Investigation of Boring Bar Dynamics for Chatter Suppression

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Abstract
Chatter is a concern in boring process, due to the low dynamic stiffness of long cantilever boring bars. Chatter suppression in machining permits higher productivity and better surface finishes. In order to improve the performance of boring operations, several researchers have investigated electro- and magneto-rheological fluids and piezoelectric and electromagnetic actuators as vibration absorbers. In this study, we investigated the feasibility of shifting the natural frequency of boring bar based on semi-active fluid control. Mass at the end of a boring bar was modulated to tune its natural frequency by adjusting the level of fluid in a reservoir. At the same time, different damping materials were used to improve dynamics of the boring bar. Experimental modal analysis was used to obtain frequency response functions for different system configurations. A finite element model was proposed and validated with experimental results. A chatter stability analysis examined chatter suppression characteristics of the proposed method.

Keywords: Semi-Active control, Chatter, Boring bar, Frequency response function, Natural frequency, Damping.

1 Introduction

Chatter is a self-excited vibration caused by variation in chip thickness resulting from a time delay between current cut and preceding cut. Chatter vibration in machining processes limits accuracy and productivity of boring processes. This leads to rapid tool wear and poor surface finishes (Altintas, 2012). One factor affecting chatter is the dynamics at tool tip. In a boring process, the long cantilever boring bar makes it vulnerable to chatter, due to its low dynamic stiffness.

In order to achieve higher aspect ratios and more efficient, chatter-free long-bar boring, it is important to increase static and dynamic stiffness of the boring bar. Static stiffness can be improved by optimizing bar geometry and using materials with higher modulus of elasticity; and, dynamic stiffness can be improved by increasing the damping of the structure (Chen et al., 2014). Moreover, tool tuning can be applied to change the natural frequency of the boring bar in order to minimize chatter.

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Different control methods have been proposed for suppressing chatter in boring bars. While active damping methods can be very effective in controlling chatter in boring bars, they are complex, expensive and energy inefficient, require online monitoring and diagnostics of the machining operation, and involve actuators, control systems, amplifiers, etc. Conversely, passive damping techniques are easier to implement, relatively cost effective and can be achieved either by improving tool design or by adding additional material that can dissipate energy and cause a damping effect. However, the damping capacity in passive methods can be limited.

Active control of boring bars has been investigated by others for chatter suppression. Piezoelectric (Barney et al., 1997; Browning et al., 1997; Chiu et al., 1997; Hanson et al., 1998; Redmond et al., 1997; Tanaka et al., 1994) and magnetostrictive (Al-Zaharah, 2006; Eda et al., 1992; El-Sinawi et al., 2005; Pratt et al., 2001; Rojas et al., 1996; Tang et al., 2004) materials use an electrical or magnetic effect to actively change their geometry. The ability to sense and actuate is simultaneously achieved when using these materials. Electro-rheological (ER) (Lei, 1995; Wang et al., 1999a, 1999b, 2001) and magneto-rheological (MR) (Mei et al., 2009; Mei et al., 2010; Paul et al., 2012) fluids are used in semi-active control of boring bars, where fluid phase is altered by an applied field, resulting in a change in the dynamics of boring bar. As a result of changing fluid rheological properties, the stiffness of the bar is continuously manipulated, with natural frequency of the system also changing simultaneously. Although these materials have relatively fast responses and cover wide ranges of operating frequencies, bulky magnetic coil setup required for MR fluid or high electric field required for ER fluid are major drawbacks for their use (Park et al., 2007).

Dynamic vibration absorbers (DVA) are a common passive control approach for chatter suppression in boring bars. Tuning is very important for DVAs to achieve the desired performance and improper tunings may adversely affect their performance. Moreover, the frequency at which DVAs can be considered effective is limited (Kari, 2007). Other researchers studied and designed DVAs for boring bars (Lee et al., 2001; Tarng et al., 2000). A systematic method based on a combination of multiple structures with a tuned DVA was proposed (Rivin et al., 1989). Also, an optimal passive control models and design concepts of boring bars was investigated (Liu et al., 1991; Rubio et al., 2013). Furthermore, the effect of using composite material interfaces on the dynamics of boring bars was studied (Daghini et al., 2009).

