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Feasibility study of in-process compensation of deformations in flexible milling

Eduardo Diez [a,*], Hilde Perez [b], Juan Marquez [c], Antonio Vizan [c]

[a] Department of Mechanical Engineering, Universidad de La Frontera, Temuco, Chile
[b] Department of Mechanical, Informatics and Aerospace Engineering, Universidad de Leon, Leon, Spain
[c] Department of Mechanical and Manufacturing Engineering, Universidad Politecnica de Madrid, Madrid, Spain

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ABSTRACT

During the machining of thin-walled parts, deformation can occur resulting in dimensional errors. These dimensional errors cause a variation on cutting forces. From the actual measured cutting forces and the estimated forces resultant from rigid machining, it is possible to determine the value of this deformation. Based on this, an on-line system for compensating workpiece errors, has been developed. The system is based on correcting the relative position of the tool-workpiece during machining by means of a piezoelectric actuator. The objective is achieved in real time to compensate for the part deformations from the measurement of the cutting forces, without the programming of the tool path trajectories in the machine tool being affected.

1. Introduction

At present, machining of low rigidity parts is a common manufacturing operation in many industrial sectors. There are examples in areas as diverse as the aeronautics and aerospace industry, the manufacture of molds and dies in the plastics industry, or the manufacture of micro-electro-mechanical systems (MEMS). In the machining of thin-walled parts, one of the most significant problems is the deformation the workpiece suffers as a result of the forces that occur during cutting. In order to reduce the errors produced by deformations, the common practice is to select conservative cutting conditions, such as lower feed rates or depths of cut (axial or radial), or to increase the number of tooth passes, thus raising machining times and costs.

In particular, in the aeronautical sector, the design of thin-walled components continues to be of great interest because they make possible the production of lightweight resistant structural parts, which provide airplanes with greater energy efficiency [1]. In this sector, high-speed machining has improved the capacity to produce thin-walled components because the forces produced are greatly reduced. In spite of this, better control of these deformations would enable more productive processes. This problem also occurs in micro-electro-mechanical systems (MEMS) components, which are desired for machining processes. In micro-milling operations, although the tool can have a greatly reduced diameter, the thickness of the walls can also be reduced. In addition, it can occur when machining worpkpieces without thin walls that their morphology may encourage deformation during machining.

2. State of the art

For decades, one of the most important aspects covered in the study of machining processes has been the estimation of the cutting forces. The interest in estimating these forces using reliable models lies in the need, among others, to obtain a more precise knowledge of the process, in having models that allow the necessary machining power to be estimated, in the possibility of accurately defining the elements of the machine-tool and in the use of the information of the cutting forces in process control algorithms that optimize the machining process. Through the cutting forces it is possible to obtain large amount of data on the material removal process, so that any variation in the values of the forces will indicate changes in the machining conditions, as for example a change in the properties of the workpiece, changes in the machining geometry, stability of the process, indirect estimation of the surface finish, etc.

In milling of low rigidity parts, limitations of the process are

* Corresponding author.
E-mail addresses: eduardo.diez@ufrontera.cl (E. Diez), hilde.perez@unileon.es (H. Perez), avizan@etsii.upm.es (A. Vizan).

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Nomenclature

a_p [mm] nominal axial depth of cut
a_{pa} [mm] actual axial depth of cut
a_e [mm] radial depth of cut (width of cut)
A_0 [mm^2] mean chip section
d [mm] tool diameter
f_z [mm/tooth] feed per tooth
f [mm/min] linear feed
F_t [N] tangential cutting force
F_r [N] radial cutting force
F_a [N] axial cutting force
F_x [N] cutting force in X direction
F_y [N] cutting force in Y direction
F_z [N] cutting force in Z direction
$\overline{h}$ [mm] mean chip thickness
k_t [N/mm] specific cutting pressure in tangential direction
k_r [N/mm] specific cutting pressure in radial direction
k_a [N/mm] specific cutting pressure in axial direction
n [rpm] spindle speed
N [-] tool flute number
R [mm] tool radius
φ [rad] tool position angle
φ_{aver} [rad] angle of the engagement arc where cutting force is applied
φ_{en} [rad] Entry angle
φ_e [rad] engagement angle
φ_{ena} [rad] actual entry angle
φ_{ex} [rad] Exit angle
φ_j [rad] angle of the tip of the flute j
φ_m [rad] approximated angle of the engagement arc where cutting force is applied
φ_{pr} [rad] projected angle of the cutting edge
δ [mm] workpiece deviation due to cutting force
λ_s [rad] tool helix angle
x_c [V] actuator command signal

caused by the flexibility of the workpiece, which contributes to both the instability of the process (high vibrations during the process, chatter) and static deformations of the workpiece during machining. Both issues directly affect the production times and the part quality. For the case of difficult-to-cut materials, like titanium alloys or nickel based alloys, deformation is produced due to high cutting forces needed to cut these materials.

