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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.

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Keywords: Energy consumption; Industrial robot; Modeling and simulation; Validation; 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

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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 $0 \ldots t_f$ [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.

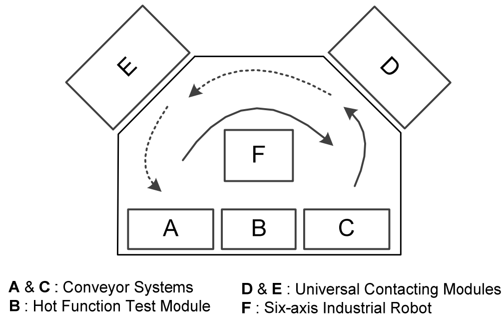

Fig. 1. The configuration of the comprehensive test platform and the robot cycles (design by IMAK GmbH).

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 analysis, the robot is simulated from position A to C, and for the dynamic behavior analysis, it is simulated from position C to D (see Fig. 1). The dynamic characteristic and execution time of the robot are used as the criteria to define these movements. During these movements, electric parameters and dynamic responses of every robot axis are analyzed.

The top level of the robot's dynamic model is shown in Fig. 2. Every robot axis consists of a motor drive and its controller, gear, and motor inertia model, while the robot structure consists of revolute joint and the axis' inertia. At the end of the robot's structure there is a payload model. The robot is simulated with two conditions (without additional payload and with 1 kg additional payload) associated with two robot speeds: 20% and 40% of the maximum speed. Using these simulation conditions, the effect of payload and speed on the dynamics and power consumption of the six-axis industrial robot are analyzed.

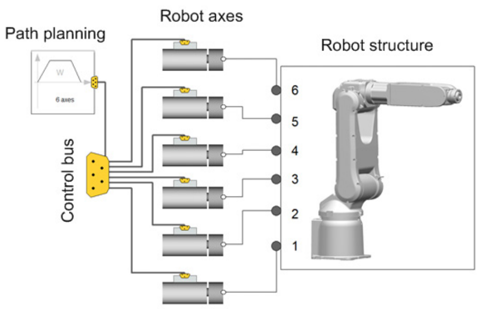

Fig. 2. The model of the six-axis industrial robot; based on [19].

3.2. Experimental setup for power consumption measurement

The experimental setup for the power consumption measurements is sketched in Fig. 3. The measuring unit used for the experiment has the ability to measure the electrical current, voltage, and power during the robot's operation. The measurement data are collected every 0.2 seconds. Similar to the modeling conditions, the speed of the robot is measured at 20% and 40% of their maximum values, and the payload is loaded with 2 kg (gripper without additional payload) and 3 kg (gripper with 1 kg additional payload). During the robot's operations, data from the measurement are automatically stored into the measurement unit's PC and can be accessed via an internal network.

4. Results and discussion

4.1. Validation of the simulation model and its results

A comparison between the simulation and experimental data is used to validate and analyze the accuracy of the robot model. From the modeling and simulation method, the values of the current, resistance, and voltage from the motor drives of every robot axis are obtained. Thus, from this data the robot's power can be calculated. While using the measurement method we obtained the current, voltage, and power of the robot.

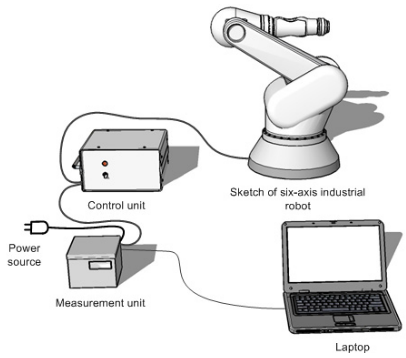

Fig. 3. A sketch of the experimental setup for measuring the robot's power.

The value of the current is used to make a comparative analysis since it is directly collected from both of these methods. A comparison of the current is presented in Fig. 4. This figure shows that the deviation of the robot's current between measurement and simulation is less than 15%. There are several factors that lead to this difference: The mechanical losses of the robot, robot operating conditions, and the robot control unit. The first factor is the electromechanical losses in robot drives, i.e., armature copper losses and armature iron losses. These effects are difficult to be modeled at high levels of accuracy since they are related to the material characteristics of the stator and rotor. The second factor is the operating conditions of the robot, such as air temperature. This is because the robot's operating condition influences the motor's resistance and current. In addition, the robot control unit that not modeled in this study also lead to this deviation.