The objective of this study was the investigation of alternative methods to tune natural frequency and increase dynamic stiffness of boring bar. Natural frequency can be modified by changing the overall mass of the boring bar by changing liquid level in a reservoir placed at the end of the bar. Additionally, the use of energy absorbent materials inside the bar was investigated. A finite element (FE) model of boring bar dynamics is also examined. Experimental modal analysis (EMA) method was used for the experimental investigation in this study, and frequency response functions (FRFs) were extracted and compared for different system configurations. The resulting stability analysis demonstrates the efficiency of the proposed method for chatter suppression.

2 Effect of variable mass and improved damping on chatter suppression

Chatter is caused by regenerative vibrations in machining process due to interactions between tool and workpiece. Phase shift between old and new cuts may cause the tool to excite at a chatter frequency \( \omega_c \) that is close to dominant structural natural frequency \( \omega_n \) (Altintas, 2012). Due to the overhang length of a boring bar, the dynamic stiffness is limited and susceptible to chatter. In some cases of boring operations, the maintenance of a constant cutting speed and a depth-of-cut are needed. Structure dynamics, therefore, needs to be altered in order to suppress chatter, which may be achieved by changing the dynamics of tool tip.
Dominant vibration in boring is radial (Lazoglu et al., 2002): for this reason, a one-dimensional (1-D) chatter analysis was considered in this study. The structural transfer function in Laplace domain for one mode in the radial direction is given as:

\[
\Phi(s) = \frac{\omega_n^2 / k}{s^2 + 2\zeta\omega_n s + \omega_n^2}
\]

where \(\omega_n\) is natural frequency (rad/sec), \(k\) is modal stiffness (N/m), and \(\zeta\) is damping ratio. In this study, only first mode is considered. The critical depth of cut, \(a_{lim}\) is given as (Altintas, 2012):

\[
a_{lim} = \frac{-1}{2K_f G(\omega_c)}
\]

where \(K_f\) is the cutting constant in feed direction, and \(G(\omega_c)\) is the real part of the transfer function.

Figure 1 illustrates the effects of changing natural frequency and damping ratio on process stability. Increasing dynamic stiffness of the system can improve the unconditional stability limit (USL), allowing deeper cuts at any operating speed. Manipulation of natural frequency results in shifting the stability lobes as illustrated in Figure 1. Natural frequency can be changed either by adjusting stiffness or mass of the system. In this study, the structure’s natural frequency was changed by controlling mass through the level of liquid in a reservoir at the end of boring bar. Cutting process changes continuously, and the system can and does shift to other unstable regions. This requires an adaptable method that is capable of preventing chatter continuously.

The advantage of controlling structural dynamics is stable boring operations that can be achieved with fixed operating speed and depth of cut. Sudden changes in operating speeds or depths of cut may have adverse effects on the machining process, since the inertia of the system changes with continuous manipulation the operating system, causing a change in the torque and consuming more power. Moreover, tool life is hindered, as dynamic stresses on the machine tool are higher when speed varies.

In order to continuously change dynamics of boring bar, a control system is needed to detect chatter and change boring bar dynamics. Chatter can be detected using a displacement sensor or microphone, and mass of the bar can then be changed by altering fluid level inside the reservoir at the end of the bar. This can be achieved using inlet and outlet valves to control recirculating flow in the reservoir. Recirculating loop draws from another reservoir using a pump. In this study, the effect of changing dynamics of the boring bar was investigated by shifting its natural frequency with fluid level in the reservoir and by damping with different materials within the boring bar.

3 Experiments

The effect of changing damping capacity and natural frequency of boring bars was examined using EMA and measurement of FRFs of the bar when different materials were placed inside the bar and when different liquid levels in the reservoir changed overall mass of the bar.

A clear acrylic tube, 12 cm in length, was attached to the free end of the bar using cyanoacrylate adhesive. The liquid used in this study was water with a density of 1000 kg/m³. Three different levels of water were investigated: 0, 35 and 65 mL. To improve damping capacity of the bar, grease (LUBRIPLATE® 1200-2 multipurpose grease) and copper-coated steel balls 4.5 mm in diameter were placed inside hollow boring bar. These two materials affect dynamic stiffness through internal interaction and friction. Steel balls provide two phenomena – friction and impact damping – that bring
about damping. Friction occurs between balls and between balls and internal cavity of the bar. Impact damping occurs when balls collide within cavity, dissipating kinetic energy (Xu et al., 2005). These passive damping materials have the ability to dampen a wide range of vibration frequencies. As a result, unconditional stability limit increases as dynamic stiffness is raised, resulting an improved depth of cut.

