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Dynamic analysis of a piezoelectric system to compensate for workpiece deformations in flexible milling

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ABSTRACT

This paper presents a system to compensate for workpiece deformations in flexible peripheral milling based on piezoelectric actuators, and its dynamic model. The compensation system is formed by a flexure hinge based worktable, which is moved by a piezoelectric actuator to compensate the workpiece deformation induced by cutting forces. The command signal to the actuator is calculated from measured cutting forces. When the compensation system is acting, the cutting force values from the flexible system reach the corresponding values for the rigid model, ensuring that the tool is cutting the nominal width of cut. The model considers the performance of three subsystems which interact between them during the machining process: the positioning system, the structural assembly and the flexible machining process itself. The parameter identification of the dynamic model was experimentally obtained from modal analysis and a system identification procedure. The cutting forces in the model take into account the workpiece deformation and its compensation on the instantaneous chip thickness and the width of cut. The proposed compensation system has its main application in the machining of small parts of thin walls although the methodology is applicable to larger parts.

1. Introduction

Smart manufacturing requires the transformation of modern factories into highly automated and efficient production systems. The development of machining processes which are able to decide autonomously is a constant in the evolution of manufacturing technologies over the last years. An increasing number of sensors and actuators are being incorporated in manufacturing, transforming it into smarter processes. Recent advances in sensors and actuators [1] have favoured the incorporation of more complex mechatronic systems in manufacturing systems [2].

Piezoelectric actuators have been successfully applied in machine tool environment [3] to improve the precision of tool positioning in turning [4] and milling [5]. The feasibility of using a piezoelectric actuator was already demonstrated to compensate static deformations which occur during milling of flexible components [6]. In flexible machining, the low rigidity of workpiece or tool may lead to machining errors due to deformations induced by cutting forces. In addition, low rigidity of the system might result in chatter, deteriorating the surface finish of the machined component.

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Nomenclature

a_p	nominal axial depth of cut [mm]
a_{pa}	actual axial depth of cut [mm]
a_e	nominal radial depth of cut (width of cut) [mm]
a_{ea}	actual radial depth of cut [mm]
c_{wp}	modal damping coefficient of the workpiece $\left[\frac{N}{m}s\right]$
c_{wt}	modal damping coefficient of the worktable $\left[\frac{N}{m}s\right]$
d	tool diameter [mm]
f_c	cutting frequency [Hz]
f_z	feed per tooth [mm/tooth]
F_t	tangential cutting force [N]
F_r	radial cutting force [N]
F_x	cutting force in X direction [N]
F_y	cutting force in Y direction
G_{pa}	first order transfer function of the positioning subsystem [–]
h_d	dynamic chip thickness [mm]
$\bar{h}_s$	static average chip thickness [mm]
K	gain of the positioning subsystem transfer function [–]
k_t	specific cutting pressure in tangential direction [N/mm]
k_r	specific cutting pressure in radial direction [N/mm]
k_{wp}	modal stiffness coefficient of the workpiece $\left[\frac{N}{m}\right]$
k_{wt}	modal stiffness coefficient of the worktable $\left[\frac{N}{m}\right]$
m_{wp}	modal mass coefficient of the workpiece [kg]
m_{wt}	modal mass coefficient of the worktable [kg]
n	spindle speed [rpm]
N	tool flute number [–]
y_{wp}	vibratory displacement (position) of the workpiece [μm]
y_{wt}	vibratory displacement (position) of the worktable [μm]
y_{pa}	position response of the piezoelectric actuator [μm]
y_{com}	position command signal [μm]
y_{com}	voltage command signal [V]
$\Delta(\varphi)$	arc of the engaged length of the cutting flute [rad]
φ	tool position angle [rad]
φ_m	average point for the engaged arc where cutting force is applied [rad]
φ_{pr}	projection of the active length of the cutting flute on XY plane [rad]
τ_p	delay of the machining process [s]
τ	time constant of the positioning subsystem transfer function [s]

The goal of this work is to develop a model to analyse the dynamic behaviour of a flexible milling operation considering in process compensation of workpiece deformations. Compensation system is based on a piezoelectric actuator, which provides high frequency and high precision response. The method has a useful application in milling of flexible components. The main contribution of this paper lies in achieving the error compensation in real time from cutting force measurement during the process. This compensation methodology is novel since previous research has been focused mainly on off-line compensation strategies.

The paper is divided into two sections. The first one is aimed at presenting the developed dynamic model. Based on this model, the compensation system is simulated dynamically, in order to prove its application to part deformations in flexible milling. Additionally, it is possible to determine stable cutting conditions for different geometries of cutting tools and workpieces used in different machining operations.

In the second part of this paper, the feasibility of the procedure is proved on the machine tool, demonstrating its adequacy to compensate workpiece deformations.

2. State of art in milling of flexible components

In flexible machining systems, the low stiffness of workpieces or the system formed by the tool, the tool holder and the spindle, can lead to machining errors due to the deformations induced by cutting forces during machining. Errors caused by cutting forces have been well described in the literature. The origin of these errors is that as a result of the cutting forces action, the relative position between workpiece and tool may vary [7]. Logically, a lower static stiffness of the machining system, favour the occurrence of deformations resulting in workpiece errors that affect the tolerances. In this context, Budak