Experiment for determining the global static stiffness of articulated-arm industrial robots

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Abstract: - This paper describes an experimental approach developed by the authors for determining the global static stiffness of a medium payload articulated arm robot. This experiment is part of a larger research project, the results being included in an analysis of articulated arm robots behavior in machining applications. The experimental setup included a 10 kg payload articulated-arm robot manufactured by Kawasaki, a Dynalog CompuGauge measuring system and a special device used to attach calibrated weights to the end of the robotic arm. The Dynalog CompuGauge system is capable of measuring static, kinematic and dynamic performance of spatial mechanisms. The experimental procedure was to progressively attach calibrated weights to the end of robotic arm and observe the displacement of the tool center point through measurements taken using Dynalog system. The experiment was repeated for two configurations of the robot’s wrist. Using the experimental results, a set of stiffness diagrams were generated which showed the global behavior of the industrial robot as end-of-arm load increases.

Key-Words: - industrial robot, static stiffness, robotic machining, elastic displacement, robot configuration, stiffness diagram

1 Introduction
Robotic arm stiffness is an important influence factor when it comes to robotic machining. It is not only the weight of the technological equipment attached to the wrist that must comply with robot’s payload, but also the machining forces that appear at tool-work piece interface [1]. Because the payload is essentially an expression of robot’s capacity to absorb a force influence without significant elastic displacement or deformation of the mechanical structure, it is a good basic indicator for robot integration in a machining application [2]. Yet, the parameter which best describes the capacity of an industrial robot to sustain forces of certain values at tool characteristic point (TCP) level is the global stiffness of the robot arm [3].

Considering these arguments, the goal of this research was to identify the global stiffness for an articulated-arm six-axes industrial robot at TCP level, along the Z axis of robot’s base coordinate system. This problem formulation is of interest in robotic machining applications because it shows the magnitude of an error-generating factor. Besides, it is important to focus the stiffness measurement at TCP level because maintaining the tool on the programmed trajectory is one of the main issues in robotic machining applications.

2 The experimental setup

2.1. The industrial robot
The industrial robot used for the research project was a 6 NC axes and 10 kg payload Kawasaki FS10E model, illustrated in Fig. 1.

Because of it’s architecture and payload, the robot is suitable for machining applications that require low machining forces, such as polishing and deburring [4]. Thus, the technological equipment mounted on robot’s wrist often includes an automatic tool changer ATI QC41, which was included in the experimental setup in order to better describe real application conditions. Also, the corresponding mounting flanges were left on, for the same specified reasons. The weight of this technological equipment was taken into account for experimental data interpretation.
2.2. The Dynalog CompuGauge system
Dynalog CompuGage is a system designed for measuring and analyzing positioning accuracy/repeatability, kinematic and dynamic performances of spatial mechanisms. The system is composed of two measuring beams, a special robot end-effector, and a data-acquisition box connected to a PC running the Dynalog Compu-gauge software. Four extensible wires are attached to the ends of the measuring beams. The special robotic end-effector is used to connect the measuring wires to the robot and also to define the TCP. A system of optical sensor measure the displacement of the wires as the robot moves, and the computer-based program triangulates TCP position, from the data obtained through the acquisition box. The concept of a measuring setup is illustrated in Fig. 2.

The Dynalog CompuGauge system was used to measure TCP elastic displacement in the negative direction of the robot’s base coordinate system Z axis when the weight of the equipment attached to the wrist increases.

Fig. 2. A measuring setup using Dynalog CompuGauge System

In Fig. 3, the components of Dynalog CompuGauge system are illustrated.

Fig. 3. Dynalog CompuGauge system elements: a) measuring beam; b) an extensible measuring wire attached to the end of a beam; c) the special end-effector

3 The experimental procedure
It is known that, for an elastic element with a single degree of freedom, the stiffness is defined as

\[ k = \frac{F}{\delta} \]  \hspace{1cm} (1)

where \( F \) is the force applied to the element, and \( \delta \) is the displacement generated by the force \( F \) along the degree of freedom. For an articulated-arm industrial robot with six degrees of freedom, the stiffness is a much more complex concept, expressed in a matriceal form, but the principles of the basic definitions are the same [5]. Thus, considering that the acting force was the gravitational force, with a value directly determined by the load placed on robot wrist, the objective of the experiment was, in fact, to determine the displacement of TCP. In order to achieve this goal, the following experimental principles had to be respected [6]:

- due to cinematic configuration of the Kawasaki FS10E model robotic arm, the influence of 1\textsuperscript{st}, 4\textsuperscript{th} and 6\textsuperscript{th} axes cinematic parameters on the structural stiffness of the robot arm is considered negligible;
- the parameters that influence the static stiffness along the robot base coordinates system Z axis are 2\textsuperscript{nd}, 3\textsuperscript{rd} and 5\textsuperscript{th} axes cinematic parameters, as well as the load attached to robot’s wrist;
- in order to illustrate the influence on robot’s static stiffness, a single parameter must vary for each measurement step.
It also had to be taken into account that certain complementary devices are already mounted on robot’s wrist (the automatic tool changer system, the corresponding adapting flanges and a special device used to add calibrated weights for increasing the load) these elements adding an initial load of 5 kg.