The experiments were conducted on a simulated boring bar consisting of a cantilevered hollow bar made of grade 303 stainless steel. The bar had an inner radius of 0.0171 m, an outer radius of 0.019 m, and a length of 0.34 m. The experiment setup is shown in Figure 2.

For all filling conditions, natural frequency of the bar was varied with different water levels inside the reservoir. As illustrated in Figure 2a, the level inside the reservoir can be changed using two valves before and after the reservoir attached to the bar (reservoir 1). When a higher level was desired, the outlet valve is partially closed, restricting flow from reservoir 1. In this case, the pump supplies water from reservoir 2 to reservoir 1. When a lower level in reservoir 1 is desired, the inlet valve is closed, allowing for more flow from reservoir 1 to reservoir 2.

Impact hammer tests were performed using a force-sensor-equipped impact hammer (PCB 208 A03) with a sensitivity of 1.86 mV/N and a wide frequency bandwidth accelerometer (Kistler 8778A774, 0.4 grams in weight) with a sensitivity of 10.84 mV/g. Force and acceleration/displacement were recorded using a data acquisition (DAQ). For determining static stiffness, a capacitive sensor (Lion DMT20) with sensitivity of 80 V/mm was used. The boring bar was excited at the free end with an impact force. A static weight tests using a pulley as shown in Figure 2b was performed to verify static stiffness. EMA was used to analyze the FRFs obtained from impact hammer and an accelerometer at the end of the bar for different experimental configurations.

4 Modeling

A numerical investigation was performed using design optimization module in FE software (ANSYS™), in order to evaluate the effects of proposed configurations on dynamic properties of the boring bar. Numerical results were compared with experimental results after updating of the model. An accurate numerical model permits prediction of the dynamic properties with different parameters. The numerical model can be used to find optimal system parameters to avoid chatter vibration in the boring bar.
Boring bar material properties were assumed to be that of published values for Stainless Steel 303, with a modulus of elasticity (\(E\)) of 190 GPa, a Poisson’s ratio (\(\nu\)) of 0.25 and a density (\(\rho\)) of 8000 kg/m\(^3\).

The dimensions of the boring bar modeled in FE were the same as those used in the experiment. Solid185 element was used to model the boring bar, which was defined by eight nodes with three DOFs at each node. Since boundary condition at the clamped end of the bar is not rigid, the boundary conditions were updated using four linear springs in axial direction (\(K_x\)) and four springs in radial directions (\(K_x, K_y\)). The initial FE model of the structure is shown in Figure 3 with its liquid reservoir.

![Figure 3: FE model of the boring bar with reservoir](image)

In order to identify boundary condition spring parameters, an optimization-based model updating technique was used to improve the accuracy of numerical results. The FE model updating enabled numerical results to be close to experimental values; consequently, this method improved the representation of experimental setup. Model updating process was done in FE (ANSYS\textsuperscript{TM}) using its design optimization module. The flowchart shown in Figure 4 illustrates the general process of the FE model updating.

![Figure 4: Model updating process](image)
The objective function for model updating was defined using natural frequencies of the initial FE model and those extracted from experiment. Following equation shows objective function used in model updating process (Merce et al., 2007):

\[
F_{obj} = \sum_{i=1}^{n} \left( \frac{\omega_{ni}^{FE} - \omega_{ni}^{Exp}}{\omega_{ni}^{Exp}} \right)^2
\]

where \( \omega_{ni}^{FE} \) and \( \omega_{ni}^{Exp} \) are the \( i \)th natural frequency obtained from the FE model and the experiments, respectively.

State variables (SV) were also needed for model updating and were defined as the difference between the numerical and experimental natural frequencies, as shown in Equation 4 (Merce et al., 2007).

\[
SV = \left[ \omega_{ni}^{FE} - \omega_{ni}^{Exp} \right], \quad (i = 1, 2, 3, \ldots, n)
\]

Spring values at clamped end of the bar in each direction were considered as design variables. Table 1 lists lower and upper boundaries of the design variables used in optimization process, as well as optimal parameters generated by the process for an empty boring bar. Figure 5 shows experimentally measured FRF and finite element FRF after using the model updating technique for an empty boring bar.

