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Modeling and characterization of an electromagnetic system for the estimation of Frequency Response Function of spindle

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ABSTRACT

The paper presents an electromagnetic system that has been developed to measure the quasi-static and dynamic behavior of machine-tool spindle, at different spindle speeds. This system consists in four Pulse Width Modulation amplifiers and four electromagnets to produce magnetic forces of ±190 N for the static mode and ±80 N for the dynamic mode up to 5 kHz. In order to measure the Frequency Response Function (FRF) of spindle, the applied force is required, which is a key issue. A dynamic force model is proposed in order to obtain the load from the measured current in the amplifiers. The model depends on the exciting frequency and on the magnetic characteristics of the system. The predicted force at high speed is validated with a specific experiment and the performance limits of the experimental device are investigated. The FRF obtained with the electromagnetic system is compared to a classical tap test measurement.

1. Introduction

The dynamic behavior of spindles has a great influence on the quality of machined parts, notably in the aircraft industry where instabilities in milling can lead to non-quality and reduced lifetime of spindle bearings [1] and cutting tool [2]. To improve the productivity of machine tools and to avoid the occurrence of chatter during milling, stability lobes diagrams are commonly used. The Frequency Response Function (FRF) at the tool tip is required and classically obtained by hammer impact test. It provides good results in classical milling. However, as shown in several studies [3–5] the dynamic behavior of High Speed Machining spindles varies at high speed due to dynamic effects. Schmitz et al. [6] were the first to make measurements on a rotating spindle. Tap tests were performed at the tool tip, during spindle rotation. The displacement was measured with eddy-current sensors. In order to improve the measurement accuracy and repeatability, Albrecht et al. [4] used a specific tool with a ball bearing to make hammer impact test measurement on a fixed surface. Active Magnetic Bearings (AMB) were then used to apply non contact excitation to the spindle [7,8] and to measure the cutting forces [9]. Rantatalo et al. [10] have presented a contact-less dynamic spindle excitation device that can apply a dynamic force of ±15 N from 400 to 2000 Hz. Matsubara et al. [11] succeeded to apply a dynamic force of 110 N from 0 to 1000 Hz with their electromagnetic system, however it presents non-linearities. Strong requirement are required in order to analyze the dynamic behavior of high speed spindles.

This paper presents an excitation device capable of applying a dynamic load of ±80 N at up to 5000 Hz. A specific current amplifier has been designed for this purpose. The control is linearized with the use of pre-magnetisation and an

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experimental protocol to measure the flux density at a large range of frequency is proposed. Thus, the applied force can be precisely estimated over the entire frequency range. First of all, the system design is described, then electromagnetic force models are developed for the static and dynamic excitation modes. The specific experiments carried out to validate the model and to update the permeability of the magnetic core are described. The dynamic characteristics of the excitation device are then studied. Finally, FRF measurement are made with the excitation system on a HSM spindle at several speeds and are compared with a classic tap test experiment.

2. Description of the excitation system

The excitation system shown in Fig. 1, consists in a radial magnetic bearing with two perpendicular axes (x and y) and a dummy tool with an HSK 63A interface for the mounting into the spindle rotor. Each axis is composed of two identical electromagnets with magnetic field of opposing directions to produce a radial force. A pre-magnetisation is applied in order to improve the performance and linearize the control. The system is designed to provide a magnetic force with amplitudes until ±190 N for the static mode and ±80 N for the dynamic mode. Each electromagnet is made of two coils of wire wrapped around a core of ferromagnetic steel sheets. The coils are wired in parallel one to each other in order to improve dynamic efficiency. The magnetic core is made from laminated sheet of grain oriented electrical steel (3% Si-Fe) The core structure comprises 170 sheets with a thickness of 0.08 mm which are assembled shifting each oriented sheet from the previous one by an angle of 90°. A large cross section A_e of the magnetic core was chosen. This configuration, studied in [12], gives the best performances concerning the magnetizing current, the core loss amount, the relative permeability and the reactive power. A stack of ferromagnetic steel sheets is also integrated in the dummy tool to strengthen the magnetic attraction.

3. Theoretical model of the electro magnetic force

In order to determine the analytic force model, a single two-pole electromagnet is considered, as presented in Fig. 2. The figure illustrates the geometrical parameters of the electromagnet, i.e. effective magnetic path length l_e, air gap s and effective cross-section area A_a in the air gap. Since the air gap lengths are sufficiently small compared with their cross-sectional dimensions, the fringing flux effect can be neglected. In this consideration, the magnetic flux ϕ is homogeneous in the core (c) and the air gaps (a), i.e. $\phi = B_c A_e = B_a A_a$. Then, the flux density B is the same along the path l_e in the magnetic core (B_c) and in the air gap (B_a), i.e. $B_a = B_c = B$. Thus, the cross-sectional areas are the same $A_a = A_e$. Under these assumptions, the magnetic system can be assumed lossless and the magnetic force can be derived from the energy W_a stored in the two air gaps, by

$$W_a = \frac{1}{2} B H_a A_e 2s \tag{1}$$

where H_a is the magnetic field intensity in one air gap, A_e is the cross-sectional area and s is the air gap length. The flux density B is obtained through the permeability of free space $\mu_0 : B = \mu_0 H_a$. Let's consider a radial displacement x of the shaft, along the radial force f. It involves a variation of the air gap of $x \cdot \cos(\alpha)$ (where α is the semi-angle between the two elementary forces, acting at each air gap). The force can be obtained from the principle of the virtual work $dW = fdx$. Assuming that B remains constant, the magnetic force f of the two-pole electromagnet derives from [13]:

$$f = \frac{dW_a}{dx} = \frac{B^2}{\mu_0} A_e \cos(\alpha) \tag{2}$$

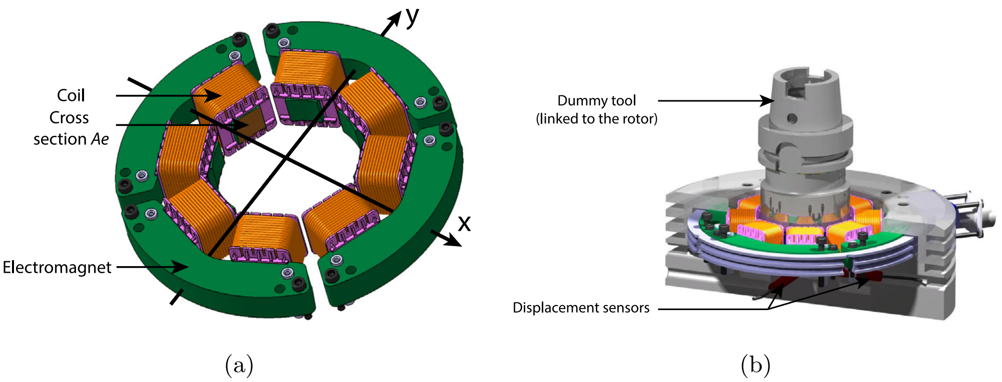

Fig. 1. (a) The arrangement of the two pairs of electromagnets. (b) Sectional view of the excitation system and dummy tool.