Chatter suppression through variable impedance and smart fluids

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ABSTRACT

A novel approach to mitigating chatter vibrations in machine tools is presented. Encountered in many types of metal removal processes, chatter is a dangerous condition which results from the interaction of the cutting dynamics with the modal characteristics of the machine-workpiece assembly. Tool vibrations are recorded on the surface of the workpiece during metal removal, imposing a waviness which alters the chip thickness during subsequent cutting passes. Deviations from the nominal chip thickness effect changes in the cutting force which, under certain conditions, can further excite vibrations. The chatter mitigation strategy presented is based on periodically altering the impedance of the cutting tool assembly. A cyclic electric (or magnetic) field is applied to the spindle quill which contains an electro-rheological (or magneto-rheological) fluid. The variable yield stress in the fluid affects the coupling of the spindle to the machine tool structure, changing the natural frequency of oscillation. Altering the modal characteristics in this fashion disrupts the modulation of current tool vibrations with previous tool vibrations recorded on the workpiece surface. Results from a simulated milling process reveal that significant reductions in vibration amplitude can be achieved through proper selection of fluid and excitation frequency.

Keywords: chatter, variable impedance, electro-rheological fluids, magneto-rheological fluids

2. INTRODUCTION

The literature discussing regenerative chatter associated with metal cutting is extensive. The mechanical process appears to be well understood. The physics of the problem can be understood qualitatively through analogy with the old Edison wax phonographs as depicted in Figure 1. As the track moves under the needle, undulations within the groove excite vibration in a speaker and sound is conveyed into the air. Similarly, sounds in the air are conveyed through the speaker and needle into the wax. Any resonances in the mechanical system will also be recorded on the record. If mechanical resonances are inadvertently recorded, playback of the record could further excite those resonances and the large signal will be rerecorded into the wax. This regenerative process is called chatter. An illustration of this effect in milling is given in Figure 2. Vibration of the cutting tool imposes a waviness on the workpiece during each cutting tooth pass. The waviness imposed then excites tool vibration during the subsequent tool pass by altering the nominal chip thickness and the resultant cutting forces.

Chatter avoidance and suppression have also been extensively considered. The primary approaches are suggested by the classical stability chart for turning processes which is defined by the dynamic stiffness of the cutting tool. A nominal stability chart is shown in Figure 3, which displays a cutting stability boundary as a function of the spindle speed and depth of

Figure 1. - The playing and recording of a wax phonograph record is an analogy of the machine tool chatter process.
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cut. For the illustrative system, all cutting processes that fall below the curve represent stable cutting. Conversely, all cutting processes falling above the curve will produce regenerative chatter. Several techniques have been explored for maintaining cutting stability:

- Taking such shallow cuts that the process stays within the stability domain no matter what the cutting speed is.
- Adjusting the depth of cut for a particular cutting speed to stay below the envelope of the stability curves.
- Adjusting the speed to stay within stability lobes for a given depth of cut (the CRACK method is a version of this).  

![Figure 2. The kinematics of the cutting process illustrates the manner in which surface texture due to tool oscillations on previous cuts contributes to the forces on the cutting tool.](image)

![Figure 3. Curve presenting stable and unstable combinations of depth-of-cut and cutting-tool speed.](image)
Maximizing the dynamic stiffness of the cutting machine and the part support through design. This results in raising the stability curve in the "depth-of-cut" direction and increasing the number of stable process conditions.

Another method, not suggested by the chart, is that of perturbing the cutting speed about the nominal speed to disrupt the modulation of current and previous tool vibrations that can lead to chatter. This process can be summarized by a horizontal line segment on the stability chart, with the cutting speed moving cyclically from side to side. The method introduced here draws on the logic of this spindle speed variation approach. Here, instead of continuously changing the cutting speed we continuously change the resonant frequency of the cutting tool. This is done through the use of "smart" fluids - ones whose flow compliance can be changed very rapidly. One design exploiting electro-rheological fluid is shown in Figure 4. A magnified view of the tool sleeve/tool interface region is also shown in Figure 5. The standard sleeve is extended, as is often done to increase the stiffness of the cutting tool, but the extended domain is bored out to create an annulus between the tool and the extended portion of the sleeve. In the configuration shown here, the annulus is filled with electro-rheological fluid and

Figure 4. - A design for modulated impedance of a cutting tool. This design exploits the modulated flow properties of electro-rheological fluid.

