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5-DOF harmonic frequency control using contactless magnetic guides

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ABSTRACT

In order to attenuate harmonic disturbances of a milling process, the contactless magnetic guide of a milling machine prototype is being used as a sensor and actuator at the same time. This paper gives an outline of an algorithm that detects such harmonic disturbances through the guide's inherent sensory capability and calculates a corresponding correction force in five degrees of freedom while adapting to the disturbance in phase, amplitude and frequency. The computed compensation force is transmitted to the spindle using the magnetic guide. The algorithm is designed with regard to low computational cost and examined in simulation and by experiment. The resulting surface is also analyzed.

1. Introduction

As a matter of principle, milling machines are subject to a process-induced vibration excitation during operation. On the basis of a full-size three-axis milling machine prototype, this paper demonstrates the active attenuation of excitations of the spindle slide originating in a milling process. It will be shown that by attenuation of the spindle slide the resulting workpiece's surface can be improved. The milling machine features a contactless magnetic guide, which is being employed as a sensor and actuator at the same time to reduce vibrations.

Subsequent to an overview of the nature of the disturbances in a milling process, a short survey on mechatronic systems in machine tools is given. Then the test rig is explained and the algorithm and its application onto the machine tool are discussed in the following. The results are analyzed by means of measurements using simulation and experiment. This work closes with a short summary and outlook.

1.1. Disturbances in milling processes

The milling process uses a rotating tool and is therefore of a periodic nature. The impact impulses of the cutting edges striking the material lead to a periodic forced excitation of the tool, the workpiece and the whole machine structure. In case of equal tooth spacing, this tooth passing frequency will amount to a multiple (according to the number of teeth) of the rotational frequency. Unequal tooth spacing can distribute the energy throughout a wider range of frequencies as investigated by Doolean [1]. Presuming run out, the rotational frequency will be clearly visible within the spectrum of a milling process. Imperfect roundness or differing wear of the cutting edges will also produce an excitation proportional to the rotational frequency. Mainly originating in non-sinusoidal excitation, higher harmonics of both, the rotational and the tooth passing frequency are also visible in the process forces, but usually in lower amplitudes. Since the impulse-shaped cutting forces form a wide-band stimulus, eigenfrequencies of the cutter, the workpiece and the machine tool may also appear. As long as the process remains stable, the rotational and the tooth passing frequency constitute the dominant excitation. In case of unstable processes such as regenerative chatter, the eigenfrequencies of the tool and the machine become predominant for the overall system dynamics and influence the chatter frequency. An essay on different chatter frequencies in milling processes can for example be found in [2] by Insperger et al. (2003).

Within this article, the investigated processes remain stable. Nevertheless, the described disturbances do not only periodically excite the cutting tool but also the underlying machine frame. Dependent on its stiffness, the structure will answer with an oscillation, possibly leading to an amplified disturbance at the workpiece compared to an ideally stiff machine. All of these disturbances may be visible in the resulting surface of the workpiece.

1.2. Mechatronics in machine tools

The extension of a machine tool by additional sensory or actuatory capabilities has been gaining impetus as promising means to raise the productivity and stability of manufacturing processes. A comprehensive overview of mechatronic systems in machine tools is given by Neugebauer et al. [3] and presents a variety of possible applications. Regarding milling machines,

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general interest is on the one hand directed towards detecting the process forces to perform process and machine surveillance. On the other hand, beneficially influencing the machine's vibration characteristics is highly desirable, since these characteristics limit the achievable operational speed and precision to a great extend.

Current approaches to introduce such new subsystems into machine tools may thereby be distinguished into solely sensory solutions and active or passive combined actor/sensor systems. The knowledge of the process forces permits detailed process diagnosis, thus among the first group this has been subject to extensive investigations. One possible solution is the integration of displacement sensors (e.g. eddy current or capacitive) into the spindle as shown by Albrecht et al. [4]. Another approach is monitoring the spindle and motor currents and combining it with a friction model as shown by Lapp [5]. Such systems have become popular in the industrial application as they can be integrated into the NC-control with a limited effort and allow simple process surveillance such as missing tool detection or even material changes and tool wear. Due to presumably imprecise wear models and relatively slow sampling intervals, today's commercially available solutions still suffer from low precision and resolution in time and amplitude compared to additional sensory equipment. This issue can be addressed through a combined process simulation as presented in [6] by Denkena and Schmidt (2006), which can be parameterized according to the instantaneous operational data from the NC-control. An attachment of rotating spindle-bound wireless dynamometers leads to precise torque and force measurements, but it comes with some significant disadvantages concerning cost, stiffness and handling. It is therefore restrained to laboratory usage. Sensors integrated into the workpiece holder or clamping system are more likely to ease this issue. Litwinski et al. use such a clamping system for diagnostic purposes in [7].