| Design Variables | Optimized Parameters |
|------------------|----------------------|
| \( 5E5 \text{ N/m} < K_x < 5E8 \text{ N/m} \) | \( K_x = 1.4E6 \text{ N/m} \) |
| \( 5E5 \text{ N/m} < K_y < 5E8 \text{ N/m} \) | \( K_y = 1.4E6 \text{ N/m} \) |
| \( 5E5 \text{ N/m} < K_z < 5E8 \text{ N/m} \) | \( K_z = 3.1E7 \text{ N/m} \) |

Table 1: Design variable limits and optimal parameters for empty bar

A reservoir filled with water attached to the bar was also investigated using FE modeling. In this case, the boring bar and the reservoir were separately modeled using Solid185 with different material properties and then attached to each other. Element Fluid30 was used in order to model water as an incompressible fluid inside the reservoir. This element is defined with eight nodes with four degrees of freedom per node, pressure, and translations in nodal x, y and z directions. The formulation of this element which is appropriate for fluid-solid interaction (FSI) is described in (Acton, 2008).

Water inside the reservoir was considered to have a \( \rho \) of 1000 kg/m\(^3\) and the sonic velocity of 1500 m/s. Since the solid and fluid elements selected in this research are both low-order elements and both...
solid and fluid volumes were similarly meshed, continuity conditions on the inner wall of the reservoir can be achieved simply by coupling the coincident nodes (Acton, 2008).

Numerical results for the boring bar equipped with the reservoir were updated using the experimental values. The formulas for objective function and state variables are the same as in Equations 3 and 4, but the modulus of elasticity and density of the reservoir were considered as design variables. After FE model updating, optimal values for $E$ and $\rho$ of the reservoir obtained as 5 GPa and 3500 kg/m$^3$, respectively. Figure 6 illustrates the results for experimentally measured and FE FRFs of a boring bar with full and empty reservoirs.

As can be seen in the figures, updated FE model of the structure provided modal parameters that were similar to experimental responses. Optimal value for each parameter of the system can be found using this model as a part of the process for designing a real boring bar that will minimize unwanted chatter vibration.

5 Results and Discussions

Chatter stability is dependent on dynamics of the structure, including stiffness, damping ratio and natural frequency. The dynamics of the boring bar were manipulated by using different filler materials and by changing the liquid level inside the reservoir attached at the end of the bar. The effectiveness of the proposed approach on the dynamic properties of the bar was investigated: EMA was performed to obtain FRFs of the modified boring bar. Primary mode and corresponding damping ratio of the system were extracted using least square curve fitting technique. The effectiveness of proposed method on the chatter stability of the boring process was also examined.

5.1 Dynamic Parameters and FRF Results

Table 2 shows the values of static stiffness, natural frequency and damping ratio for the modified boring bar using both the damping material and the reservoir at the end of the bar. For static stiffness, FRFs of the system were first measured by performing EMA using impact hammer and capacitive sensor. The static stiffness was then obtained from the inverse of FRF magnitude at zero frequency.

| Damping Material Packing | Added Liquid Volume (mL) | Static Stiffness [N/m] | $f_n$ [Hz] | $\zeta$ |
|--------------------------|--------------------------|------------------------|------------|--------|
| Empty                    | 0                        | 8.16E4                 | 94.22      | 0.228  |
|                          | 35                       | 8.35E4                 | 88.65      | 0.220  |
|                          | 65                       | 8.36E4                 | 74.51      | 0.185  |
| Grease                   | 0                        | 1.04E5                 | 81.17      | 0.218  |
|                          | 35                       | 1.04E5                 | 76.67      | 0.209  |
|                          | 65                       | 1.08E5                 | 71.63      | 0.186  |
| Steel balls              | 0                        | 1.12E5                 | 59.65      | 0.186  |
|                          | 35                       | 9.34E4                 | 60.20      | 0.173  |
|                          | 65                       | 9.70E4                 | 56.49      | 0.182  |

Table 2: Dynamic parameters using different packing materials inside the bar with liquid reservoir

From Table 2, filling boring bar with grease and steel balls increased its static stiffness by 32 and 38%, respectively. Increases in static stiffness can be attributed to the structure to resist deformations caused by applied loads (Wahyuni et al., 2010). There were no notable differences found in the values of damping coefficients for each configuration compared to empty boring bar. The values for damping
ratio could have been varied during curve fitting process, since there are uncertainties associated with the curve fitting of FRFs, which is dependent on the selected range of frequencies. More investigations are required to determine materials that can cause significant changes in the damping ratio.

