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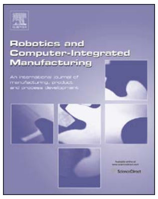

Drive based damping for robots with secondary encoders

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ABSTRACT

Robot machining is a growing field due to the combination of large working envelope with relatively low investment and operating costs, compared to milling machine. Besides, the flexibility, which robot serial kinematics bring along, makes application of robot machining possible for different use cases. However, an occurring drawback of robot based machining systems is low stiffness compared to milling machines and, thus, poor accuracy and low eigenfrequencies with few damping. By that, robots for machining are prone to vibrations, resulting in poor machining results. In this paper the authors therefore present an approach for damping these vibrations, using state-of-the-art drives. Secondary encoders, which are increasingly available on industrial robots, are applied to detect these vibrations. This presented strategy has already been proven applicable on feed drives in milling machines and is now applied on industrial robots. To do so, the robot's vibrational behavior, like eigenfrequencies and eigenmodes, is examined in the whole workspace via measurements on real robots. Additionally the excitation by the milling process has been examined in relation to the occurring oscillations at the robot structure. The results of these research is adduced to estimate the applicability of this approach. Based on these results simulations are carried out to test the applicability of the damping strategy on industrial robots. As compliance of robots results mostly from gearboxes, simulation is carried out using a rigid-body-flexible-joint model. The simulations show that the dynamic behavior of the robots axes can be influenced in a positive way and vibration of the robots tool center point can be reduced significantly. Based on these findings, it is planned to implement this method on real hardware to perform tests, develop it further and optimize it.

1. Introduction

The combination of a large working envelope as well as low investment and operation costs compared to a milling machine are only two advantages of robot-based machining systems. Accompanied with high flexibility and the trend that large-volume parts are replacing several smaller parts, robot machining represents a cheap alternative to milling machines [4]. The serial kinematics empowers robots to machine even at spots, which are inaccessible to milling machines. Furthermore, robots can accomplish other tasks while waiting for new parts, such as pre- and post-operations like deburring, gaging etcetera. Along with the latest safety standards, robots are also able to work together with humans in so-called human-machine-cooperation. So the question is: why has robot-based machining not substituted milling machines yet?

On the one hand, the serial structure of robots enables them to operate in a large working space using only small installation space at the same time. On the other hand, the serial structure in combination with compliant gears is exactly what makes robots prone to inaccuracy and oscillation [5]. So the advantages of robot-based machining are coming inseparably along with the named disadvantages. In order to minimize inaccuracy and oscillation, various efforts have been and are still made. This paper presents an approach that uses secondary encoders (encoders measuring the position on the output side of a gear), which already exist to enhance accuracy, to reduce oscillation by drive-based vibration damping for the first three axes. Because the actuator, in this case the particular drive, has to react on oscillation, this approach is restricted to those low frequent oscillations only where the dynamics of the drives are sufficient for vibration damping.

2. Statement of the problem

Oscillation and chatter are effects milling machines are permanently confronted with. Research and development have ever since tried to overcome these problems by various methods. However, due to the difference in mechanical structure these effects and the according measures cannot be transferred one-to-one to robots. Regarding robot dynamic behavior, much lower eigenfrequencies have been identified.

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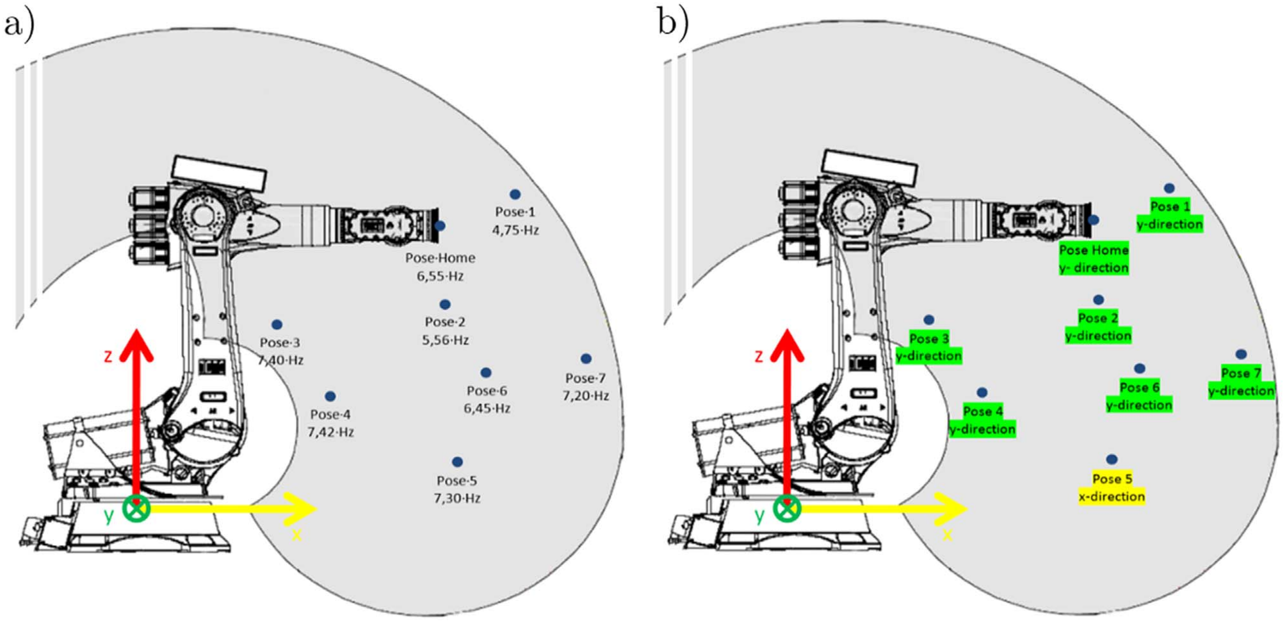

Fig. 1. a) Eigenfrequencies and b) Eigenmodes of a KUKA KR 500-2 MT.

