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Energy consumption and dynamic behavior analysis of a six-axis industrial robot in an assembly system

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Abstract

This paper presents an experimental study to validate a dynamic model of a six-axis industrial robot as part of an assembly system and to analyze its power consumption as well as its dynamic behavior. Furthermore, the effect of robot operating parameters (i.e., payload and speed) on the power consumption and the dynamic behavior are analyzed. The investigation shows that the comparative study between simulation and experimental results can be used to improve the model's accuracy and prove that the simulation model represents the real system. Both simulation and experimental results show that the robot operating parameters strongly influence the industrial robot's power consumption and dynamic behavior.

1. Introduction

The application of simulation tools for analyzing the system behavior of mechatronic systems was widely used in many areas, including assembly systems. This is due to the simulation method's ability to analyze complex mechatronic systems easily and in a short period. Therefore, system engineers are able to design and optimize the mechatronic systems without waiting until the actual construction is completed [1]. The main issue concerning this method is how to validate its results since most of the modeling work uses assumptions and approximations. Thus, a validation of the simulation models and their results is mandatory in almost every engineering simulation project. This work is used to ensure that the digital models are an accurate representation of the real system under study [2,3].

A trustworthy method to validate the simulation model is to compare the simulation results with the data obtained from the actual measurement. In special cases when it is impossible to obtain necessary data, for example, the experiment is too expensive and too dangerous, or the system needed for the experiment does not yet exist, the validation can be done using other methods such as by performing a sensitivity analysis of the model and/or comparative study with the analytical solutions [4]. However, since an experimental investigation for analyzing the mechatronic behavior of assembly system components can be performed, the validation of the simulation models and their results is mandatory.

2. Energy consumption analysis

Recently, the analysis of energy consumption of assembly system components (e.g., industrial robots) has become a main issue in manufacturing systems [5]. This has occurred because the energy-efficient use of industrial robots has a great impact on the production costs [6]. For example, in the automotive industries, the energy consumption from industrial robots is about 8% of the total energy usage in the production phase [7]. Therefore, the focus of this study is on the energy

consumption analysis of a six-axis industrial robot as part of an assembly system. This analysis is used to predict a strategy for reducing the energy usage in manufacturing systems.

By 2013, several methods had been proposed to reduce energy consumption in industrial robots, such as optimizing the robot's path planning [8-10], optimizing its parameters [11] and scheduling robot operation [12,13]. A method using integrated control strategy based on data of friction, speed, and gravity of robot axes was also patented by ABB [14]. Nevertheless, an energy consumption analysis using a multi-domain simulation approach under several operating conditions is still rare. Hence, the aims of this research are not only to validate the industrial robot model but also analyze the effect of the payload, acceleration, and velocity on the energy consumption of an industrial robot.

Based on [15,16], the active power (*P*) exerted by the robot's mechanics is formulated in Eq. 1. This equation indicates that the robot's payload and its velocity highly influence the robot's power consumption since is a function of robot torque (*T*), the angular velocity (*ω*), and the mechanical and electrical efficiencies (η_{mec}, η_{el}) of the drives.

$$P_{robot} = \sum_{i=1}^{n} T_i . \omega_i . \frac{1}{\prod_{i=1}^{n} \eta_{mec,i} . \eta_{el,i}} \tag{1}$$

$$W_{act} = \int_{0}^{t_f} P_{robot} . \mathrm{d}t \tag{2}$$

As shown in Eq. 2, the active energy consumed (*W_{act}*) by a robot is the integral of active power over time *0 ... t_f* [16]. Using these equations, the power consumption rate of the industrial robot can be calculated. However, in an actual setting many factors influence the power consumption of the robot such as friction, vibration and electromechanical losses [17]. Therefore, the validation of an industrial robot's model using a comparative study with real measurements is greatly advocated than an analytical calculation.

In this research, simulation and experimental investigations are conducted on the small six-axis industrial robot, Motoman MH5L. It is a 5 kg payload robot, which is commonly used in assembly systems for material handling. This robot is used as a component of a manufacturing cell that is a part of an electronic production facility (see Fig. 1). The manufacturing cell is used as a comprehensive test platform for testing electronic devices, which consists of a six-axis industrial robot with special grippers, a transport system, two platforms for in-circuit testing and functional testing of electronic components, and a hot function test module. The configuration of the test platform is shown in Fig. 1.

There are three contributions outlined in this paper. The first contribution is the convenient simulation approach that can be used to analyze the energy consumption and dynamic behavior of the industrial robot manipulator. This method uses a simulation tool based on open source Modelica language. Since Modelica is a non-causal and object-oriented language,

even system engineers with some knowledge of control systems can use this method. The second contribution is a comparative analysis to validate the dynamic model of the industrial robot. The comparative analysis can be used to validate and improve the robot model accuracy. This is very important in engineering simulation work since design engineers always use assumptions and simplifications in their models. The final contribution is that the results from this research can be used as a reference to choose and optimize the operating parameters of the industrial robot with respect to a reduction in the robot's energy consumption.
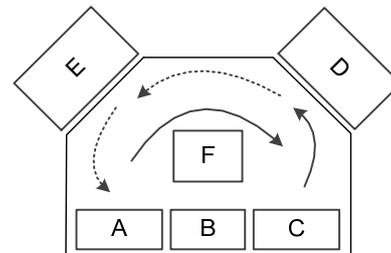
A & C : Conveyor Systems   **D & E** : Universal Contacting Modules
B : Hot Function Test Module   **F** : Six-axis Industrial Robot

Fig. 1. The configuration of the comprehensive test platform and the robot cycles (design by IMAK GmbH).

The remainder of this paper is structured as follows. Section 3 presents the modeling method of the six-axis industrial robot and provides the detailed experimental setup for the power measurement. Section 4 describes the results from both simulation and experimental investigations and their discussion. In this section, a validation process of the industrial robot model and a comparative study in experimental and simulation results are conducted. Finally, concluding remarks are given in Section 5.

3. Modeling and experimental setup

3.1. Modeling method

The Modelica-based simulation tool, CATIA Systems Dynamic Behavior Modeling (DBM) is used for creating a digital model of the six-axis industrial robot. The modular industrial robot' models that were developed are stored in the Modelica Library, which is divided into several packages, such as controller, body and axis packages. Thus, it can also be used to simulate other robot models with changing the parameter of the model corresponding to the real robot properties. The parameters of the MH5L model are mainly obtained from the robot specifications [18] and from the Modelica Standard Library. Actual measurements were also conducted in order to define the robot's inertia and payload. The models are created to analyze the dynamics and power consumption of the industrial robot. The path planning from the Modelica Standard Library (i.e., PTP2) is used to generate the movement of the robot. For the power consumption