be seen in Figure A1.1. The actual cutting is performed at the cutting tool mounted at the tip of the boring bar. During a cutting operation the boring bar is fed in the feed direction at a specific cutting depth and a specific rotational speed of the workpiece. The vibration of the boring bar is influenced by three parameters, feed rate, cutting depth and cutting speed. The vibration in the boring bar is in the cutting speed and the cutting depth direction. The term "chatter" is often used instead of vibration in the cutting process.

Figure A1.1 A Schematic view of a boring operation

The main objective of the proposed work is to design damped tool for exiting machine tools with low cost. In this investigation, improvement of the damping capacity and suppression of chatter vibration of boring tool,
using three types of damping materials namely: nitinol, tungsten carbide, tungsten- nickel-copper alloy are tried. These materials are having high density and so that inertia mass of the boring tool is increased to suppress the chatter vibration of boring operation. The result suggests suitable damping material to suppress the chatter vibration in boring operations.

A1.2 LATHE CHATTER

It is known from mechanics of metal cutting that cutting forces decrease with increase of cutting speed. Effect of this phenomenon is equivalent to some negative damping in the system. This is one major case of chatter to occur. Of course, there are other reasons due to which chatter occurs. To avoid the prominence of stick slip motion cases of with moderate and heavy cuts occurs should only be considered to suppress the chatter vibration. Because in case of small cuts, friction between the sliding surfaces of the tool and job will take the major part in chatter generation. Therefore, it is clear that development of tool wear may also become important in cases of small cuts. Effect of tool wear on vibration amplitude has been given in Figure A1.3.

Figure A1.2 Effects of tool wear on vibration amplitude
But with moderate and heavy cuts it is possible to analysis the problem of chatter from the point of view of variation of the cutting variable. In lathe machines the equivalent stiffness of the machine body is much more than the equivalent stiffness of the tool and job support. Therefore, the chatter mainly remains confined in the cutting tool and job support and the characteristic of the structure of the lathe body, as a whole has been excluded from being desired. The single degree of freedom chatter theory will be considered for only those cases where rigidity of the tool and support is relatively small in one direction, so as to allow the tool to vibrate in one direction only. Otherwise the tool motion will not be straight and two-degree of freedom theory will have to be used for analyzing the problem.

A1.3 ELIMINATION OF VIBRATIONS

When designing new machine tools, the design should be such that the unwanted vibrations are absent or at least reduced. During the design of the machine tool all the possibilities of vibration elimination are to be considered. The stiffness and damping capacity are two predominant features for determining dynamic characteristics of the machine tools and components. To reduce intensity of vibration, it is also necessary that damping should be introduced from the conceptual stage of design stage. Two types of damping techniques are available for chatter suppression namely; Passive damping and Active damping.

A1.3.1 Passive Damping

For example Vibration absorber which comprises of a parallel spring damper combination couples the main structure to an auxiliary mass. Removing the coupling spring the absorber system results in the well-known ‘Lanchester damper’ and if the damping element is removed ‘impact damper’
is obtained. This group of dampers is categorized as passive dampers. The basic principle of vibration absorber depends on the principle of transferring vibrational energy to an auxiliary system. Conventional damper dissipate energy and reduce vibrational amplitudes. The major limitation of passive damper arrangement is the requirement of the auxiliary system parameters to be matched to the main system. Mismatching will result in adverse results.

### A1.3.2 Active Damping

Active vibration control in boring operations clearly is a possible solution to reduce the vibrations present in this kind of machining. Embedding the actuator and accelerometer into the boring bar, measuring the vibration during the machining and reducing the vibration in on line mode is called active damping.

### A1.4 PROPERTIES OF DAMPING MATERIALS

#### A1.4.1 Nitinol

Nickel titanium, also known as nitinol, is a metal alloy of nickel and titanium, where the two elements are present in roughly equal atomic percentages. Nitinol alloys exhibit two closely related and unique properties: shape memory and superelasticity (also called pseudoelasticity). Shape memory refers to the ability of nitinol to undergo deformation at one temperature and then recover its original, undeformed shape upon heating above its "transformation temperature". Superelasticity occurs at a narrow temperature range just above its transformation temperature; in this case, no heating is necessary to cause the undeformed shape to recover and the material exhibits enormous elasticity, some 10-30 times that of ordinary metal. The material compositions of nitinol are,
Nickel (nominal) - 55.8 wt.%
Titanium - 44.13 wt.%
Oxygen (max) - 0.05 wt.%
Carbon (max) - 0.02 wt.%

The important properties of the nitinol are

Density - 6450 kg/m$^3$
Young’s modulus - 700x10$^2$ N/mm$^2$
Poisson’s ratio - 0.3

A1.4.2 Tungsten carbide

Tungsten carbide is an inorganic chemical compound (specifically, a carbide) containing equal parts of tungsten and carbon atoms. In its most basic form, tungsten carbide is a fine gray powder, but it can be pressed and formed into shapes for use in industrial machinery, cutting tools, abrasives, other tools and instruments.

