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Analysis of ultrasonic assisted machining (UAM) on regenerative chatter in turning

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ABSTRACT

Ultrasonic assisted machining (UAM) is an advanced technology for improving the machining process, especially for hard materials. This paper presents an experimental and theoretical study toward the effect of UAM on chatter. Theoretical explanation of the effect of UAM on chatter is not fully presented in the available literature yet. In this paper, considering fixed tool geometry, theoretical dynamic equations for UAM are represented. The approach is demonstrated by deriving dynamic formulation of UAM in turning, considering both turning equation and Merchants ultrasonic machining equations. A time domain analysis is fulfilled on each machining condition to verify whether it has a stable vibration or an unstable chatter vibration. Subsequently, an experimental setup is designed and manufactured to investigate UAM effect on regenerative chatter. Special conical shape for workpiece is designed to experimentally generate different points of stability lobe. The generated oscillation by a piezoelectric actuator is transferred, amplified, and concentrated on the tip of the tool by appropriate design of a cutting tool, which is vibrated in its bending mode. The obtained results are encouraging, and indicating good agreement between experimental and theoretical results.

1. Introduction

Machining is the most widespread metal processing technology in the manufacturing industry. Recently, there is considerable research on development of high speed machining processes, to achieve accurate finishing and maximum chip removal in a cutting process. In this context, metal cutting has a troublesome obstacle in achieving perfect surface finish, named chatter. It also has deteriorating effect on accuracy of cutting, disturbs workpiece finishing, decreases metal cutting rate, and shortens tool lifetime.

Tlusty (2000) defined chatter as self regenerative vibration, which happens in a particular spindle speed when the chip width is too large in comparison with dynamic stiffness. Chatter is a self excited vibration, which can happen due to different reasons. Among various types of chatter, regenerative chatter is considered to be the most dominant type of the chatter in the turning operations. Regenerative chatter is generated as a result of the interaction between the structural dynamics of the machine, and the cutting process (Merrit, 1965). If properly applied, UAM can provide positive effects on chatter suppression. In UAM, the cutting tool is vibrated in an ultrasonic frequency, which has shown effective positive impact on finishing of hard materials, such as diamond turning of stainless steel (Moriwaki and Shamoto, 1991) and ceramics (Kumabe et al., 1989), but the effectiveness of UAM on chatter avoidance with the aim to achieve high chip removal has not been studied. The main advantage of UAM is decreasing the required amount of cutting force (Wang and Zhao, 1987). Moreover, it increases the rate of heat removal, which in turn decreases the tool temperature and increases the tool lifetime (Kumabe and Masuko, 1958). UAM has shown significant advantageous in productivity; for example reducing the manufacturing time by about 5–10%, as well as the machining cost by about 30% (Ma et al., 2005). There is considerable literature on the effect of elliptical ultrasonic vibration on different aspects of the machining process. Shamoto and Moriwaki (1999) have compared the effect of elliptical vibration cutting of hardened steel with the conventional vibration cutting. Ma et al. (2004) have shown both theoretically and experimentally that the machining accuracy is improved by applying ultrasonic elliptical vibration. Subsequently, they investigated the regenerative chatter suppression by applying ultrasonic elliptical vibration (Ma et al., 2010). In this method, vibration is applied to the cutting tool in two directions. However, they did not discuss the effect of the UAM on the stability lobe diagrams to understand this effect in different spindle speeds. In the current research, regenerative chatter suppression is investigated for high chip removal by considering bending mode of vibration. In addition, results are discussed on the well known stability lobes diagram.

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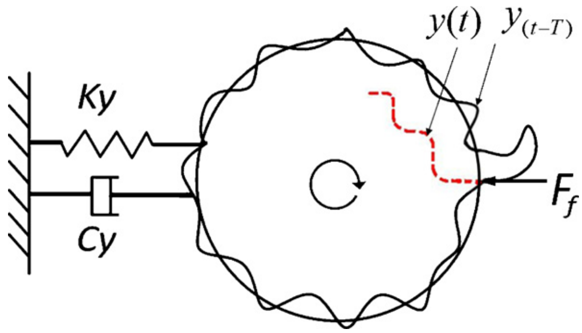

Fig. 1. Orthogonal chatter due to regenerative effect.

Xiao et al. (2002) experimentally showed that chatter is suppressed in UAM regardless of the tool geometry, while it had considerable effect in conventional machining. Without providing any analytical justification, they claimed that UAM always achieves a higher cutting stability as compared with conventional cutting process.

The work within this paper focuses on the validation of the presented model for UAM and its effect on chatter. First, a theoretical review of regenerative chatter and UAM are presented. Then, considering the set of equations, a new dynamic model for UAM effect on chatter is derived. Time domain simulation of the derived model indicates whether or not a particular machining condition is stable. Obtained results demonstrate that UAM helps suppress chatter in some machining conditions, while it may worsen the stability against chatter in some other conditions. An experimental setup is designed and manufactured to evaluate the developed theoretical model. A piezoelectric transducer vibrates the tool in its bending mode, in a constant ultrasonic frequency. Cutting tool configuration is designed to have the optimum vibration on the tip of the tool. In addition, an innovative conical shape for the workpiece is designed to effectively determine the allowable depth of cut for each spindle speed in the presence of ultrasonic vibration. By this workpiece geometry, stability lobes for turning can be investigated via test.

