Available online at www.sciencedirect.com

ScienceDirect

Procedia CIRP 67 (2018) 262 – 267

www.elsevier.com/locate/procedia

11th CIRP Conference on Intelligent Computation in Manufacturing Engineering - CIRP ICME '17

Vibration analysis of robotic milling tasks

Marco Leonesio[a,*], Enrico Villagrossi[a], Manuel Beschi[a], Alberto Marini[a], Giacomo Bianchi[a], Nicola Pedrocchi[a], Lorenzo Molinari Tosatti[a], Vladimir Grechishnikov[b], Yuriy Ilyukhin[b], Alexander Isaev[b]

[a] *CNR – Institute of Industrial Technology and Automation (ITIA), Via Corti 12, 20133 Milan, Italy*
[b] *STANKIN Moscow State Technological University, Moscow, Russia*

* *Corresponding author. Tel.: +39-0223699952; fax: +39-0223699915. E-mail address: marco.leonesio@itia.cnr.it*

Abstract

Conventional material removal systems, like CNC milling machines, have proven to be very effective and accurate. Their major drawbacks are related to machine cost, restricted working area and limitations on the allowed workpiece geometry. In principle, industrial robots (IRs) could be an excellent alternative for machining, being both flexible and cheap (if compared to a CNC machine). On the contrary, IRs do not offer sufficient positioning accuracy and they are prone to vibration onset due to a low capacity of disturbance rejection. These critical aspects currently limit the use of robots in typical machining applications. In this paper, the cutting capability of a serial IR, for light milling operation on aluminum alloy, has been analyzed with respect to the multiple poses allowed by its kinematics redundancy. Firstly, an experimental modal analysis has allowed to identify the variability of the robot static and dynamic compliance over different poses, which influence both tool deflection and vibration onset during milling. The static stiffness of the robot end-effector (EE), which causes tool deflection, has been analyzed by means of an elastic model with lumped parameters. It is shown that the usual static compliance criterion for the optimal pose selection does not guarantee the best performance in terms of vibration level and, thus, surface roughness. This claim has been supported by a set of cutting tests in two significant cases. The results are explained considering the pose-dependent static and the dynamics properties.

Keywords: Robotic Machining; Chatter Vibrations; Pose Selection; Milling with Industrial Robots

1. Introduction

Despite the huge amount of work present in the scientific literature [1]-[6], robotized milling is still nowadays considered an open issue. One of the main problem is the low performance of the robot in terms of static and dynamic accuracy that strongly affects the process quality. Most of the scientific works presented in literature are related to the technological process and to kinematics calibration issues. Conversely, robot dynamics modelling and the study of the process effects on the robotic arm (e.g. the milling process) is a rather recent topic [7][8].

A great improvement in milling accuracy and in tracking error of the TCP trajectory can be reached integrating the model of the machining process [9]-[10] to the robot elastic model. In particular, for IRs, the relatively low pose-dependent stiffness (static and dynamic), which often deteriorates the overall accuracy and surface integrity, suggests the possibility to carry out a process-aware pose optimization. In fact, it is desirable to use the robot in regions of the workspace where kinematic, static and even dynamic performances are highest, thereby reducing the errors induced by EE displacements and vibrations. This objective has been tackled in [11] and [12] where the pose selection is driven by a proper map based on a *deformation evaluation index*, estimated by a milling force model coupled with robot elasticity model. Anyway, this index takes into account only static deformation. So far, no works have addressed pose optimization with respect to dynamic performance.

In this paper, it is presented a vibration analysis of robotic milling operations aimed at optimal pose selection. The basic idea is to analyze if it is possible to exploit robot kinematics redundancies to improve EE dynamic response and, hence, workpiece surface quality by reducing the vibration level. Firstly, EE dynamics compliance is measured in two poses of the robot, which are characterized by maximum and minimum

