Measurement 128 (2018) 170–179

Contents lists available at ScienceDirect

Measurement

journal homepage: www.elsevier.com/locate/measurement

Accuracy of a new online method for measuring machining parameters in milling

E. Leal-Muñoz[a], E. Diez[b,*], H. Perez[c], A. Vizan[a]

[a] Departamento de Ingeniería Mecánica, Universidad Politécnica de Madrid, Madrid, Spain
[b] Departamento de Ingeniería Mecánica, Universidad de La Frontera, Temuco, Chile
[c] Departamento de Ingenierías Mecánica, Informática y Aeroespacial, Universidad de León, León, Spain

ARTICLE INFO

Keywords:
End milling
Cutting parameters
Uncertainty analysis
Milling dynamics

ABSTRACT

The development of new methodologies to monitor, control and optimize manufacturing systems is on the increase. In this sense, the aim of this paper is to analyze the accuracy of an online method for measuring machining parameters from cutting force signals in milling processes. The method is based on time measurement which, in principle, provides sufficient precision to detect minor variations in cutting parameters. In order to assess the accuracy of the method, the sensitivity and uncertainty of the variables involved have been determined, classifying them according to their influence on the results. The dynamic response of the tool may affect the accuracy of the measurement. For this reason, a function that relates the response time to the input variables in the process is determined. The force signal is obtained with a dynamometric platform using piezoelectric sensors, which provides robustness to the proposed measurement method. The results of the measurement of depths of cut show a high degree of precision with uncertainties below 4%.

1. Introduction

For years, the manufacturing industry has raised automation levels thereby increasing productivity. Currently, emphasis is being placed on increasing the intelligence level in production processes, which is intended to allow the process to evaluate its own performance. Consequently, the process acts on this information in order to optimize it, by self-adapting under varying conditions or by resolving incidents.

Milling processes are frequent in the machining sector for machining prismatic workpieces, mostly pockets and slots. Machined pieces generally involve changes in their geometry and therefore, in the cutting conditions. These changes give rise to variations in the efficiency of the cutting operation and consequently, to tool life.

In the context of machining processes, sensoring is becoming more frequent for the optimization of processes related to cutting conditions, so as to know the state of the machine or to monitor tool wear, among others. The purpose is to obtain a greater amount of information so that decisions can be made in real time in order to improve the efficiency of the process.

To this end, it is necessary to have precise machining models and a reliable measurement method which is able to detect any variation in machining conditions. Currently, there are well-developed milling models, which optimize the milling process [1]. However, the detection of variations in machining conditions is still an issue to be solved. The difficulty here is to find a measurement procedure which is sufficiently robust and capable of being used in real manufacturing conditions and which, at the same time, allows for the measurement of the machining parameters in a variety of geometries and materials.

A procedure for measuring machining parameters based on the measurement of cutting forces has been developed by the authors. The calculation procedure is based on time measurement from the cutting force signal. This signal contains all the necessary information in order to determine the axial and radial depth of cut. However, to make this a success, the precision of the measurement method is crucial.

The online knowledge of these parameters during the process, a_e and a_p, will help to determine variations with respect to the nominal parameters. This has not been possible to achieve in an efficient way until now. The knowledge of a_p and a_e in real time and online, allows for the optimization of the cutting process through adaptive or optimized controls.

The study presented here focuses on analyzing the accuracy of the measurement method, through the evaluation of the sensitivity and uncertainty of the variables involved in the process. These are evaluated and classified according to their influence on the results.

The dynamic response of the machining process may affect the cutting force signal and consequently, the result of the measurement.

* Corresponding author at: Avenida Francisco Salazar 01145, Temuco, Chile.
E-mail address: eduardo.diez@ufrontera.cl (E. Diez).

https://doi.org/10.1016/j.measurement.2018.06.018
Received 13 April 2018; Received in revised form 27 May 2018; Accepted 11 June 2018
Available online 14 June 2018
0263-2241/

Nomenclature

a_e	radial depth of cut, mm
a_{e_i}	radial depth of cut of the flute i, mm
a_p	axial depth of cut, mm
a_{p_i}	axial depth of cut of the flute i, mm
a_{pa}	actual axial depth of cut, mm
φ_{en}	entry angle, rad
φ_{en_i}	entry angle of flute i, rad
φ_{en_0}	nominal entry angle, rad
φ_{pr}	projected angle of the cutting edge, rad
D	tool diameter, mm
N	tool flute number, –
λ_s	tool helix angle, rad
λ	tool runout position, rad
ρ	tool runout value, µm
R_i	radius of the flute i, mm
n	spindle speed, rpm
f_z	feed per tooth, mm
V	cutting speed, m/min
F_y	cutting force in Y direction, N
t_{pul}	time between the analogic pulse and the reference pulse, s
t'_{pul}	entry time of the analogic pulse with respect to the measurement, s
t_{en_i}	entry time for i flute with respect to the reference, s
t'_{en_i}	entry time for flute i with respect to the measurement, s
t_{exit_i}	exit time for flute i with respect to the reference, s
t'_{exit_i}	exit time for flute i with respect to the measurement, s
t_{pr_i}	projected time of flute i, s
t'_{ref}	time for positioning the reference pulse with respect to the measurement, s
t_{ex_i}	exit time for flute i related to exit angle, s
T	period of spindle rotation, s
$\Delta_{t_{exit}}$	retard time, s
D_{r_i}	real diameter considering runout, mm
S_r	samples per revolution, S/revolution
δ	uncertainty, [–]