As expected, the amount of primary natural frequency decreased with the addition of different materials to the boring bar, as they increased the overall mass of the system. The smallest natural frequency (56.49 Hz) was resulted from a ball-filled bar with a reservoir full of water. The FRF results for different water levels in the reservoir are shown in Figures 7 and 8. For empty bar in Figure 7, first natural frequency at 65 mL level shifted from 94.22 Hz to 74.51 Hz, an approximately 21% reduction compared to the bar without a reservoir.

For the bar filled with grease and equipped with a reservoir in Figure 8, first natural frequency with a water level of 65 mL shifted from 81.17 Hz to 71.63 Hz, an 11.75% reduction. For the bar filled with steel balls and equipped with a reservoir, first natural frequency shifted from 59.65 Hz to 56.49 Hz, a 5.30% reduction in the natural frequency. Due to its mass, the ball-filled bar had the smallest range of variations in natural frequency.

The extracted dynamic properties can be used to find chatter stability lobes of the system to predict stable cutting conditions in real boring operations. The design of the reservoir and liquid properties (i.e. viscosity, density, etc.) should be selected carefully for this method to be effective. Larger reservoirs or higher density liquids may be needed to achieve the desired shift in natural frequency for heavier boring bars.

5.2 Chatter Stability Simulations

One-dimensional (1-D) chatter stability theorem of boring process was used to predict stability, and the resulting lobes were compared for different reservoir liquid levels and packing conditions. The dynamic parameters obtained from experiments were used to predict the lobes. The stability lobes were obtained using the critical depth of cut given in Equation 2, where the cutting coefficient was considered to be $K_r = 1000\text{E}4\text{ (N/m}^2\text{)}$.
Figure 9 shows the stability lobes for the empty bar equipped with the reservoir at different liquid levels (full and empty). The unconditional stability limit declined when the natural frequency decreased due to a reduction in damping ratio at smaller natural frequencies. The stability lobes were successfully shifted, especially at higher operating speeds. Figure 10 shows stability lobes for the grease-filled bar with empty and full fluid levels in the reservoir attached to the end of it.

Stability is affected when system dynamics are continuously altered when controlling liquid level, so that the process falls in an unstable condition when cutting. To address this challenge, robust chatter stability method based on the edge theorem can be implemented (Graham et al., 2014). Robust chatter stability is based on minimum and maximum bounds of changing dynamics, and the method guarantees stability within the range of changing parameters.

Advantages of the proposed scheme are cost-effectiveness and simple implementation of the chatter suppression compared to other active boring bar systems. This approach can also be readily used in other machine tool structures (i.e. milling machines) to alter the desired dynamics. However, the frequency bandwidth of this approach is limited, due to the inability to rapidly change the fluid levels.

Future study will include investigation of the effects of viscosity and friction, which may affect damping parameters, and performance of physical boring operations that prevent chatter vibrations. Experimental chatter tests on physical boring bars are needed to investigate feasibility of the approach. Moreover, the proposed method will be applied on other machine tool structures to improve the dynamics.

6 Conclusion

In boring operations, a long overhang boring bar presents a critical challenge due to low dynamics stiffness. This often causes chatter, which leads to tool breakage and part failure. Moreover, maintaining the constant depth of cut and cutting speed is desirable in boring operations, in order to minimize sudden changes in inertia and cutting forces. In order to achieve high productivity in boring operations, the suppression of chatter is important. In this study, different types of boring bar filler materials were investigated to examine static stiffness and damping characteristics; and, a reservoir was installed at the end of the boring bar and filled with different levels of water. The natural frequency of boring bar was altered by changing fluid level in the reservoir. Two different types of filler materials – grease and steel balls – were used to fill the hollow bar, due to their ability to dissipate energy in the system through internal interactions and frictions.

EMA was used to extract FRFs of the system at different conditions. Static stiffness improved by adding materials inside the bar. By adding different materials inside, deformation resistance of the bar against external loads increases. The damping coefficient did not change significantly with modification of the boring bar, which can be attributed to challenges of the curve fitting of FRFs; further investigations are needed. The natural frequencies of the boring bar were manipulated by changing overall mass of the bar by adding fluids in the bar’s reservoir. FE numerical simulations were performed by modeling the boring bar with and without the reservoir at different liquid levels. FE models exhibited similar trends as the experimental results for the different cases. These models can be used to effectively design optimized structures with desired dynamics.
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