Beyond sole measurements, an adjustable alteration of the machine's dynamic behavior requires some kind of an actuator. The electric feed drives of a machine tool do usually offer relatively low dynamics (usually <50 Hz at -3 dB), so additional highly dynamic actuators are being installed in machine tools. Piezoelectric devices and low-inductive electromagnetic actuators in particular have proven to be well-suited for this task. Again both, the spindle and the workpiece can be targeted. For example, a piezoelectric holder for the workpiece presented in [8] by Rashid and Nicolescu (2006) allows quick workpiece relocation in two directions. Here, the dynamic properties do rely on the mass of the workpiece. In [9] Denkena et al. (2006) relocate the whole main spindle in three directions with the help of piezoelectric actuators, thus the dynamic properties are decoupled from the workpiece's weight. Primarily targeting non-rotating tools like those being used in turning applications, highly dynamic actuation sytems have been referred to as Fast Tool Servos (FTS). Such a tool that is actuated by electromagnets has been constructed by Trumper and Lu [10]. Brecher and Schauerte (2008) have presented a piezoelectrically actuated boring bar in [11], where the blades are individually controlled and vibration damping can be achieved. Rotational electromagnetic bearings have been successfully used for vibration detection and process influence, such as by Kern et al. [12].

2. Test rig

A new machine design approach which for the first time integrates an adaptronic linear electromagnetic guide as a core component into a full-size three-axis milling machine has been developed at IFW in collaboration with IDS and is presented in [13]. An image of the machine is shown in Fig. 1. In this machine concept

Fig. 1. Machine tool with active magnetic guides.

the spindle is installed in a Z-axis slide (see Fig. 2) that is guided employing the principle of electromagnetic levitation. The X- and Y-axis are guided by conventional linear ball bearings. As an additional feature, each machine axis is driven by linear direct drives, allowing very high axis accelerations between 4.3 and 4.7 g.

The stabilization of the Z-slide in five degrees of freedom (DOF) represents the mechanical guidance function and is achieved by a state-space controller using Kalman filtering. To control the magnetic guide, the air gaps at each electromagnet are measured and transformed into a generalized coordinate system ($q_1, \ldots, q_5$) representing five of the slide's six physical rigid body DOF as shown in Fig. 2. Additionally, accelerations in these five DOF are being measured by multi-axis acceleration sensors on the front and back sides of the slide.

Based on the instantaneous air gaps and accelerations, a normalized position controller calculates corrective forces in each DOF. These are then inversely transformed back into forces for the individual electromagnets and applied to the guide. The controller is currently running at 5 kHz and implemented on a Power-PC platform running at 366 MHz. In its traverse direction the Z-axis' linear direct drives are operated by a standard Siemens 840D industry controller. In result, each DOF of the spindle is being actively controlled. There is no physical contact between the spindle and the machine frame, due to the contactless guide and drive. It is therefore possible to relocate the whole spindle by dynamic adjustment of the air gaps, as it has been shown by Kallage [14]. This can be used to significantly improve machine precision. As a matter of principle the magnetic guide takes direct part in the distribution of forces. Thus, disturbances and forces at the tool center point (TCP) may be detected or impressed through the active guide.

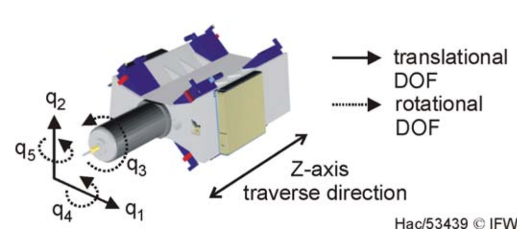

Fig. 2. The Z-axis slide.