Figure 5. - A magnified view of annulus between the tool sleeve and the cutting tool. Electrodes and electro-rheological fluid are placed in that region.
a perforated frustrumal shell electrode. The electrodes are charged through slip rings on the outside of the sleeve. Altering the electrical field applied to the fluid induces a change in the natural frequencies of the system. A cyclic variation of the field causes a side to side shift of the stability lobes as the process parameters are held constant.

3. FLUID MECHANICS

To understand the significance of this design one must examine some of the properties of electro-rheological fluids. These are fluids that are mildly shear thinning, viscous materials in the absence of an electrical field, but behave similarly to a Bingham fluid in the presence of electric fields. In the presence of an electric field, these materials appear to have a yield stress before flow and an elevated viscosity during flow. In the analysis performed for this study, the electro-rheological fluid - 27% zeolite in silicon oil - is approximated as a Bingham fluid having a distinct yield stress ($\tau_0$) and a perfectly Newtonian viscosity ($\eta$) in the presence of an electric field as shown in Figure 6. The difference between the viscosities in the presence and the absence of electric field is ignored. Magneto-rheological fluids behave in much the same manner in response to applied magnetic fields.

Referring to Figures 4 and 5, we see that charging the slip rings will create an electric field through the electro-rheological fluid, increase the flow resistance through the annulus, and enhance both mechanical energy dissipation and mechanical coupling between the sleeve and the cutting tool. That increased coupling corresponds to an increased natural frequency to the system. The strategy proposed here is to modulate the electric field in the annulus between each tool passing. Thus the oscillations recorded in the part by one flute passing are encountered by tool with a different resonant frequency during the next flute passing.

The resultant system is modeled assuming that the length of the annulus is large compared to the radius of the annulus and that the radius of the annulus is large compared to the gap dimension. Under those assumptions, the flow within the annulus resulting from the relative motion $V$ between the cylinders can be assumed to be entirely in the circumferential directions and the lubrication approximation can be invoked. With the lubrication approximation, the flow-rate to pressure relationship is approximated by that of flow through a slit as shown in Figure 7. The relative displacement of the centers of the cylinders is $\Delta y$. The relative velocity of the two cylinders $V$ determines the flow rate $Q$ per unit depth through each cross section through conservation of volume according to

![Bingham Fluid](image)

Figure 6. - Bingham fluid is characterized by a yield stress near zero strain rate and strain rate that increases linearly with the excess of stress beyond yield. An electro-rheological fluid is approximated as a Bingham fluid when exposed to an electric field and as a Newtonian fluid in the absence of an electric field.
\[ Q(\theta) = -VR\sin(\theta) \tag{1} \]

Flow of a Bingham fluid through a slit involves two shear flow domains and a plug flow domain as shown in Figure 8. The solution of the flow rate/pressure relationship for such problems requires identification of those domains and that is done with the aid of the following equation:

\[ \beta^3 - 3\beta^2 - 2Q^* \beta + 2Q^* = 0 \tag{2} \]

where \( Q^* = \frac{Q}{Q_0}, \ Q_0 = \frac{2}{3}H^3 \frac{r_0}{\eta H}, \ \beta = 1 - b/H, \ 2H \) is the slit thickness \((2H = (R_2 - R_1) + \Delta y \cos \theta)\), and \(2b\) is the thickness of the plug flow region. Once the flow domains are determined, the pressure gradient \( \nabla p \) is found from

\[ Q = \frac{2}{3}H^3 \left( -\frac{\nabla p}{\eta} \right) \frac{\beta^2}{2} (3 - \beta) \tag{3} \]

Having the pressure gradient around the annulus as a function of relative velocity, \( V \), one integrates to find the pressure and integrates the vertical component of traction to obtain the net force, \( F \), between the two cylinders. This is all done.

**Figure 7.** - The diameter of the cutting tool is \( R_1 \) and the inner diameter of the tool sleeve at the annulus is \( R_2 \). It is assumed that the nominal dimension of the annulus \((R_2 - R_1)\) is small compared to the inner radius, \( R_1 \). The relative displacement of the centers of the cylinders is \( \Delta y \). Under these geometric constraints, the relative velocity of the cylinders \( V \) excites fluid flow in the circumferential direction in the annulus.