Tungsten carbide is approximately three times stiffer than steel, and is much denser than steel or titanium. It is comparable with corundum or sapphire in hardness and can only be polished and finished with abrasives of superior hardness such as cubic boron nitride and diamond. The material compositions in tungsten carbide are,

<table>
<thead>
<tr>
<th>Component</th>
<th>Percentage</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tungsten</td>
<td>92.6%</td>
</tr>
<tr>
<td>Cobalt</td>
<td>5.7%</td>
</tr>
<tr>
<td>Strontium</td>
<td>1.4%</td>
</tr>
<tr>
<td>Iron</td>
<td>0.2%</td>
</tr>
</tbody>
</table>
The important properties of the tungsten carbide are

- Density: 15.8x10^3 kg/m^3
- Young’s modulus: 713.82x10^3 N/mm^2
- Poisson’s ratio: 0.24

### A1.4.3 Tungsten-Nickel- Copper Alloy

The tungsten-nickel-copper alloy is an important class of tungsten heavy alloys. Nickel and copper are added to tungsten in the ratio of 3:2. It is having relatively good thermal conductivity properties, often used in the occasion of some special requirements, such as the rotor of the gyroscope and other requirements in the magnetic field devices and instrumentation components, high voltage electrical switches, electrical touch head as well. This alloy called as vibration-free material, because which is mainly used for reduction of vibration amplitudes in various applications. The compositions of tungsten-nickel- copper alloy are

- Tungsten: 90%
- Nickel: 6%
- Copper: 4%

The important properties of the tungsten-nickel- copper alloy are

- Density: 17x10^3 kg/m^3
- Young’s modulus: 275x10^3 N/mm^2
- Poisson’s ratio: 0.22
A1.5 RESULTS OF MODAL ANALYSIS

Figure A1.3 Solid model of the boring tool modeled in Pro-E

Figure A1.4 Solid model of the boring tool imported to ANSYS
Figure A1.5 Boring tool with damping material

Figure A1.6 Boring tool with meshing
Figure A1.7 First mode shape of boring tool without damper

Figure A1.8 First mode shape of boring tool with nitinol
Figure A1.9 First mode shape of boring tool with tungsten carbide

Figure A1.10 First mode shape of boring tool with tungsten-nickel-copper
Figure A1.11 Second mode shape of boring tool without dampers

Figure A1.12 Second mode shape of boring tool with nitinol
Figure A1.13 Second mode shape of boring tool with tungsten carbide

Figure A1.14 Second mode shape of boring tool with tungsten-nickel-copper
Figure A1.15 Third mode shape of boring tool without dampers

Figure A1.16 Third mode shape of boring tool with nitinol
Figure A1.17 Third mode shape of boring tool with tungsten carbide

Figure A1.18 Third mode shape of boring with tungsten-nickel-copper
Figure A1.19 Fourth mode shape of boring tool without dampers

Figure A.20 Fourth mode shape of boring tool with nitinol
Figure A1.21 Fourth mode shape of boring tool with tungsten carbide

Figure A1.22 Fourth mode shape of boring tool with tungsten-nickel-copper
Figure A1.23 Fifth mode shape of boring tool without dampers

Figure A1.24 Fifth mode shape of boring tool with nitinol
Figure A1.25 Fifth mode shape of boring tool with tungsten carbide

Figure A1.26 Fifth mode shape of boring tool with tungsten-nickel-copper
Results of modal analysis are given below in Table A1.1. The table indicates the frequencies at various modes ranging from the first mode to fifth. The mode shapes are shown from Figures A1.10 to A1.29.

<table>
<thead>
<tr>
<th>Mode</th>
<th>Without any damping materials (Hz)</th>
<th>With nitinol damper (Hz)</th>
<th>With tungsten carbide damper (Hz)</th>
<th>With tungsten-nickel-copper damper (Hz)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>99.06</td>
<td>110.89</td>
<td>121.60</td>
<td>143.40</td>
</tr>
<tr>
<td>2</td>
<td>117.96</td>
<td>118.98</td>
<td>121.73</td>
<td>143.54</td>
</tr>
<tr>
<td>3</td>
<td>379.38</td>
<td>383.71</td>
<td>390.67</td>
<td>430</td>
</tr>
<tr>
<td>4</td>
<td>481.45</td>
<td>514.05</td>
<td>538.15</td>
<td>593.34</td>
</tr>
<tr>
<td>5</td>
<td>559.77</td>
<td>563.07</td>
<td>574.22</td>
<td>637.85</td>
</tr>
</tbody>
</table>

A1.6 DISCUSSION ON MODAL ANALYSIS

Natural frequency of the boring tool for overhang length of 75mm first mode without damping material is 99.06 Hz, with nitinol is 110.89 Hz, with tungsten carbide is 121.60 Hz and with tungsten-nickel-copper is 143.4 Hz and the corresponding mode shapes for these are vertical bending.

