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On-line control of machine tool vibration in turning operation using electro-magneto rheological damper

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ABSTRACT

Purpose of this work is to develop and implement an Electro-Magneto-Rheological damper that can be used to monitor and control the process dynamics of the cutting tool in hard turning operation. Magneto-Rheological (MR) damper consists of non-suspended magnetic iron particles and oil (MR fluid) whose viscosity and shearing stress can be controlled by changing the magnetic field around it with the help of current passing through the coils wrapped around the cylinder damper containing MR fluid. Study involved the characterization of MR fluid as well as vibration characterization of MR damper. MR damper provides variable stiffness and better damping ability and hence better control over the noise and frequency responsible for unstable machining. The experimental results show that dynamic response of the cutting tool system is improved by a maximum of 77% in terms of acceleration ratio with the Electro-Magneto-Rheological damper. Transmissibility approach and half power band width method in the paper was successfully used to analyse the signal amplitude ratio, the damping ratio and the time required by MR damper to settle down the frequency generated by dynamic fluctuation of cutting force. In addition, dynamic stability of the cutting tool holder was obtained with second mode of vibration using finite element software. The damper has improved the machining process in terms of better surface finish on the workpiece by 22.2%, reduced tool wear by 20%, reduced cutting force by 12.9% and enhanced productivity overall.

1. Introduction

Tool vibration in cutting process is primarily due to the fluctuations in cutting force during shearing of chip and the presence of frictional force between the tool and the workpiece. Two major types of vibration experienced by tool are self-excited and forced vibration. Instability in the cutting process is primarily caused by chatter which occurs when the rigidity of the cutting tool and its support is smaller in one direction and allowing the cutting tool to vibrate in one direction only (Type 1 or Type 2 chatter [1]). Type 1 chatter indicates the movement of cutting tool in longitudinal direction while Type 2 in transverse direction depending on the relative stiffness in the corresponding motion of the cutting tool. Here in this work Type 2 chatter is considered for the analysis because magnetorheological damper is placed at the bottom of the cutting tool in the direction of cutting speed to suppress the cutting tool vibration, assuming that no motion of the cutting tool takes place in the longitudinal direction. To understand and control the tool vibration (non-linear responses), theoretical modelling and its analysis pose a great importance. Many research works are still in progress for proper theoretical analysis of tool vibration. Practically, cost involved in eliminating machine vibration is too high. Therefore, industries have to find certain alternatives to achieve machining process free from vibration. In view of that, this work emphasizes on introducing an active damper with less operating cost. MR damper consists of piston cylinder (containing MR fluid) arrangement and coils that are wrapped around the cylinder. In this electromagnetic damper, with supply of electric current to the coil, eddy current developed inside the piston-cylinder arrangement. According to the Lenz law, this eddy current created time varying magnetic field of opposite polarity, leading to the formation of chain-like structure of MR particles. The strength of this chain depended on viscosity and shear stress which were controllable. This created a reaction force which would try to balance the main cutting force in order to suppress vibration.

Even though a lot of research works have been conducted on tool vibration, only a few studies can be found on controlling tool vibration on-line using controllable damper. Therefore, this work focuses on the design and development of controllable damper

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which can be easily installed making it competent to diminish tool vibration on-line. Yan et al. [2], Gluiduo et al. [3] and Metered et al. [4] have primarily focused on the design and development of MR damper whose design parameters were theoretically calculated and properties of MR fluid were found out through bi-viscous hysteresis analysis. Experimentally they were able to identify the dynamic behaviour of the MR damper. Xiao et al. [5] and Al-Regib et al. [6] have proposed a model to suppress chatter by optimal section of the spindle speed. Tarang et al. [7] and Park et al. [8] have emphasized on suppressing tool vibration by implementing active or passive damper in turning and other cutting processes. Frumusanu et al. [9] and Chen et al. [10] have stabilized the chattering in turning process by implementing online monitoring technique. Kovacic [11] has proposed a nonlinear model of cutting force and nonlinear analytical model of chatter based upon shear zone model. Lacerda and Lima [12] have experimentally evaluated the natural frequency, damping and residual stresses developed in the machine-workpiece-tool system. They were able to select the cutting parameters resulting into better surface finish and reduced chatter vibration in milling process. According to literatures in above discussion it was obvious that in general higher cutting velocity was responsible for occurrence of chatter. This is possible only when the cutting force increased with the increase in cutting speed as reported by Pan et al. [13]. Rusinek et al. [14] have concluded that even at higher cutting velocity chatter can be suppressed provided there was no regenerative effect on the work material. Lipski et al. [15] have observed that the vibration occurred due to the disturbance in the tool and workpiece which resulted into large noise because of higher amplitude in cutting force. Researchers [16,17] have studied the effect of magnetic field on the damping ability of the MR damper in hard turning operation. Their investigation is based on the selection of three different shapes of the piston plunger followed by carrier fluid and different mesh size of iron particles. Promising result of damping was obtained with the use of conical plunger, 75 μm size of iron particle mixed with SAE 40 oil as carrier fluid. But the characterization of MR fluid and its magnetic properties with the simulation studies were not done by the authors. Therefore, it can be concluded from the above literature survey that most of the researchers had focused on suppressing machine vibration and chattering by developing a theoretical model by employing well known stability theorem namely, Lyapunov stability, Asymptotic stability, Poincare stability, Lagrange stability, Rayleigh self-excitation model and others. Many works were focused on the occurrence of chatter because of cutting speed and the random fluctuations of cutting force. In the past, engineers had tried to design the machine and its supporting structure (for increasing static stiffness) to minimize the unbalance. But even today, during machining with such newly designed advanced machines undulation marks (regenerative effect) are encountered on the work material. This gives the thought to research community to develop or modify machines to produce desired product for higher industrial applications.