For this reason, the method takes into account the dynamic response in the measurement for any condition in the milling process.

1.1. State of the art

The efficiency of the cutting process and the quality of the resultant workpieces are conditioned by setting cutting parameters adequately. Even though the machining parameters are set to optimized values, they should be changed during the machining process, as the process is variable due to tool wear, variations in geometry or other types of disturbance. Therefore, the monitoring of parameters such as feed and depths of cut has become an important issue for the development of adaptive control systems in machining processes, as well as optimizing new milling strategies.

The progress in monitoring systems has been focused on the development of adaptive controls [2], which have been used to adapt the cutting conditions accordingly, in order to minimize production costs, to improve the quality of the resultant part [3] and to lengthen tool life [4,5].

In this way, the need to determine the depth of cut so as to control the influence on vibrations and surface finish has been studied by numerous researchers. Among them, Ratnam et al. [6] studied the effect of machining parameters on surface roughness and tool vibrations. With the aim of finding the best combination of machining parameters to reach the lowest level of vibration. Olejárová et al. [7] extend the analysis to cutting speeds and also to depths of cut. On the other hand, Ribeiro et al. [8] have studied the optimization of cutting speeds, feed rates and depths of cut in order to reduce surface roughness by applying the Taguchi-based method; the influence of these parameters in the process is clear.

All these papers are based on previous knowledge of cutting parameters and do not present a method for their determination in real time, although they would lead to an improvement in the optimization of the process.

For this reason, several researchers have focused on the determination of depths of cut in machining processes. Altintas et al. [9] proposed a depth of cut estimation method that uses a force ratio, calculated from two components of cutting forces measured during the process. Choi et al. [10] developed an algorithm to estimate depths of cut as well, but from the average cutting forces.

Kwon et al. [11] and Hwang et al. [12] presented an approach that is based on the ratio between cutting forces in feed and cross feed directions and it allows for the estimation of immersion ratio using an iterative procedure. The work proposed by Yang et al. [13] shows a method to estimate depths of cut from the cutting force shape. The estimation procedure is able to detect flute overlap which is beneficial for multi-edged tools.

The variability of the cutting force signal used in these papers affects the accuracy of the estimation of depth of cut. Consequently, other procedures should be explored.

While the determination of the axial depth of cut has been studied frequently, the calculation of the width of cut still requires further study. As a result, an algorithm to estimate the radial depth of cut was developed by Tarn et al. [14], they used the cutting force signal to identify the entry of the tool tip into the workpiece.

Prickett et al. [15] developed an ultrasonic sensor-based system to measure the axial depth of cut. Two sensors are mounted on either side of the cutter, both in front of the cutter path and behind the cut. The estimation procedure shows good results, although the measurement can be affected by chips and cutting fluid.

Marinescu and Axinte [16,17] used acoustic emission (AE) sensory measurements for monitoring both tool and workpiece surface integrity to enable the milling of surfaces without damage. These approaches can be adapted to determine depths of cut as can be seen in the paper presented by Gaja [18]. Gaja used AE measurement and a neural network-based model to estimate axial depth of cut in end milling. The estimation procedure shows good results when the cutting flute is in a uniform cutting zone, but worse ones during the entry and exit of the tool from the workpiece.

Castaño et al. [19] developed a method which is able to determine the amplitude of the engagement arc of the milling tool during the cut as well as its position. The method is based on the measurement of the electrical resistance during contact between the tool and the workpiece. This contact varies along the arc and thus allows us to determine the position of the edge.

An important issue that has not been addressed in previous papers is the uncertainty of the proposed measurement procedures. It is important to take into account the quality of the measurements, so as to meet the required and usually narrow tolerances. The determination of the uncertainty associated with the measurements has also beee addressed in this research.

In the context of the increasing use of sensors in machine tools and smarter systems, this paper presents a method for measuring, in real time, depths of cut in milling. The method is based on the measured cutting forces by means of piezoelectric sensors. These sensors are sufficiently robust to be used in industrial applications for the control and the monitoring of machining processes. This procedure to measure the axial and radial depths of cut opens up the possibility to optimize