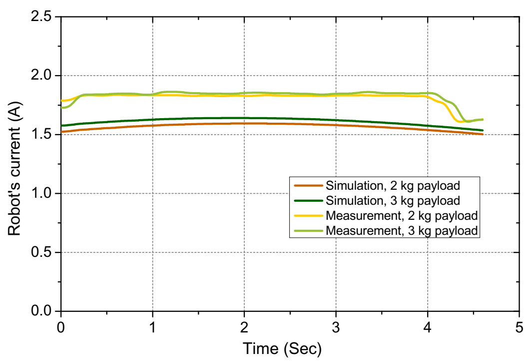

Fig. 4. Current of the robot at 20% of maximum speed.

Fig. 4 also shows that an additional 1 kg payload contributes to an approximately 10% increase in current. This shows that payload has a significant effect on the current of the robot's motor drives. This means it also affects the robot's power consumption. Furthermore, from the current measurement and simulation found that at the beginning and the end of the robot's movement path, the current is relatively low. This occurs because the motor drives are not yet loaded at the beginning, and their speed is reduced at the end (see Fig. 5: Axis 2).

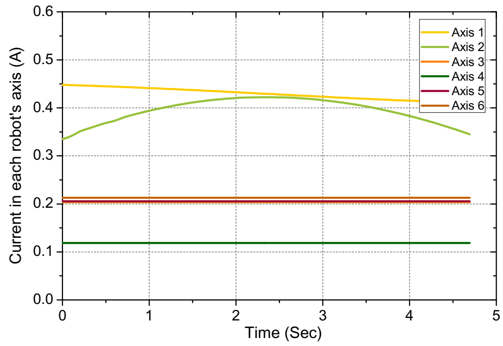

Fig. 5. Current in every robot axis; data from the simulation results without additional payload.

The value of the current for every motor drive is shown in Fig. 5. It shows that current in the robot's motor drive Axis 1 and Axis 2 is higher than the other axes. This is because these axes have a greater distance of motion and higher velocity than the others. However, although Axis 4 did not move, the motor still needed a current (of about 0.1 A) to maintain the position of the robot axis.

4.2. Effects of the robot operating parameters on the power consumption

In this sub-chapter, the power usage of a robot with different operation parameters is investigated. Both simulation and real measurements are used for this investigation. The industrial robot's power consumption at varying speed is shown in Fig. 6.

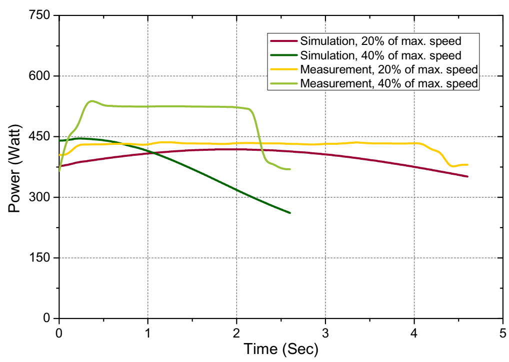

Fig. 6. Power consumption of the robot with additional payload 1 kg.

Fig. 6 shows that the speed of the robot influences its power usage. Both simulation and experimental results illustrate that higher speeds lead to higher power usages. However, higher speeds to be able reduce the operation time, which means having the potential to reduce energy consumption of the robot. This data can be used for energy flexible control of the workcell.

From Fig. 7 (a,b) show that the robot axis' torque strongly correlates with the current of the robot's motor drives. At the beginning of axis movement, a higher payload (i.e., higher torque) requires a higher current. This is because the motor drives need more power to accelerate the robot structure. However, after about 1 second the effect changes in contrast to the previous phenomena. This is caused by the inertia-effect, a phenomena similar to the flywheel effect in an automotive transmission system. Higher torque can reduce the friction of the robot mechanism. However, this phenomenon only occurs on Axis 1 since it has a higher mass. The others show that higher loads lead to a higher motor current. Therefore, the power consumption of the robot is linear with respect to the robot's payload, as shown in Fig. 8.