**Figure 8.** - The solution of the flow rate/pressure relationship for such problems requires identification of the shear flow and the plug flow regions within the slit.
numerically, but summarized in Figure 9 which shows a chart of dimensionless force, $F^* = \left( \frac{F}{\tau_0 R} \right) \left( \frac{2H}{R} \right)$, versus dimensionless relative velocity $V^* = \frac{V \eta}{(2H) \tau_0} \left( \frac{R}{2H} \right)$

For the purpose of our analysis, we approximate the above curve by the formula

$$F^* = m V^* + b \text{sgn}(V^*)$$

where $m = -75.36$ and $b = -11.9$. For the Newtonian fluid we set $b = 0$.

4. DETERMINATION OF FLUID FORCES ON THE CUTTING TOOL

For simplicity, the sleeve is assumed rigid in the following calculations. We also consider a single cantilevered deformation mode of the tool in each of the lateral directions. Letting the axial spatial coordinate be $z$ and the lateral spatial coordinates be $x$ and $y$, the velocity of the tool is:

$$V(z, t) = \phi_x(z)\dot{q}_x(t)i + \phi_y(z)\dot{q}_y(t)j$$

where $i$ and $j$ are unit vectors along the x and y axes as defined in Figure 2. We assume symmetry of the tool so that

$$\phi_x(z) = \phi_y(z) = \phi(z)$$

The magnitude of the velocity along the tool is given by

$$|V(z, t)| = \dot{q}(t)\phi(z)$$

in which

![Figure 9. - Dimensionless force vs. dimensionless lateral relative velocity of inner cylinder with respect to outer cylinder.](image-url)
Substituting these kinematics into the non-dimensional force given in equation 4, we have an expression for the magnitude of force per unit length of the tool

\[ f(z, t) = \left( \frac{R}{2H} \right)^3 m \eta \phi(z) \dot{q}(t) + \left( \frac{R^2}{2H} \right)^2 \tau_0 b \text{sgn} \dot{q}(t) \]  

(9)

where any flow along the axial direction has been neglected. The vector force per unit length acts opposite the instantaneous velocity with the \( x \) and \( y \) components given by

\[ f_x(z, t) = f(z, t) \frac{\dot{q}_x(t)}{\dot{q}(t)} \]

\[ f_y(z, t) = f(z, t) \frac{\dot{q}_y(t)}{\dot{q}(t)} \]  

(10).

In formulating the Lagrange equations for motion of the tool, we compute the generalized forces associated with the resisting force of the Bingham fluid. This is done by assuming that the sleeve envelopes the entire tool from the point of cantilevered attachment to the end. Integrating over this effective tool length \( L \) yields the generalized forces according to

\[ Q_x = \int_0^L f_x(z, t) \phi(z) dz \quad Q_y = \int_0^L f_y(z, t) \phi(z) dz \]  

(11).

In our calculations, we use the first vibrational mode shape for a circular cantilevered Euler-Bernoulli beam, given as

\[ \phi(z) = \frac{1}{\sqrt{\rho \pi R_1^2 L}} \left[ \cos \gamma z - \cosh \gamma L + \frac{\sinh \gamma L - \sin \gamma L}{\cos \gamma L + \cosh \gamma L} (\sin \gamma z - \sinh \gamma L) \right] \]  

(12)

in which \( \rho \) is the bar mass density and \( \gamma = 1.875 \) is the first solution to the characteristic equation

\[ \cos \gamma L \cosh \gamma L = -1 \]  

(13).

5. SIMULATED MILLING ENHANCEMENTS

Incorporating the generalized forces \( Q_x \) and \( Q_y \) as well as the cutting and inertial forces into the governing equations for the Euler Bernoulli beam, we solve for the generalized degrees of freedom \( q_x(t) \) and \( q_y(t) \). The cutting forces are assumed to be proportional to the instantaneous depth of cut which is influenced by current and previous vibrations. The corresponding metal removal is recorded and exploited as a boundary condition in subsequent tool passes.