In order to improve the machining operations of flexible workpieces, one of the most frequently studied aspects for several years has been the stability of the process and dynamic related issues, with the goal being to avoid chatter during machining. These studies have concentrated mainly on determining the operating conditions that maximize material removal, avoiding the instability of the process associated with one or more of the eigenmodes of the structure of either the spindle-tool system or the workpiece. An extensive amount of literature on this subject has been published. Since the topic of this article is related to compensation of the errors due to static deformations of the machining system under stability conditions, literature review in this article do not cover dynamic related issues.

In the case of static deformations during the machining of low rigidity components, studies mainly concentrate on quantifying the errors by means of direct measurement or numerical simulation. In the case of simulation, the deformations and the cutting forces must be calculated simultaneously. These calculations have been made using finite element simulation [2] and mechanistic models of the cutting process [3]. In any case, once the errors have been quantified, an offline correction is made by reprogramming the CNC code or by creating machining strategies that include the deformations the workpiece will undergo. Ratchev et al. [4,5] proposed a methodology to evaluate and correct the deformations that a flexible workpiece suffers during machining. The approach is based on identifying and modeling key characteristics of the process that affect the deformation of the workpiece, modeling the cutting process numerically (calculation of forces), predicting the deformations using the finite element method, and finally correcting the deformation by programming an improved tool trajectory. A variant of this methodology, in which the forces are calculated by means of force and deformation models, was developed by Ratchev et al. [6]. A similar approach, applied to machining of tubular workpieces, was developed by Bera et al. [7]. Such methodologies base their effectiveness on the hypothesis that the machining operation has high repeatability. Another approach to correcting machining errors due to deformations is by

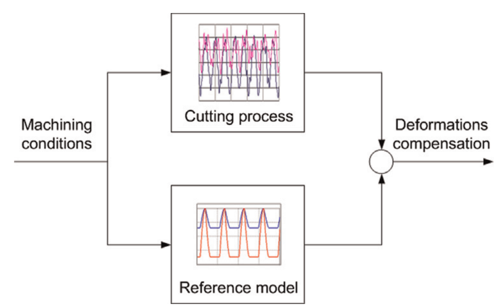

Fig. 1. Basic diagram of the system to compensate for deformations.

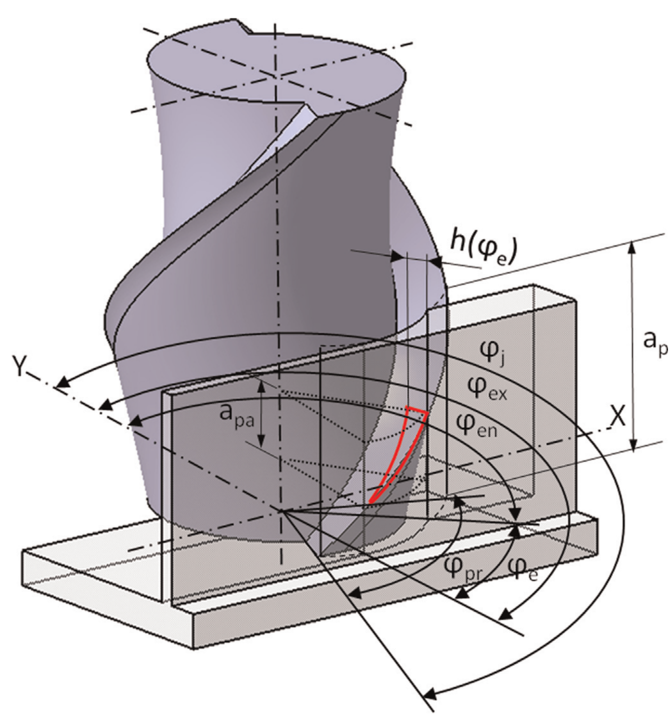

Fig. 2. Cutting geometry for milling of low-rigidity parts.