This means less rigidity leading subsequently to oscillations with amplitudes that can cause severe damage to the robot's mechanic. Milling machines exhibit the first eigenfrequency typically in the range of 50–70 Hz [8], whereas robots have their first eigenfrequency in a much lower range [6]. Fig. 1 shows the eigenfrequencies and modes that have been determined by an experimental modal analysis using a KUKA KR500 MT robot.

Fig. 1 a) underlines the fact that robots have a low stiffness and thus very low eigenfrequencies. Furthermore, Fig. 1 a) shows that the eigenfrequencies vary from 4.75 Hz to 7.42 Hz which means a change of 56%. Therefore another result of these investigations is that robots have a distinct dependency of the eigenfrequencies on the current pose. Milling machines do show this dependency, too. However, it is not nearly as marked as it is regarding robots. Additionally Fig. 1 b) illustrates that throughout the working envelope of a robot the first eigenfrequency oscillates predominantly in y-direction. Oscillation in y-direction implies that the whole robot structure is moving around the robots Z-axis. Thus, the carousel (gear and engine included) can be identified as the most critical link regarding the dynamic behavior.

Milling tests carried out at ISW and MAG IAS GmbH using a KUKA KR500 MT robot show that machining harder materials with robots necessitates conservative parameterization at the worst pose. Fig. 2 shows a robot machining the root-end of a rotor blade of a wind turbine. On the left, the robot has a quite stiff pose but still operates with the parameters set at the compliant pose on the right of Fig. 2.

Another investigation carried out at MAG IAS GmbH was milling a chock in aluminum with a rising depth of cut (DOC), as illustrated in Fig. 3. The adopted pose was between pose 6 and 7 according to Fig. 1. It can be seen that robot machining exhibits very bad surface quality (see also Fig. 6) as soon as the excitation from the milling process is enough to lead to self-excitation of the robot structure. The point where self-excitation occurs abruptly is marked at approx. 14 s and corresponds to a depth of cut of approx. 1.3 mm. The milling was done with a tool ⌀25 mm with four replaceable cutting inserts at a feed rate of 8.48 mm/s. The width of cut (WOC) was 12.5 mm at a spindle rate of 1270 rpm. The cutting force was steadily increased by setting the robot at an angle of 0.656 degrees with respect to the work piece and up-milling a chock. In this example, the tooth meshing frequency was 84.67 Hz.

Performing a Fourier transformation of the position signal at the Tool Center Point (TCP) of the robot in the frequency domain, the position spectrum can be calculated. This frequency responses at two different times - one before self-excitation occurs (Fig. 4) and the other at the end of the milling process (Fig. 5) - again show that the low eigenfrequencies are responsible for bad surface qualities.

In Fig. 4 two peaks can be identified at 21.1 Hz and 84.67 Hz, both resulting from the rotation of the milling tool. The amplitudes are quite small and correspond to the depth of cut at segment 1 in Fig. 3. Fig. 5 exposes the frequency response after the critical depth of cut has been passed. After self-excitation, peaks are detected at the first (7.62 Hz) and at the third (16.4 Hz) eigenfrequency. The amplitude at the first eigenfrequency is comparatively small and can be ascribed to the milling direction, which is the same as the oscillation direction of the first eigenfrequency. The TCP is thereby supported by the work piece

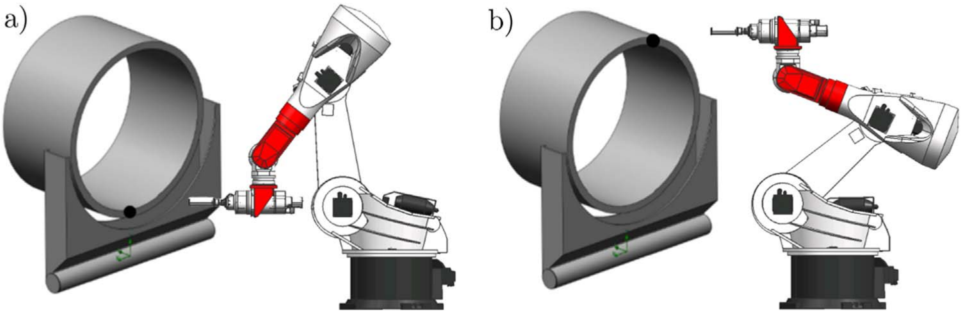

Fig. 2. Same parameters used for different pose a) stiff b) compliant *imagesource*: *MAG IAS GmbH*.