Peer-review under responsibility of the scientific committee of the 11th CIRP Conference on Intelligent Computation in Manufacturing Engineering
doi:10.1016/j.procir.2017.12.210

static compliance along the direction of the average cutting force for the selected milling task. Maximum/minimum compliance poses have been selected exploiting a model of the robot that takes into account joints elasticity, according to the approach presented in [13]. Then, this classical pose selection criterion, based on EE static stiffness maximization to optimize geometrical accuracy, is compared with a criterion aimed at increasing dynamics stiffness to improve surface quality. Measurements show that the dynamics compliance resonance peaks are higher when the static compliance is lower, that can be explained by a loss of damping capability due to a lower involvement of motors control loop. A stability analysis, carried out exploiting the 0-order approach presented in [15], shows that the stability limit in terms of depth of cut (DoC) is extremely low, but the limitation is mainly ascribable to the spindle-tool assembly and involves frequencies at about 500Hz, which do not leave relevant marks on the machined surface. On the other side, cutting tests reveal an important affection due to the low frequency dynamics, excited by transient phenomena induced by the robot motion and the milling process variability. Such phenomena generate low frequency components in the milling force. In order to evaluate quantitatively this effect, the concept of *Oriented Dynamic Compliance* is introduced, which can be derived from the dynamic compliance matrix. It consists in the response between EE displacement in Z direction (responsible of roughness generation on the final machined surface) and an input force oriented as the average milling force. It is also shown that the pose selection can significantly alleviate the effect of these dynamics on workpiece surface quality.

The paper is structured as follows: Section 2 describes the targeted milling application and the related experimental setup (Section 2). In Section, 3 the robot poses corresponding to the maximum and the minimum static compliance along the cutting force direction are identified. In Section 4, the dynamic compliance at the tool tip, measured for the two poses identified in the previous section, is presented and discussed: the most important resonances will be associated to the mode shapes identified via Experimental Modal Analysis (EMA), showing that they involve joints compliance. Section 5 reports and analyze the results of the milling tests. A harmonic analysis is performed on the accelerations recorded at EE, on the wrist flange and on the motors velocities, comparing them to the workpiece surface quality in terms of standard roughness. Results interpretation and conclusions are presented in Section 6.

2. Setup description

The robot under consideration is a COMAU NS16 equipped with a C5GOpen controller. On the robot EE , an ISEL UFM 1050 spindle (rated power: 1.05kW, max. speed: 25000rpm, max. torque: 0.32Nm) is mounted through a customized mechanical support. The spindle support is sensorized with two tri-axial accelerometers: the first one is mounted close to the robot flange (A1), while second one is mounted close to the spindle nose (A2) (see Fig. 1).

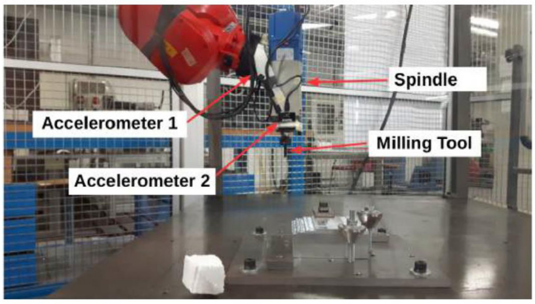

Fig. 1. Available setup for the milling tests.

As already mentioned in the introduction, the goal of the experiments is to mill a pocket in an aluminum (Al 6082) sample block. The milling path is reported in Fig. 2 while cutting parameters are resumed in Table 1.

Table 1. Cutting parameters for the test.

Depth of cut [mm]	Spindle speed [rpm]	Feedrate [mm/min]	Width of cut [mm]	Tool diameter [mm]	N. flutes	Type
1.5	13000	1080	6	8	2	Down milling

The milling force model to be coupled with robot pose-dependent static compliance ellipsoid for pose optimization is presented in [14]. The adopted cutting coefficients are reported in Table 2.

Table 2. Cutting parameters for the test.

Ktc [N/mm^2]	Kte [N/mm]	Krc [N/mm^2]	Kre [N/mm]	Kac [N/mm^2]	Kae [N/mm]
600	10	300	5	200	5

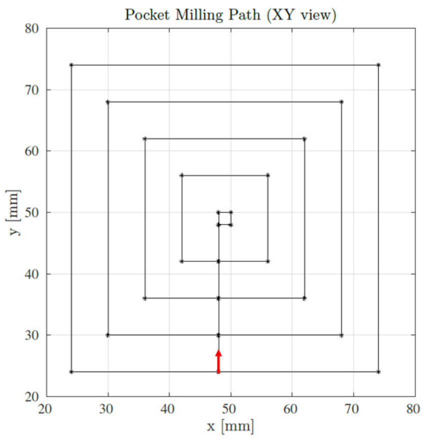

Fig. 2. Pocket toolpath.