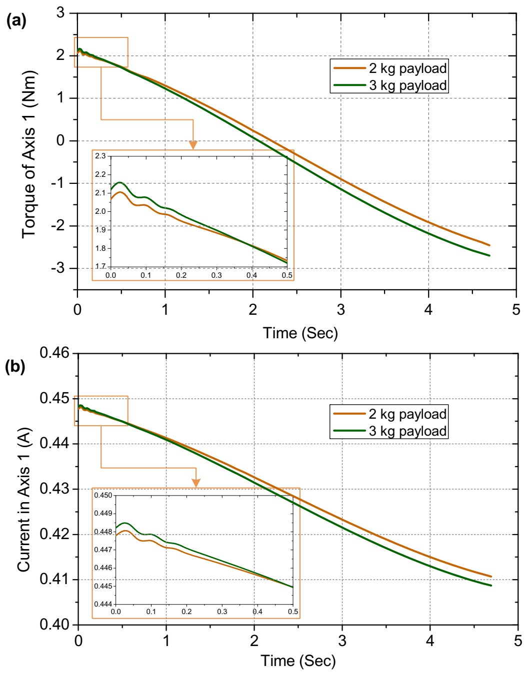

Fig. 7. Robot's torque (a) in relation to the robot's current (b); data from the simulation results.

Fig. 8 also shows that the difference in the robot's power usage between simulation and measurement is about 100 Watt. This has occurred because the robot control unit is not included in the simulation model, the mechanical losses of the robot actuator, and the operating condition of the robot, such as robot operating's temperature (as mentioned in Section 4.1). In addition, Fig. 8 shows that the power usage from the simulation results is decreasing constantly. This is due to fact that the friction of the robot structure's model also decreases continuously.

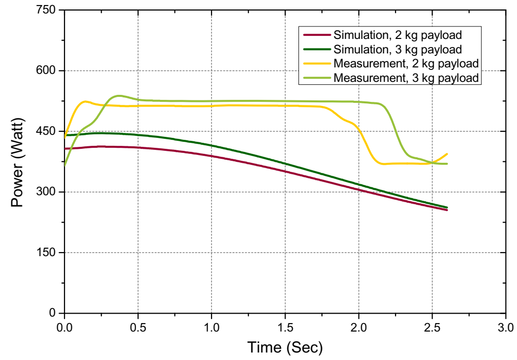

Fig. 8. Power consumption of the robot at 40% speed.

4.3. Dynamic behavior analysis of the industrial robot using multi-domain simulation tools

Concerning the payload's effect on the dynamics of an industrial robot, many studies have been conducted. Several researchers have presented an analysis of the initial parameters of an industrial robot's load in order to improve the dynamic accuracy of the robot. These analyses showed that the mass, inertia, and the location of the center of the robot's payload are important factors that influence the robot's dynamics [20,21].

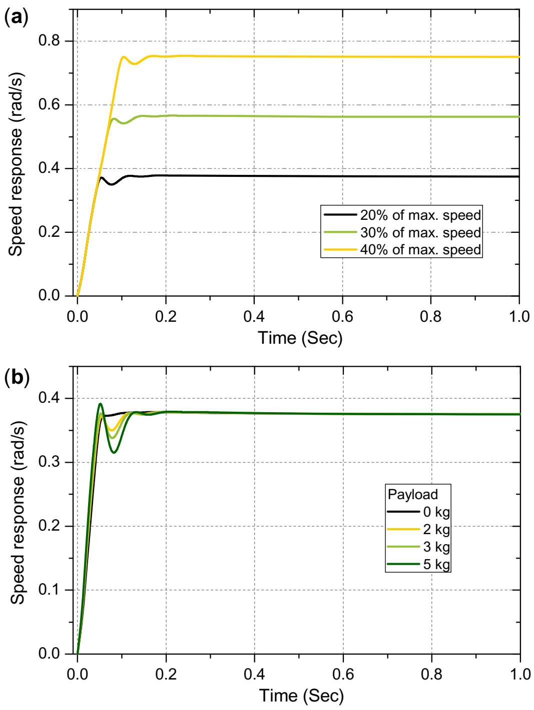

Fig. 9. Dynamics of the industrial robot at varying speeds (a) and with varying payloads (b).

