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Comparison and validation of implementations of a flexible joint multibody dynamics system model for an industrial robot

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ABSTRACT

In this paper, different implementations of elastic joint models of industrial robots are described and compared established in ADAMS and SimMechanics. The models are intended to be used for path prediction under process force load due to Roboforming and high speed cutting, respectively. The computational results have been compared and showed good agreement. In experiments of robot forming and robot milling the measured and simulated path deviations according to the process force are compared. The experiments are descriped and the results are discussed within the paper as a basis of a next step model based compensation of the path deviation.

1. Introduction

Industrial robots are widely used in various fields of application. However, when it comes to tasks where high stiffness of the machine is required, usually structural robust machine tools are used instead of industrial robots. Industrial robots, on the other hand, have a high work space and are very versatile in terms of possible applications. The goal of ongoing projects for two specific purposes, namely high speed cutting and Roboforming, is to overcome the deviations resulting from the elasticities by modifying the trajectories of the joint angles offline. No additional sensors or other modifications to the robot hardware are necessary. By combining computational models of both the robot and the Roboforming or high speed cutting process the behavior of the robot, the process and their interaction can be predicted. In a second step, upon this data the undesired effects can be compensated.

The parts of the robot that have the largest impact on overall positioning accuracy have been identified to be the elasticities in the joints and gears. Especially in the first three axes, where long lever arms exert high forces and torques, not only elasticities in direction of the motion axis but also orthogonal to it must be taken into account. For the other axes it might be sufficient to consider only elasticities in the direction of motion. The robot links are assumed to be stiff. Thus, the robot can be modeled as a multibody system (MBS).

For the two ongoing projects of roboforming and high speed cutting, different multibody system models of the industrial robots have been set up. In this paper, the different implementations of a robot model with common robot parameters are compared: an implementation based on the commercial MBS software package ADAMS and an implementation using the Matlab/Simulink SimMechanics toolbox. ADAMS gives the reliability of a tool that is widely accepted in industry and offers a 3D based graphical interface supporting the user in pre- and postprocessing of a model and interfaces to several other commercial tools. SimMechanicsis suitable for very fast model set-up and debugging in the Matlab environment. For compensation methods that do not involve sophisticated optimization techniques, both implementations can be used. They both allow the easy exchange of parts of the model or parameters of links or joints.

In accordance with [1] in the first part of this paper an overview of the two different implementations of the underlying robot model will be given and the two approaches will be compared for standardized robot trajectories, both in the case of unloaded and loaded motion. Based on this model based validation, in the second part of this article the robot model will be experimentally validated with use of test data of the two applications Roboforming and high speed cutting.

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2. Elastic joint model of industrial robots

2.1. Basic multibody system dynamics model

The basic model of the robot is a tree structured multibody system. All kinematic and kinetic parameters of the robot like length, mass, center of mass and inertia of the links and the orientation of the axes must be stated. The robot then follows the well known differential equations for general multibody systems without contact, which are given by

$$M(q)\ddot{q} = B\tau - C(q,\dot{q}) - G(q) \quad (1)$$

Here, N is the total number of joints in the system and m is the number of the actively controlled joints. $M \in R^{N\times N}$ is the square, positive-definite mass-inertia matrix. $C \in R^N$ contains the Coriolis and centrifugal forces, $G \in R^N$ the gravitational forces, and $\tau \in R^m$ are the control input functions (the applied joint torques in the case where no detailed motor models are used) which are mapped by the constant matrix $B \in R^{N\times m}$ to the actively controlled joints. In the context of this paper, Eq. (1) shall be evaluated by the simulation packages ADAMS and SimMechanics.

2.2. Extension to a flexible joint model

The standard stiff joint model for the robot is extended to flexible joints by adding additional joints in the direction of motion, which are coupled to the driven joints by spring and damper elements. Furthermore, the gear backlash is taken into account by defining the extension-force relationship of the elasticities, cf. Fig. 1. Furthermore, joints for tilting, which are not directly driven but resemble the spring and damper properties of the tilting in the bearings, are added. The inertia of the motor rotor is not yet taken into account.

2.3. Example robot

For direct comparison of computational results of different implementations of the robot model, an example robot with reasonable but virtual parameters was set up. The basic kinematic structure of the robot is sketched in Fig. 2.