In next section, the background theories are reviewed to demonstrate how dynamic equations of UAM are derived. Afterwards, the detailed design of the utilized Langevin type piezoelectric transducers is described. Moreover, cutting tool geometry and innovative conical form of workpiece are presented. Subsequently, simulation results and laboratory experiments are presented, and then obtained results are compared. Following a discussion on the comparison of theoretical and experimental results, the conclusions of the research are outlined.

2. A review of the theory

2.1. Chatter modeling and equations

Fig. 1 illustrates the mechanism of regenerative chatter in a turning process, which is proved to be the most dominant mechanism in occurrence of instable chatter in machining (Altintas, 2000).

Obviously, the machine may vibrate as a result of dynamic machining forces. The dynamic equations of the vibration of the machine can be presented in the following form:

$$[M]\ddot{y}(t) + [C]\dot{y}(t) + [K]y(t) = F_f(t) \quad (1)$$

where M, C and K represent mass, damping and stiffness matrices of the lathe machine respectively, and $F_f(t)$ is the cutting force.

It is supposed that the tool remains perpendicular to workpiece during machining. As illustrated in Fig. 1, due to the vibration of the system, real amount of chip thickness is not equal to the intended chip thickness. Dynamic chip thickness is:

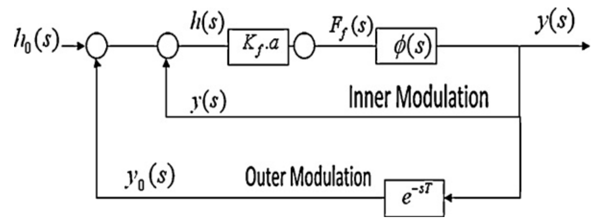

Fig. 2. Block diagram of system.

$$h(t) = [h_0 + y(t-T) - y(t)] \quad (2)$$

where h_0 is the intended chip thickness, $y(t)$ is the equation of the waves on the current cutting surface, which can be derived from the structural dynamic equations of the machine (Eq. (1)), and $y(t-T)$ represents the wave equation in previous revolution. Let a and K_f be the width of the cut and the cutting coefficient, respectively. According to the theories of mechanics of machining, the machining force can be computed by:

$$F_f(t) = K_f \cdot a \cdot h(t) = K_f \cdot a[h_0 + y(t-T) - y(t)] \quad (3)$$

Transferring Eqs. (1) to (3) to Laplace domain, the system dynamics can be represented by the block diagram shown in Fig. 2 (Altintas, 2000).

Then, the transfer function between the intended chip thickness and the dynamic one would be:

$$\frac{h(s)}{h_0(s)} = \frac{1}{1 + (1 - e^{-sT})K_f \cdot a \cdot \Phi(s)} \quad (4)$$

where $\Phi(s)$ is the transfer function between the relative tool-workpiece displacement and the cutting force exerted on the tool-workpiece contact point. Critical stability of the system can be derived by substituting $s = j\omega_c$, where ω_c is the chatter frequency. Equating both real and imaginary parts of the nominator equation (characteristic equation) to zero leads to determination of the stability boundary of machining. Considering $G(\omega)$ and $H(\omega)$ as the real and imaginary parts of the transfer function, following equations can be derived (Altintas, 2000).

$$a_{\lim} = \frac{-1}{2K_f \cdot G(\omega_c)} \quad (5)$$

$$\tan\ \psi = \frac{H(\omega_c)}{G(\omega_c)} = \frac{\sin\ \omega_c T}{\cos\ \omega_c T - 1} = \tan\left[\left(\frac{\omega_c T}{2}\right) - \frac{3\pi}{2}\right] \quad (6)$$

$$\omega_c T = (2k+1)\pi + 2\psi, \quad k = 1, 2, 3, \ldots \quad (7)$$

According to Eq. (5), chatter can happen in frequencies that $G(w_c)$ is negative. Eqs. (6) and (7) compute those spindle speeds (n [rev/s] = $60/T$) which can generate a particular chatter frequency (ω_c). Stability lob diagrams are common graphical representation of the border between stable and unstable cutting conditions, which can be generated using Eqs. (5) and (6). The procedure of drawing the stability lobs has been illustrated by Altintas (2000). It determines the maximum allowable depth of cut in each spindle speed. As shown in Fig. 3, area beneath the lobes represents stable cutting conditions, while any point above the borders leads to an unstable cutting.

2.2. Ultrasonic assisted machining (UAM)

In UAM, the cutting tool is vibrated by means of an external source – usually a piezoelectric transducer – in an ultrasonic frequency, with some micrometers amplitude. Consequently, the cutting force is also periodic. A commonly accepted model for