The above formulation was incorporated into a computer code and used to simulate a slotting cut made with the paradigm system defined in the following table:

<table>
<thead>
<tr>
<th>Table 1: Cutting Tool System Parameters</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tool Metal</td>
</tr>
<tr>
<td>Length, ( L )</td>
</tr>
<tr>
<td>Inner Bar Radius, ( R_1 )</td>
</tr>
<tr>
<td>Gap Size, ( R_2 - R_1 )</td>
</tr>
</tbody>
</table>
Table 1: Cutting Tool System Parameters

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Number of Flutes</td>
<td>4</td>
</tr>
<tr>
<td>Part Metal</td>
<td>Aluminum</td>
</tr>
<tr>
<td>ER Fluid</td>
<td>27% Zeolite in Silicon Oil</td>
</tr>
<tr>
<td>Viscosity, ( \eta )</td>
<td>0.1 Pa-s</td>
</tr>
<tr>
<td>Yield Stress at 0 V, ( \tau_0 )</td>
<td>0 Pa</td>
</tr>
<tr>
<td>Yield Stress at 2.5 kV, ( \tau_0 )</td>
<td>500 Pa</td>
</tr>
<tr>
<td>Revolution Speed</td>
<td>375 rpm</td>
</tr>
<tr>
<td>Depth of Cut</td>
<td>4 mm</td>
</tr>
<tr>
<td>Chip Loading</td>
<td>0.3 mm/tooth</td>
</tr>
</tbody>
</table>

The first case considered is that in which no electric field is imposed. The compliance of the tool is fairly large and a characteristic chatter response evolves as illustrated in Figure 10. The normal displacement (in the feed direction) of the tool tip shows maximum displacements on the order of 0.4 mm. The static component of the tool deflection is due to a steady state normal force pushing the tool against the substrate.

The next case is that of the imposition of a steady state electric field of 2.5 kV. The vibration amplitude decreases as the mechanical impedance of the cutting system is increased as shown in Figure 11. However, this reduced level of vibration is still caused by regenerative chatter.

The case of a modulated electric field and the resulting modulated impedance of the cutting tool is particularly interesting. In this case the mechanical impedance is changed as a step function for each tool passing by alternating the electric field applied to the fluid between 0 and 2.5 kV. As shown in Figure 12, the amplitude of chatter is significantly reduced, though there does seem to be a visible inception of oscillation each time the field is turned off. It is important to note that the resultant tip displacement is visibly less than that of the case of the continuously stiff structure.

Figure 10. - Normal displacement of tool as a function of time for the case of no applied electric field. The tool assembly is compliant and large amplitude chatter results.
The most interesting case is that in which the electric field is applied sinusoidally so that it achieves its maximum of

![](image1)

Figure 11. - Normal displacement of tool as a function of time for the case of a steadily applied electric field. The tool assembly is less compliant and a lower amplitude chatter results.

![](image2)

Figure 12. - Normal displacement of tool as a function of time for the case of an applied electric field turned on for every-other tool passing. The resultant tip displacement is visibly less than that of the case of the continuously stiff structure.
2.5kV on every-other tool passing and hits zero at the center of the remaining tool passings. Since the tool frequency changes throughout each tooth pass, the waviness imposed on the workpiece as a result of tool vibrations is more random in nature. Consequently, the regeneration of waviness is entirely suppressed and the chatter vibrations for this case have been eliminated as shown in Figure 13.

6. CONCLUSIONS

This paper presented a strategy for mitigating regenerative chatter vibrations in machine tools. The approach developed is based on altering the modal characteristics of the machine tool to disrupt the regeneration of waviness on the workpiece surface. A design for a variable impedance tool using an electro-rheological fluid to influence the coupling of the tool to the sleeve was presented. The viability of this approach was demonstrated using computer simulations of a milling process with a variable impedance tool. Results indicate that significant reductions in chatter vibrations can be achieved by varying the electric field applied to the fluid during each pass of the cutting tool. Although a step variance in the electric field proved moderately successful at reducing chatter vibrations, best results were obtained through a sinusoidally varying field with a half-period of oscillation equal to the time interval between cutting passes. Success was demonstrated using only modest changes in the tool impedance which can be achieved using existing technology. Hardware verification of this approach will be investigated later in the year, although a configuration involving a magneto-rheological fluid will be used instead of the electro-rheological fluid discussed here.

7. ACKNOWLEDGEMENTS

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![Figure 13. Normal displacement of tool as a function of time for the case of an oscillating applied electric field. The resultant tip displacement is almost entirely suppressed.](image-url)
8. REFERENCES


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