Natural frequency of the boring tool for overhang length of 75mm second mode without damping material is 117.96 Hz, with nitinol is 118.98 Hz, with tungsten carbide is 121.73 Hz and with tungsten-nickel-copper is 143.5 Hz and the corresponding mode shapes for these are horizontal bending.

Natural frequency of the boring tool for overhang length of 75mm third mode without damping material is 379.38 Hz, with nitinol is 383.71 Hz, with tungsten carbide is 390.67 Hz and with tungsten-nickel-copper is 430 Hz and the corresponding mode shapes for these are twisting.
Natural frequency of the boring tool for overhang length of 75mm fourth mode without damping material is 481.45 Hz, with nitinol is 514.05 Hz, with tungsten carbide is 538.15 Hz and with tungsten-nickel-copper is 593.34 Hz and the corresponding mode shapes for these are horizontal bending.

Natural frequency of the boring tool for overhang length of 75mm fifth mode without damping material is 559.77 Hz, with nitinol is 563 Hz, with tungsten carbide is 574.22 Hz and with tungsten-nickel-copper is 637.85 Hz and the corresponding mode shapes for these are vertical bending.

From these discussions on the modal analysis, five modes of extraction have been carried out such modes shapes are two vertical and two horizontal bending and one twisting. The frequencies of modal analysis of boring tools without and with damping materials are not coincide with each other in different modes shapes of the boring tool.

A1.7 RESULTS OF HARMONIC ANALYSIS

![Figure A1.27 Harmonic analysis of boring tool without dampers](image.png)
Figure A1.28 Harmonic analysis of boring tool with nitinol

Figure A1.29 Harmonic analysis of boring tool with tungsten carbide
Figure A1.30 Harmonic analysis of boring tool with tungsten-nickel-copper

The results obtained from the harmonic analysis of boring tool with and without dampers are plotted as shown from Figures A1.30 to A1.33. The peak value of the amplitude has been reduced with respect to the frequencies in this analysis.

Table A1.2 Comparisons of peak value

<table>
<thead>
<tr>
<th>Damping materials</th>
<th>Peak value (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Without any damping materials</td>
<td>0.35</td>
</tr>
<tr>
<td>With nitinol material</td>
<td>0.30</td>
</tr>
<tr>
<td>With tungsten carbide material</td>
<td>0.24</td>
</tr>
<tr>
<td>With tungsten-nickel-copper alloy</td>
<td>0.117</td>
</tr>
</tbody>
</table>

A1.8 RESULTS OF TRANSIENT ANALYSIS

Results of transient analysis are given in the Table A1.3. The graphical results are presented from Figures A1.35 to A1.38.
Figure A1.31 Transient analysis of boring tool without dampers

Figure A1.32 Transient analysis of boring tool with nitinol
Amplitude of the boring tool without damping materials starts from 8.8µm and is reduced to 8.6µm with tungsten-nickel-carbide damper which is very less reduction but the time taken to decay the amplitude is reduced considerable amount. Time taken to decay the amplitude of boring tool
without damping materials starts from 4.6 seconds is reduced to 2.3 seconds with tungsten-nickel-copper material.

Table A1.3 Time to decay the amplitude of boring tool

<table>
<thead>
<tr>
<th>Damping materials</th>
<th>Time taken to decay (sec)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Without any damping materials</td>
<td>4.6</td>
</tr>
<tr>
<td>With nitinol material</td>
<td>3.0</td>
</tr>
<tr>
<td>With tungsten carbide material</td>
<td>2.75</td>
</tr>
<tr>
<td>With tungsten-nickel-copper alloy</td>
<td>2.3</td>
</tr>
</tbody>
</table>

A1.9 COMPARISON OF DAMPING RATIO

The amplitude value are taken from ANSYS transient analysis result which is stored in Note Pad (list variables) then it is converted to MS-excel graph format for calculations of damping ratio. From the transient analysis, we know the amplitude decay with respect to the time with damped boring tools when compared with undamped boring tool. So the damping ratio can be calculated from the transient analysis by using the logarithmic decrement which is ratio between the successive amplitudes($x_1, x_2$).

$$\delta = \ln \left( \frac{x_1}{x_2} \right)$$

$$\xi = \frac{\delta}{2\pi}$$

The amplitude of vibration decays shown in the graph from Figures A1.39 to A1.42. The graphs are drawn between the amplitude (mm) and time (sec). The graphs show the amplitude of vibration decay with respect to the time. So from the graphs, the damping ratio can be calculated by using damping ratio formula.
For boring tool without damper, the damping ratio is 0.0204

![Amplitude of vibration decay in boring tool without dampers](image)

**Figure A1.35** Amplitude of vibration decay in boring tool without dampers

For boring tool with nitinol material, the damping ratio is 0.0357

![Amplitude of vibration decay in boring tool with nitinol](image)

**Figure A1.36** Amplitude of vibration decay in boring tool with nitinol

For boring tool with tungsten carbide material, the damping ratio is 0.040.

