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Compensation of Disturbances on Force Signals for Five-Axis Milling Processes

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Abstract

Products and hence processes for todays manufacturing industry sectors become more and more complex in terms of geometry. Increasing quality demands furthermore prove the need for deep process understanding, product-oriented process monitoring and adaptive control of the machining process. For all of these topics production-suitable sensor solutions are needed, especially the precise measurement of cutting forces. This paper describes the application of stationary force measurement platforms for five-axis milling processes with compensated force signals. The sensor system is developed for the use on a multi axis machining centre and suitable for all processes with non-stationary workpiece axis, e.g., turning operations and five-axis milling processes. The present paper focusses on the scientific and technical challenges for the development of an appropriate measurement system for five-axis milling processes. The main technical challenges are the compensation of the dynamic forces, the consideration of the gravity force and the changing mass due to the metal cutting process. For this reason, information about the current workpiece position, velocity and acceleration is used for compensating forces that are not resulting from the machining process itself. The compensation of these disturbance forces is executed by means of a suitable, intelligent calibration methodology. Test results on a machine tool in a production environment and the theory for compensation will be presented in this paper. Furthermore, details about the functional design of the system will be provided.

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1. Introduction

The manufacturing of products in high-wage countries is more profitable when producing complex and high-value added parts. Such complex parts e.g., aero engine components or parts of tool and die making require complex machining operations. Especially aero engine components consist of hard-to-machine materials like titanium or nickel based super alloys which lead to high requirements on the tools and machining processes. Furthermore, the high value of the rough-machined parts and even the raw material demand manufacturing processes operating at very high level.

In most cases machining of these components can only be done by means of five-axis milling processes. Due to the part's high value from the early beginning of the manufacturing process, monitoring the machining operation becomes essential for economical success. Furthermore, manufacturing safety critical parts for aero engines demand a continuous monitoring of the manufacturing process to ensure product quality and avoid failure during life cycle.

For milling, measurement of forces has proven to be suitable to monitor the milling process [1]. In general, all measurement is affected by unrequested influence which has to be taken into account when analyzing the data. Force measurement in each milling process is dynamically affected through the entering and exiting of the tool's teeth during every revolution [2]. Using five-axis milling processes, additional effects influencing the force measurement occur due to the process kinematic and movement.

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This paper describes the technical challenges of compensating static and dynamic effects on the force signals in five-axis milling in order to be able to distinguish process forces and dynamic forces evoked by motion.

2. Force Measurement for Milling Processes

The measurement of forces in milling processes can either be done on the workpiece or on the tool side [3]. Solutions measuring the forces on the tool side are not applicable for production in a real industrial environment, hence measurement on the workpiece side is conducted in industrial and scientific practice [4]. Machine tools for five-axis machining most often realize the linear movement in three axis on the spindle side and the additional rotational movement of two axis on the table side. Hence, the workpiece mounted on a force measurement platform underlies the two overlaying rotational movements which lead to static and dynamic forces acting on the workpiece. Whenever a dynamometer is in motion during measurement, the force signals are affected by side effects such as gravitation. These disturbing signals overlay the real process forces.

Measuring the cutting force has proved particularly suitable for understanding and quantifying machining processes. On the one hand, the knowledge of the cutting force is essential for the machine tool design and its components such as drives and machine tool structure. On the other hand, it provides a valuable insight into the process. With the help of the cutting force one can define optimum cutting conditions, estimate the level of the workpiece accuracy, identify plasto-mechanic processes and even understand tool wear mechanisms. The cutting force is a common standard to evaluate the cutting characteristics such as a material's machinability .

Force measuring devices based on piezoelectric technology, so-called dynamometers, play an important role in the analysis of machining processes. The ability to acquire high-quality signals of high-dynamic processes is an outstanding feature of piezoelectric force sensors in general. Its sensitivity to measure even the smallest variation on the process is favored but misleading to some extent when used for 5-axis machining.

3. Disturbance Forces on Five-Axis Milling Process

The measurement of forces during the five-axis milling process inheres several sources of disturbances that have to be considered when taking signals during the machining process. On the machine tool side the changing alignment of tool and workpiece coordinate system needs to be taken into account. Besides the forces that occur through the machining process itself there are other effects that need to be considered, namely the dynamic forces, the weight forces due to gravitation and the loss of mass due to the metal cutting process itself.

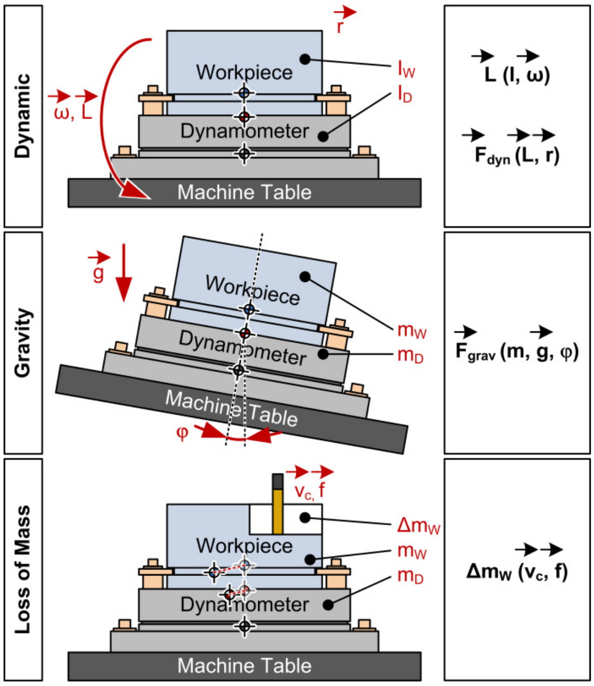

Fig. 1. Overview of Disturbance Forces during Milling Process.

3.1. Dynamic Forces

The dynamic forces occur due to fast rotational movement and acceleration of the workpiece mounted on the measurement platform. The effect takes strong influence especially in finishing operations of e.g., turbine blades where fast move ment of the rotational axis is needed to machine around the leading and trailing edge. Due to the rotational acceleration a dynamic torque acts on the platform as shown in Fig. 1 at the top. The torque **L** can be calculated by the product of the body's moment of inertia **I** and the angular velocity ω:

$$\vec{L} = I \cdot \vec{\omega}, \tag{1}$$

where **L** and **ω** are vectors and **I** is a matrix [5]. The torque **L** can be considered as the disturbance torque that acts on the dynamometer due to rotational movement. With the known dimensions of the force measurement platform the real force can be calculated by:

$$\begin{aligned} \vec{F}_{real} &= \vec{F}_{measured} - \vec{F}_{dyn} \\ \vec{L} &= \vec{r}_{Piezo} \times \vec{F}_{dyn} \end{aligned}, \tag{2}$$

where $\mathbf{F}_{\mathbf{real}}$ is the vector of the real force, $\mathbf{F}_{\mathbf{measured}}$ is the force that is measured from the force measurement device and $\mathbf{r}_{\mathbf{Piezo}}$ describes the position of the force piezo-sensors on the platform.