Another study also showed that the payload influences the robot's performance and its energy consumption [22]. However, most of these studies use experimental investigations or mathematical calculations to analyze the effect of payload. For system engineers, these methods are inconvenient and time-consuming. Therefore, the analysis of an industrial robot's dynamic behavior using a convenient method is needed. In addition, in order to analyze the energy consumption of the robot, a dynamic behavior analysis is mandatory since the power consumption of the industrial robot is closely related to its dynamic behavior.

The dynamic analysis of the robot is centered around the sixth axis due to its high vibrations. An analysis was done using data from the simulation results. Fig. 9 depicts the speed responses of the robot with the different payloads and at varying operating speeds. As can be seen in Fig. 9(a), the initial speed response of the robot is not strongly influenced by its operating condition. The robot control system is very able to reduce excessive acceleration. The speed response behavior of the robot with several robots' payloads is plotted in Fig. 9(b). It shows that a higher robot payload leads to a higher response speed, especially during the beginning of the movement. This shows that the payload is influencing the speed response.

4.4. Robot operating parameter optimization for efficiency and productivity

From the simulation and measurement results, it can be concluded that the robot speed and payload strongly influence the robot's power consumption. The robot has higher power consumption when speed and payload are set to higher values. This means that to reduce the power consumption of an industrial robot, the operating speed and payload must be reduced. However, a slower speed will lead to longer operating times (thus, higher energy consumption) and in some situations when higher productivity is needed the robot must perform as quickly as possible with a maximum payload. Therefore, an optimization of the robot's operating parameters is needed.

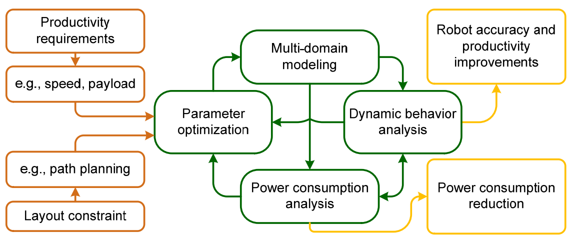

Fig. 10. Key elements' interactions in optimizing operating parameters for industrial robots.

The correlation between dynamic behavior, power consumption and parameter optimization is depicted in Fig. 10. As shown in this figure, the power consumption has a direct correlation to the dynamic behavior. Furthermore, data from power consumption and dynamic behavior can be used to optimize the operating parameters of the robot. However, the productivity requirement [22] and layout constraint must be considered. When the robot operation is not limited by productivity, a reduction in the robot's speed could limit its power consumption.

The layout of the industrial robot will also influence defining the path planning of the robot. Effective robot path planning will lead to a reduction in execution time, and thus, a reduction in energy consumption. Briefly, to optimize the robot's operating parameters, the execution time (related to productivity) and power usage (related to efficiency) as well as the layout constraints (related to path planning) must be considered.

4. Conclusion and future research

This paper addressed the power consumption and dynamic behavior analysis of a six-axis industrial robot under several operating conditions. First, a commercial multi-domain simulation tool based on the Modelica language was used to analyze power consumption and dynamic behavior. Afterward, this model is validated against experimental results collected from an actual robot. The results show that robot operating parameters, such as speed and payload, strongly influence the power consumption and dynamic behavior of industrial robots. A higher payload and speed will increase the power needed by a robot. One kg of payload will add about 10 Watt of robot power consumption, and increasing 20% of the robot's speed will add about 90 Watt. However, since high-speed operation offers high productivity and short operation time, an optimization of these parameters is needed.

Furthermore, this study showed that both simulation and experimental methods can be used to analyze the power consumption of industrial robots. A strong correlation between robot operating parameters and power consumption was found that proves the validity of the simulation method. The deviation between the experimental and simulation results is relatively low and is mainly caused by environmental effects and electromechanical losses in the motor drives. However, based on this result the application of a multi-domain modeling method can serve as a promising alternative to energy consumption and dynamic behavior analysis of an industrial robot. Further potential works may deal with the investigation of mechanical and electrical losses of the robot drives, as well as the investigation of the robot control unit for an analytical validation.

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