![Amplitude of vibration decay in boring tool with tungsten carbide](image)

**Figure A1.37** Amplitude of vibration decay in boring tool with tungsten carbide
Boring tool with tungsten-nickel-copper alloy, the damping ratio is 0.071.

![Figure A1.38 Amplitude of vibration decay in boring tool with tungsten-nickel-copper](image)

From the comparisons, the damping ratio has been increased with damped boring tool when compared with undamped boring tool. The performance of nitinol and tungsten carbide damped materials are comparatively small when compared with tungsten-nickel-copper. The tungsten-nickel-copper damping material gives the significant improvement in the damping ratio.

### A1.10 SUMMARY

The conclusions drawn from the investigations can be summarized as follows: In passive suppression of boring tool chatter the possibilities of implementing the impact damper is analyzed. The inertia mass of the dampers have been increased to suppress the chatter vibration. The materials selected for the dampers are nitinol, tungsten carbide and tungsten-nickel-copper alloy. Finite elements analysis has been performed to study the dynamic behaviour of tool using the selected different damping materials.

- The results were obtained from the modal analysis of boring tool with and without dampers. It is observed that the natural frequency of boring tool has been enhanced with damping materials.
• From the harmonic analysis, it is observed that amplitude of the vibration has been reduced with damping materials. From the analysis it is found that the amplitude of tungsten-nickel-copper alloy damped boring tool has been reduced by 66.57% when compared with undamped boring tool.

• From the transient dynamic analysis, it is observed that there is reduction in time taken to decay the amplitude of boring tool with dampers. From the analysis, time taken to decay the amplitude of tungsten-nickel-copper alloy damped boring tool has been reduced by 50% when compared with undamped boring tool.

Hence the results of finite element analysis of tungsten-nickel-copper alloy damped boring tool shows that there is a significant improvement in the dynamic behavior of the structural analysis, when compared with other damping materials such as nitinol and tungsten carbide.

A1.11 JUSTIFICATION FOR ACTIVE DAMPING

Vibration control during machining is called active chatter suppression. On the other hand passive techniques will not be useful to control the chatter during machining process, due its own limitation. Upon going through the research it is found that the chatter control through active damping by MR damping is better than passive damping. Active damping technique find outs the present level of vibration and determines the amount of current that is to be supplied to the MR damper. Hence this will improve the surface finish of the workpiece that is being machined and will reduce the tool wear.
APPENDIX 2

DATA ACQUISITION SYSTEM DETAILS

The preliminary details of data acquisition system (DAQ) were presented in chapter 3. Here, some more details are presented. In DAQ, the first task is to configure the DAQ system. The snap shots of the same are presented in Figures A 2.1 to A2.3. As described earlier, LabVIEW was used along with sound and vibration card (NI USB – 4432) for acquiring vibration signals. Once DAQ assistant from LabView is dragged and dropped in block diagram, there is a pop up window for choosing the parameter for acquisition. Here ‘voltage’ was selected. Then the channel has to be selected. In the sound and vibration card, there are five input channels namely, AI0, AI1,…AI4. The piezoelectric accelerometer was attached to AI0 channel. The channels will be listed as shown in the Figure A2.2. After choosing the channel, one need to set the sampling rate and number of samples to read. The Figure A2.1’s bottom portion is enlarged and presented in Figure A2.3, which shows provisions for setting sampling rate and number of samples to read. With these major channel parameters are set. Then vibration signals will be available in DAQ assistant. To compute some statistical parameters, the statistical express VI was chosen from labVIEW and the selected statistical parameters will be computed and made available as shown in Figure A2.4.
Figure A2.1 Adding a channel for DAQ

Figure A2.2 Choosing a channel for DAQ
Figure A2.3 Setting samples and sampling rate for DAQ

Figure A2.4 Statistics tool bar
Figure A2.5 A Schematic of ELVIS II
The controller output has to be given to the MR damper. The signals given by the regression model is a number and an equivalent voltage can be sent out of the computer through DAQ card. Here, ELVIS II (Figure A2.5) was used for this purpose. The channel configuration procedure is same as explained earlier. The Figure A2.6 depicts the process. The front panel of the input signal and controller are shown in Figure A2.7 and Figure A2.8.
Figure A2.7 Front panel of input signals

Figure A2.8 Front panel of Controllers