Taking into account all above, the following experimental procedure had been established:

- the initialization configuration of the experiment (and the first measurement position) was considered with the following parameters: 2\textsuperscript{nd} axis at 0\degree, 3\textsuperscript{rd} axis at -90\degree, 5\textsuperscript{th} axis at -90\degree, wrist load at 5 kg. This configuration is illustrated in Fig. 4;

![Fig. 4. The initialization configuration for the experimental procedure (with the 5\textsuperscript{th} axis at 90\degree)](image)

- for the same initial robot configuration, four more measurement steps were recorded, for each step the load being increased by 1 kg (an error margin of 1 kg was assumed, in order to avoid overloading the mechanical structure of the industrial robot above the specified payload);

- the measurement process was further divided into two stages: for the first stage, the 2\textsuperscript{nd} axis parameter varied and the second segment of the robotic arm was kept parallel to the ground, while for the second stage, 2\textsuperscript{nd} axis parameter had a constant (maximum) value and the 3\textsuperscript{rd} axis parameter varied;

- in order to avoid getting too close to robot’s workspace limits, in the first stage the parameter for the 2\textsuperscript{nd} axis was gradually increased up to 60\degree with increments of 10\degree. In order to keep the second segment of the robotic arm parallel to the ground, the configuration was compensated by gradually increasing the parameter on the 3\textsuperscript{rd} axis up to -30\degree. For each robot configuration, five measurements were taken, the first one with a load of 5 kg, and the others four by increasing the load gradually by 1 kg / measurement. The final robotic arm configuration for the first experimental stage is shown in Fig. 5;

![Fig. 5. The final robotic arm configuration for the first experimental stage](image)

- for the second stage of the experiment, the parameter for the 2\textsuperscript{nd} axis was kept constant (at 60\degree) and the parameter for the 3\textsuperscript{rd} axis was gradually decreased up to -70\degree. Also, for each robot configuration five measurements were taken by varying the wrist load in a similar way to the first stage procedure. The final robotic arm configuration for the second experimental stage is shown in Fig. 6;

![Fig. 6. The final robotic arm configuration for the second experimental stage](image)

- in order to illustrate the influence of the 5\textsuperscript{th} axis parameter on robot’s static structural stiffness [7], measurements from both previously mentioned experimental stages, together with the initial configuration, were repeated with a parameter for the 5\textsuperscript{th} axis of 0\degree. The initial configuration with the parameter of the 5\textsuperscript{th} axis at 0\degree is shown in Fig. 7.
The measuring process for two basic configurations, in the first and second experimental stage, is shown in Fig. 8. Some experimental results (for the initial and next two robot configurations in experimental stage one) are shown in Table 1.

<table>
<thead>
<tr>
<th>Measured coordinates</th>
<th>Applied load [kg]</th>
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<td>$x_m [\text{mm}]$</td>
<td>$y_m [\text{mm}]$</td>
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<td>R1-0</td>
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Table 1. The experimental results for the initial and the first two configurations of experimental stage one

4 Conclusion

Following the experimental procedure, a number of 22 different robotic arm configurations were used for measurements (11 configurations for a 5th axis parameter of -90° and 11 configurations for a 5th axis parameter of 0°). Thus, the data obtained can be divided in 11 sets of TCP coordinates, for each set being calculated 5 displacement values (corresponding to an initial load value of 5 kg and progressive increasing of load by 1 kg up to a maximum load value of 9 kg).

The interpretation of the experimental results was made in the form of 11 stiffness diagrams shown in Fig. 9. Each diagram shows, by comparison, the evolution of the displacement at TCP level for the corresponding robotic arm configuration in both cases (5th axis parameter at -90° and 5th axis parameter at 0°).

As it can be observed in Fig. 9, the 5th axis has an important influence on static stiffness of the industrial robot, the influence being greater as the load increases.

By putting together the stiffness diagrams for each of the 5th axis parameters situations (-90° and 0°), as shown in Fig. 10 and Fig. 11, a comparison analysis can be made in each case.
Fig. 9. Stiffness diagrams for each robotic arm configuration
From the above illustrated stiffness diagrams, it can be observed that the displacement for the configurations in which 5th axis parameter values was at -90° is between 40% and 60% less than the displacement for the corresponding configuration with 5th axis parameter at 0°. Also, the displacement growth ratio in the second stiffness diagram series (with 5th axis at 0°) is twice the displacement growth ratio in the first stiffness diagram series (with 5th axis at -90°).

Regarding maximum displacement values, it must be specified that Configurations 1 (1.1) through 7 (7.1) belong to the first experimental stage, while Configurations 8 (8.1) through 11 (11.1) belong to the second experimental stage. Thus, from the stiffness diagrams it can be observed that:

- in the first experimental stage, for the case of 5th axis at -90° (Configurations 1 through 7), the maximum recorded displacement was 0.462 mm, corresponding to the maximum supplementary load in Configuration 7 (2nd axis at -60°, 3rd axis at -30°);
- in the second experimental stage, for the case of 5th axis at -90° (Configurations 8 through 11), the maximum recorded displacement was 0.483 mm, corresponding to the maximum supplementary load in Configuration 8 (2nd axis at -60°, 3rd axis at -40°);
- in the second experimental stage, for the case of 5th axis at 0° (Configurations 8.1 through 11.1), the maximum recorded displacement was 0.942 mm, corresponding to the maximum supplementary load in Configuration 8.1 (2nd axis at -60°, 3rd axis at -40°);

Also, from Fig. 10 and Fig. 11 it can be concluded that, in both situations regarding 5th axis parameter value (-90° and 0°), in the first experimental stage the displacement evolution is more predictable and constant, but in the second experimental stage it becomes more erratic as the parameter value on the 3rd axis decreases.

References:

Fig. 10. Comparison chart for the configurations with 5th axis parameter at -90°

Fig. 11. Comparison chart for the configurations with 5th axis parameter at 0°