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Electromagnetic actuator for determining frequency response functions of dynamic modal testing on milling tool

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ABSTRACT

Machine tools are the main driving forces of industrialization of a country. However, poor machinability because of chatter vibration results in poor surface quality, excessive noise, and reduced material removal rate. Modal testing is a useful method to investigate dynamic properties of a cutting tool system and improve material removal rate. However, at present, modal testing using impact hammer is limited by certain problems. This paper developed a non-contacting electromagnetic actuator (EMA) to determine frequency response functions (FRFs) under amplitude and speed dependencies of cutting milling tools. The geometry was designed using magnetic circuit analysis and generalized machined theory before finite element analysis was conducted using magnetostatic-ansys software. Next, EMA was used as a contacting and non-contacting exciter of a conventional milling machine to determine the FRFs and dynamic properties of milling tool with amplitude and speed dependencies including comparison with static FRFs. Subsequently, dynamic properties and FRFs are used to establish stability lobe diagram. Stability lobe diagram also shows an improvement of up to 5% of depth of cut at lower spindle speed. In conclusion, by generating force that applies to static and dynamic modal testing, an EMA can determine dynamic properties and stability lobe diagram for increasing material removal rate and production rate.

1. Introduction

Milling is one of the most common process in manufacturing sectors. However, high-speed machining problems, particularly tool chatter in function of both spindle speed and depth of cut. Thus, many researchers found that to detect or reduce chatter, its dynamic characteristics, such as natural frequency, damping ratio, mode shapes, and frequency response functions (FRFs), need to be determined.

To predict the stability of a cutting tool system, modal testing is required to gain its dynamic properties and FRFs [1,2]. Traditionally, impact hammer and shaker were commonly used as exciters. An impact hammer provides a point impulse force with the width of the impulse defining the frequency content. However, a variety of waveforms is not available, and the magnitude is not controllable unless an additional mechanism is integrated to control the amplitude of excitation [3–5]. In addition, steps must be taken to ensure that the impacts are positioned with sufficient precision on the tool. Shakers also do not apply a point force to the structure when the fixture, on which it is mounted, is shaken. Additionally, setting up the test stand of the structure is often difficult.

For chatter modeling, analytical empirical models, such as those presented by Altintas et al. [6], were used. These models can be derived by performing cutting tests under different machining conditions and recording cutting forces using a dynamometer. Once both structural and

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process parameters were determined, different methods such as frequency-domain or time-domain approaches may be employed to predict the stability of the machine process. Process methods take advantage of the lobe pattern of the stability charts to determine suitable machining conditions. Structural dynamics can be identified via FRF measurements at the tooltip and on the workpiece to obtain the relative tool-workpiece receptance functions. For instance, mass of the accelerometer might disturb measurement [7]. The receptance functions can also be estimated using modeling methods. In Cao et al. [8], the finite element method was used. However, because stability predictions were very sensitive to the modal properties of the critical modes of the machine, especially the modal damping, only qualitative predictions could be obtained. A combined approach can be employed using measured FRFs on a spindle nose coupled with finite element (FE) model of the tool via receptance coupling methods [9]. Recently, Koroishi et al. [10] presented a vibration active control technique devoted to rotating machinery by incorporating electromagnetic actuators (EMA), which considers uncertainties in the parameters of the system. The gains of the EMA are determined by using linear matrix inequalities.

Another approach for chatter control consists of adapting structural parameters such that the process stability can be guaranteed for the specified machining conditions. Yang et al. [11] suggested the use of multiple tuned mass damper (TMD) for stabilization of the turning process and demonstrated the possibility of improving performance over a single TMD without significantly increasing total additional mass. Moreover, active magnetic bearings are well-suited for high speed cutting applications characterized by high cutting speeds and low cutting forces. Their active nature can be used for self-balancing or improvement of process stability. Fittro [12] and Kyung [13] developed a milling spindle shaft suspended by five-axes active magnetic bearings where each was independently controlled using a proportional-derivative controller. However, it gives extremely high cost; its usage is limited to special applications. A hexapod kinematic structure using three pairs of piezoelectric actuators controlled by proportional-derivative controllers was presented in Neugebauer et al. [14]. The system was used to create an irregular surface in a boring operation. Teo et al. [15] focused on modeling of flexure-based supporting bearings, thermal modeling of electromagnetic module, and the unique characteristics of the system having predictable and re-configurable open-loop positioning resolution. In an experiment, Schmitz et al. [16] identified an increase in dynamic stiffness and stability limits at high spindle speeds for a particular spindle system. In Cao et al. [8], the frequency split by gyroscopic moment was not usually detected in experiment measurements. Increasing or decreasing the damping ratio directly affects this phenomenon. The common damping ratio shown in machines was less evident on the FRFs split, while lower damping ratios increased FRF split. According to Grossi et al. [17], specific cutting coefficients were identified at different spindle speeds. The obtained speed-varying force coefficients were used to improve reliability of stability lobe diagrams (SLD) for high speed machining as proven by experiments.

According to the literature review, noncontact actuators have potential in reducing chatter. However, the previous design did not have a linear relationship between the forces and input amplitude. Thus, another method was developed to overcome this limitation. This paper presents a non-contacting and linear EMA developed for static and dynamic used under amplitude and speed dependencies. The EMA is a non-contacting excitation way yet its setup is more simple and easy. The analyses throughout the design and experimental processes are shown.

2. Electro Magnetic Actuator design

The actuator design focused on creating the required 10 N force amplitudes. This design was made after the calculation in Eq. (7), followed by the EMA stability test that is presented in the results section. Furthermore, such a process enabled accurate FRFs measurement for a representative range of machine tools. The EMA was designed for use along with ferromagnetic tool materials as these can provide an ideal path for magnetic flux. It was also designed to produce controllable force profiles to tool blanks mounted in the tool holder of a conventional milling machine. Current and voltage supplied to the core windings created a magnetic flux via the actuator core and across the air gap. When the tool was positioned in the gap, a magnetic attraction and reluctance force was developed in proportion to the core flux. This reluctance force provided controllable yet non-contacting excitation to achieve one kHz frequency range. The target bandwidth for the EMA was therefore set to 1000 Hz and the swept-sine excitation signal was set to sweep from 0 to 1000 Hz. Furthermore, this generation of prototype utilized a solid ferromagnetic core similar in performance characteristic to the first generation EMA prototype [18].

An E-frame core was selected because of its potential to have higher electromagnetic force compared to the C-frame that was previously used by other researchers [19,20]. The E-frame names from the core structure resemble the capital E as shown in Fig. 1. A single winding was wrapped around each layer of laminated electrical soft steel core. The initial design started by considering the E-frame electromagnet core with a rectangular cross-section. A rectangular cross section was chosen because of the shape that can minimize flux leakage, whereas the straight section provided sufficient length for coil windings. In addition, Esterling et al. [4] also found that the criteria used to evaluate candidate core design were maximization of electromagnetic force on cutting tool, maximization of stable magnetic flux, and minimization of overall actuator size.

In Fig. 1, when a high current signal was applied to the coil, a controllable and stable magnetic flux was found in the core and air gap. Thus, when the cutting tool was placed in this air gap, the magnetic flux created a controllable force that can be used for FRFs excitation [18]. Based on the criteria in evaluating candidate core design stated earlier, the main consideration of EMA was the