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ScienceDirect

Procedia Manufacturing 14 (2017) 89–96

Procedia MANUFACTURING

www.elsevier.com/locate/procedia

17th Machining Innovations Conference for Aerospace Industry, MIC 2017, 6-7 December 2017, Garbsen, Germany

Design and optimization of a machining robot

Berend Denkena[a], Benjamin Bergmann[a], Thomas Lepper[a]*

[a]*Leibniz Universität Hannover, Institute of Production Engineering and Machine Tools, An der Universität 2, 30823 Garbsen, Germany*

Abstract

For manufacturing of large parts made of lightweight materials like aluminum, fiber reinforced plastics or composites for example for the frame in aerospace or automotive industries more and more industrial robots are used. Their main challenge is the low stiffness compared to conventional machine tools resulting in positioning errors. A lot of research is done in order to compensate trajectory errors and enable them for milling operations, which result from the weaknesses in the kinematic. Nevertheless, dynamic properties influence the process stability, which cannot be compensated with the robot control as the dynamic of the joint, and the cycle time of the robot control is limited. Therefore, different robot designs are presented and compared regarding their stiffness, dynamic properties and costs. Afterwards the main weaknesses of the selected design were identified and used for optimization to reduce the deflection and positioning errors during cutting operation. Furthermore, the machine tool structure was topologically optimized for different poses to achieve a higher accuracy in the working space.

Keywords: industrial robot, machining, topology optimization

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1. Main text

Today, more and more parts are made of fiber-reinforced plastics (FRP) and composites as the weight has one of the most important impact on the energy efficiency of cars, planes or accelerated machine components. Parts made of FRP require machining operations at connecting or functional surfaces and to achieve the final geometry. Mostly

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* Corresponding author. Tel.: +49-511-762-5334; fax: +49-511-762-5115.
E-mail address: lepper@ifw.uni-hannover.de

10.1016/j.promfg.2017.11.010

operations like trimming, drilling and milling are used [1]. These cutting operations have different requirements on the machine tool than metal cutting processes [2]. Compared to metal cutting operations the accuracy required for these operations is much lower. While metal cutting operations require an accuracy of 0.01 mm or even less, the tolerances allowed at parts made of FRP are ten times higher. Today, mostly conventional machine tools, designed for metal cutting operations are used for machining FRP [3]. However, the market of contract manufacturers specialised on FRP machining asks for cheap machine tools with less requirements on the stiffness than conventional machine tools. A survey of manufacturers showed that a stiffness at the tool holder of 2 N/µm and a total trajectory accuracy of 0.1 mm is sufficient. Although the mechanical requirements are lower, no cheap machine tools are available. Thus, the main objective of the research project EFFECTIVE is the development of a new machine tool for machining of FRP, which meets the requirements of the end-user and enables cutting of FRP and aluminum composites with one machine tool.

Industrial robots might be an alternative to conventional machine tools for machining of FRP and composites. However, tests show that the positioning accuracy as well as the trajectory accuracy, which includes dynamic effects, need to be improved for the use in cutting operations [4, 5]. Errors occurring on industrial robots can be classified into geometric and non-geometric errors [6]. Geometric errors influence the positioning accuracy by incorrect geometric dependencies between the angular joint position and the tool center point (TCP). These errors can result from the manufacturing process and the assembling due to tolerances in the contact surfaces of the components. The geometry of the link is used for the coordinate transformation, which is generally described with Denavit-Hartenberg (DH) parameters [7]. As errors in the transformation directly lead to wrong joint positions, different approaches for geometric or kinematic calibration are presented in literature [8]. Chen-Gang et al compare different approaches and show the benefit of the additional degrees of freedom for the position and orientation accuracy. As the accuracy values are taken from different publications a reliable comparison cannot be made. However, the pose accuracy could be significantly improved by calibrating the kinematic parameters [9]. The positioning error was reduced to 0.4 mm that is about one fifth of the original error measured for a not calibrated kinematic. As the research on the field of kinematic calibration becomes sophisticated, manufacturers or providers reduce geometric errors in the field. Nevertheless, besides the geometric errors, there are more sources leading to positioning errors of industrial robots. Measurements show that joints have a huge influence on the positioning accuracy. Due to the serial kinematic, high mass and long lever arms, the joints need to apply a high torque for holding and accelerating the links. Thus, most robotic joints are driven by a servo drive combined with a high ratio gear. These gears suffer from a bad torsional compliance and a backlash, which leads to low eigenfrequencies. The state of the art shows that a lot of research on optimizing positioning accuracy by geometric calibration as well as compensation approaches is done.

As a geometric model cannot compensate errors resulting from interactions with the process, many researchers address this issue by developing compensation strategies. The offline programming for backlash and compliance compensation is analyzed by Brüning et al. [10]. They implemented a compensation of process or trajectory-dependent errors in their CAM Software and showed the restrictions concerning the varying process states due to tool and machine wear as well as tolerances in the preformed workpiece. However, the offline compensation requires a well-suited model describing the machining errors and a process simulation for force estimation. Zäh and Rösch developed a compensation of static deflection due to cutting forces by a model-based fuzzy controller. This approach uses a force dynamometer at the workpiece to measure process-forces and an acceleration sensor at the spindle to detect chatter. With this approach Zäh and Rösch reduced the deviation caused by process forces by 70 % [11]. Another approach for online compensation uses a spindle holder with integrated force sensors to measure cutting forces and calculate the resulting deviation. Thus, the drawback of additional sensors required and their setup is cancelled [12].

While actual research projects deal with the optimization of the positioning accuracy during milling operation by the robot control, this paper presents a new robot design. The aim of optimization is the reduction of dynamic impacts as well as static compliance. Therefore, a cooperation with industrial and research partners initiated the research project EFFECTIVE to develop an innovative machine tool for milling of FRP. Their main objective is to design a, compared to conventional machine tools, cost-efficient and more flexible universal machine tool for dry machining of FRP.