The first five joints of the robot are modeled as elastic joints with backlash, the first three axes in addition have tilting elasticities. The parameters of the robot which are not displayed in Fig. 2 are:

- elasticities in direction of joint motion: 3×10^5 Nm/deg for the first three joints and 3×10^4 Nm/deg for joints 4 and 5,
- tilting elasticities: 3×10^7 Nm/red for the first joint and 2×10^7 Nm/red for joint 2 and 3,

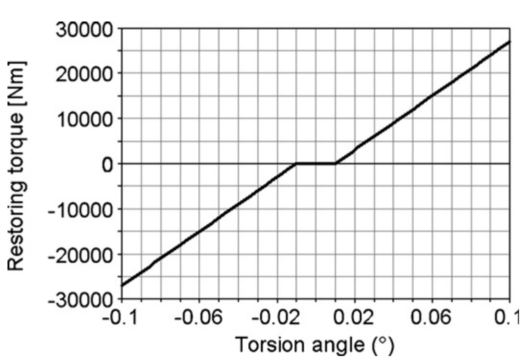

Fig. 1. Modeling of the gear backlash by the relationship between joint angle and joint torque.

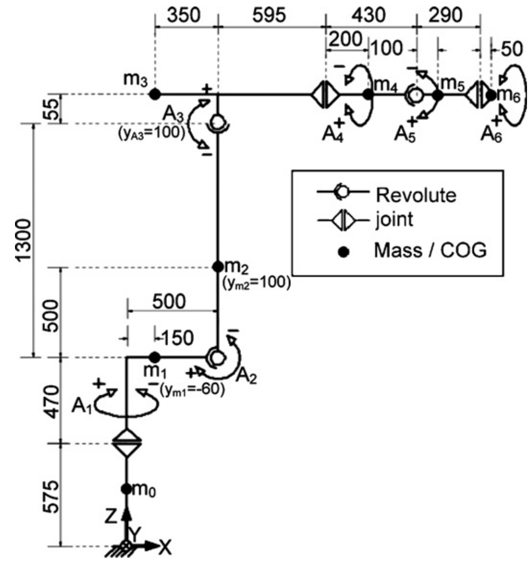

Fig. 2. Example robot.

- damping elements of 1×10^4 Nms/red for each elasticity,
- masses $m_1, \ldots, m_6$ in kg: 700, 400, 400, 100, 70, 200 (note that the last mass m_6 is set to a very high value to test the heavily loaded case),
- inertia matrices of bodies 1–6 are the diagonal matrices with the following entries (in kg m^2): (100, 100, 100), (130, 130, 20), (30, 60, 60), (3, 15, 15), (1, 5, 5), (0.1, 1, 1).

3. Implementation of the model

3.1. ADAMS implementation

The open kinematic chain of the robot is built up in ADAMS as a fully parametrical model. Each joint is defined using variables which represent the three Cartesian coordinates of the position, the three Euler angles of the orientation and the joint type. Simple cylinders representing the robots' links automatically connect all relevant consecutive joints. Their mechanical properties mass, center of gravity and moment of inertia are also parametrically defined. This allows a quick change of the overall kinetic behavior of the simulated robot.

Fig. 3 shows a sample joint able to simulate its forced motion as well as its specific compliance characteristics a sit is modeled in ADAMS. Therefore, a massless dummy part is added which allows the division in a drive unit and a compliance unit. The drive unit connects the dummy i to the robot link i through the prior chosen link connecting joint (here a revolute joint). The angular motion which drives this joint is given by a characteristic curve. The compliance unit consists of a spherical joint, connecting dummy i to link $i+1$, combined with a torque vector element, an in ADAMS so-called VTorque. While the spherical joint allows rotation in all three rotational DOF the VTorque induces a restoring torque depending on the torsion angle and torsion velocity of the spherical joint for each of the three DOF. This way for the directions x, y (tilt directions) and z (direction of motion) different values of stiffness and damping can be set. The restoring torque is defined by

$$M_k = S(\Delta\varphi_k) - d_k\Delta\dot{\varphi}_k, \quad (2)$$

where S is a spline function (Akima method [2]) according to a characteristic curve including torque as a function of the torsion angle including backlash, d_k is the damping coefficient, $\Delta\varphi_k$ is the torsion angle and $\Delta\dot{\varphi}_k$ the torsion velocity. The index k depicts the