Thus, many researchers had tried to suppress the vibration of cutting tool through the modelling by appropriately selecting cutting velocity so as to avoid the random fluctuation of cutting force. Main focus in this paper is to design a Magneto-Rheological damper and install at the bottom of tool in hard turning process, ensuring that this arrangement is highly responsive to the applied force at given cutting parameters. Number of turns of coils required to achieve the possible amount of magnetic field at varying DC power supply through external source was calculated. In addition, characterization of magneto-rheological fluid and damper was studied. Transmissibility approach was adopted to determine the damping factor of cutting tool in vibratory motion on machining hardened AISI D2 steel in turning process.

2. Design and characterization of magneto-rheological fluid damper

Magneto-Rheological fluid is non-suspension and non-colloidal mixture of micron sized magnetisable particles mixed with non-magnetic carried fluid. 70% Fe-particle mixed with 30% viscous SAE 40 oil has been used in this work based on the recommendation given in the Lord Corporation data hand book for Magneto-Rheological fluid. In the presence of magnetic field, these micron-sized Fe-particles in SAE 40 oil begin to align along the flux path and form particle chain-like structure which is shown in Fig. 1. This particle chain helps to restrict the fluid movement by increasing the viscosity of the MR fluid. Due to this behaviour of MR fluid, it is used as a medium in the damper to enhance the damping force required to suppress the cutting tool vibration exerted in the turning process. The main advantage of MR fluid is its ability to reversibly change from free-flowing linear viscous liquid to semi-solid substance with controllable yield strength. This can be achieved by controlling the induced magnetic field by controlling current across the coil. MR fluid was stirred till the MR particles were homogenously distributed within the oil. The viscosity of the mixture is a measure of flow characteristic and is an important property. A rheometer (Anton Paar MCR 301 MRD 180 attachment) was used to measure the viscosity and other flow properties (shear stress, shear rate) of the mixture in the presence of magnetic field when subjected to varying temperature. Weight constituent of MR fluid in damper with 40 mm diameter and 25 mm height was found out from Eq. (1). The composition of MR fluid is shown in Table 1.

$$\text{Weight of sample} = \frac{V_T \times S_{weight(\%)} \times \rho_{Sample}}{100} \quad (1)$$

Where V_T is total volume of MR fluid in cc, $S_{weight(\%)}$ is weight percentage of sample, ρ_{Sample} is sample density in gm/cc.

In order to understand the rheological behaviour of MR fluid it is very important to do the characterisation of MR fluid. Fig. 2(a) shows variation of the shear stress with respect to shear rate for the MR fluid with the application of current supplied to the system. Viscosity of MR fluid with respect to shear rate is shown in Fig. 2(b). It was observed that MR fluid behaviour is quite Non-Newtonian due to the alignment of MR particles in the direction of magnetic flux path created due to the supply of electric current while shear thinning was observed when there was no magnetic field at zero electric current. Further, Fig. 2(b) demonstrates the shear thinning behaviour of MR fluid with increasing shear rate at individual supply of electric field. With increase in supply of electric field, shear thickening was observed. This is because of increase in magnetic field due to increase in electric field that restricts the mobility of Fe-particles between the two poles (N-S). The trend observed was also in agreement with the inverse relation that exists between viscosity and shear rate in case of Non-Newtonian fluid. At a temperature of 25 °C and varying electric current (1A, 1.1A and 1.2A), mean viscosity values of MR fluid were found to be 0.9 kPa s, 1.6 kPa s and 1.7 kPa s respectively and that at zero electric current (i.e., no magnetic field generated) viscosity was 0.9 kPa s.

Fig. 3 shows the relationship between viscosity and shear rate for MR fluid at varying temperature. It was observed that with increase in temperature MR fluid loses its viscosity and becomes thinner making it ineffective in suppressing the tool vibration. Viscosity of the fluid stabilizes at higher values of shear rate. Mean yield viscosity for this case was observed to be less than 0.5 kPa s.

Magneto-Rheological damper consists of piston-cylinder arrangement filled with MR fluid. Standard Cu wire was used for the windings of the damper, as shown in Fig. 4. The magnetic field generated by supplying electric current determines the physical behaviour of MR damper. Damping can be controlled by controlling the shear stress and viscosity of MR fluid. These rheological