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Chatter reduction in boring process by using piezoelectric shunt damping with experimental verification

Ufuk Yigit [a], Ender Cigeroglu [a],*, Erhan Budak [b]

[a] The Department of Mechanical Engineering, Middle East Technical University, 06800 Ankara, Turkey
[b] Manufacturing Research Laboratory, Sabanci University, Orhanli, 81474 Tuzla, Istanbul, Turkey

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ABSTRACT

Chatter is a self-excited type of vibration that develops during machining due to process-structure dynamic interactions resulting in modulated chip thickness. Chatter is an important problem as it results in poor surface quality, reduced productivity and tool life. The stability of a cutting process is strongly influenced by the frequency response function (FRF) at the cutting point.

In this study, the effect of piezoelectric shunt damping on chatter vibrations in a boring process is studied. In piezoelectric shunt damping method, an electrical impedance is connected to a piezoelectric transducer which is bonded on cutting tool. Electrical impedance of the circuit consisting of piezoceramic transducer and passive shunt is tuned to the desired natural frequency of the cutting tool in order to maximize damping. The optimum damping is achieved in analytical and finite element models (FEM) by using a genetic algorithm focusing on the real part of the tool point FRF rather than the amplitude. Later, a practical boring bar is considered where the optimum circuit parameters are obtained by the FEM. Afterwards, the effect of the optimized piezoelectric shunt damping on the dynamic rigidity and absolute stability limit of the cutting process are investigated experimentally by modal analysis and cutting tests. It is both theoretically and experimentally shown that application of piezoelectric shunt damping results in a significant increase in the absolute stability limit in boring operations.

1. Introduction

Chatter is a self-induced vibration problem that results from the variation of chip thickness under cutting conditions. The mechanism of chatter for different machining processes was first understood and explained by Tobias [1] and Tlusty [2]. Chatter instability can be recognized by a rapid increase of noise during the cutting process. Due to this instability, high variable cutting forces could develop resulting in poor surface quality, reduced tool life and violation of dimensional tolerances in the workpiece. Chatter problems can be grouped in two categories based on their formation mechanisms: regenerative and mode coupled chatter. In general, regenerative chatter is taken as the criteria for determining cutting stability as it is less stable compared to mode coupling [2]. The source of regenerative chatter is the variation of chip thickness due to vibration marks left on the surface in two subsequent passes. The phase difference between previously machined and the new cutting surfaces creates variation in chip thickness. Changes in cutting force due to these variations developing at the chatter

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* Corresponding author.
E-mail address: ender@metu.edu.tr (E. Cigeroglu).

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frequency limit the stable depth of cut in machining processes. Stability limit for regenerative chatter in an orthogonal cutting process was derived by Tlusty and Polacek [3] where stable depth of cut limit was obtained as

$$b_{\lim} = -\frac{1}{2K_f\, Re[G(\omega)]} \tag{1}$$

where K_f is the cutting force coefficient in the chip thickness direction and $Re[G(\omega)]$ is the real part of the frequency response function (FRF) at the cutting point. Note that, in order to have a physically meaningful chip width, $Re[G(\omega)]$ should have negative values. In other words, chatter frequency must be higher than the natural frequency. Absolute stability limit is defined as the guaranteed stable depth of cut for all cutting speeds, i.e. the minimum stable depth, and can be determined by substituting $Re[G(\omega)]_{\min}$ which represents the minimum of real part of tool point FRF in Eq. (1). As the chatter frequency varies with the rotational speed due to its effect on the period between two subsequent passes, so do $Re[G(\omega)]$ and stability limits resulting in stability lobes. A sample stability lobe diagram is given in Fig. 1 which illustrates the unstable (chatter) and stable (chatter free) regions.

Analysis of chatter stability in boring and turning processes are more complicated compared to orthogonal cutting process stability model given by Eq. (1) where process dynamics as a function of tool inclination angle, nose radius, depth of cut and feed rate was investigated by Atabey et al. [4,5]. Their experiments showed that runouts in axial and radial directions create periodic cutting forces perpendicular to the longitudinal axis of the boring head. Another study on boring stability was performed by Ozlu and Budak [6,7]. They developed a multi-directional dynamic force and response relations, which yielded an eigenvalue problem for the solution of stability limit. They demonstrated that increase in insert nose radius drastically decreased stability limit in boring processes due to increased effect of vibrations on the chip thickness.

In case of rotating tools such as in milling operations, the stability analysis become more complicated due to time varying system dynamics. Budak and Altintas [8,9] developed a method for prediction of stability limits in milling using Floquet's theorem, Fourier series and Hill's determinant. Boring process is used to enlarge or finish the diameter of a pre-drilled hole in order to improve its dimensional and surface quality. In these operations, slender and long boring bars, which are usually highly flexible, and thus prone to chatter, are used. As the chatter frequency-to-spindle rotation frequency ratios for boring operations are usually very high, stability pockets are very narrow; hence, absolute stability limit guarantees the stable cutting which is directly a function of the minimum of real part of tool point FRF as shown in Eq. (1).

Piezoelectricity is the coupling between mechanical and electrical behavior of a material. A piezoelectric material produces the displacement of the electrical charges inside when a mechanical stress is applied on the polarization direction. This phenomenon is called direct piezoelectric effect. Conversely, under the application of an electric field they can produce strain which is called converse piezoelectric effect as explained in detail by Leo [10]. In piezoelectric shunt damping (PSD), an electrical impedance (resistor and inductance) is placed as a shunt on the electrical terminals of a piezoelectric transducer bonded on a mechanical structure. The dynamics of electrical circuit (shunt and the electrical capacity of the transducer) is similar to the dynamics of a second order mechanical structure (the same frequency of resonance). Piezoelectric shunt circuits are formed by series and parallel combinations of resistances, capacitances and inductors. According to Moheimani, and Fleming [11], the idea of adding shunting circuits to a mechanical structure was first proposed by Forward [12] in 1979. Passive linear shunt circuits can be classified in two groups as single mode shunting circuit (if one mode of a structure is damped) and multi-mode shunting circuit (if damping of multiple modes with one piezoceramic pair is aimed).

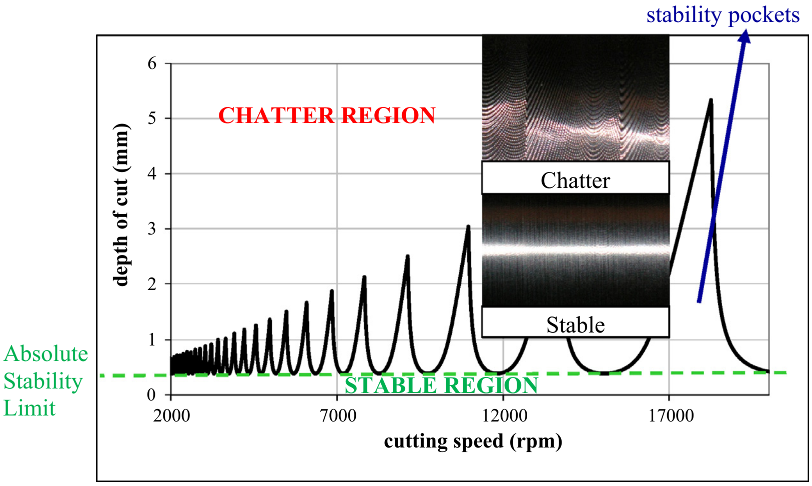

Fig. 1. Stability lobe diagram for chatter problems.