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Comparison 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. The models are intended to be used for roboforming and high speed cutting, respectively, and have been established independently from each other into ADAMS and SimMechanics. To be able to compare the models, they have been adapted to the same robot parameters. The computational results have been compared and showed good agreement. For the two scenarios, process forces lead to deviations from the desired path. As a first step towards model based compensation of the path deviation it is crucial to predict the behavior of the robot.

Keywords:

Elastic Joints, ADAMS, SimMechanics, Roboforming, High Speed Cutting

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 machine tools are used because of they are stiffer than 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. In this paper an overview of different implementations of the underlying robot model will be given and compared.

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. SimMechanics is suitable for very fast model setup 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.

The two approaches will be compared for standardized robot trajectories, both in the case of unloaded and loaded motion. The comparison of the computational results is a first step towards the validation of the models and can be done without the use of experimental data.

2 ELASTIC JOINT MODEL OF THE INDUSTRIAL ROBOT

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 lengths, 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

$$\mathcal{M}(\boldsymbol{q})\ddot{\boldsymbol{q}} \quad = \quad B\boldsymbol{\tau} - \mathcal{C}\left(\boldsymbol{q},\dot{\boldsymbol{q}}\right) - \mathcal{G}\left(\boldsymbol{q}\right). \tag{1}$$

Here, N and m are the number of joints resp. actively controlled joints in the system. $\mathcal{M} \in \mathbb{R}^{N\times N}$ is the square, positive-definite mass-inertia matrix. $\mathcal{C} \in \mathbb{R}^N$ contains the Coriolis and centrifugal forces, $\mathcal{G} \in \mathbb{R}^N$ the gravitational forces, and $\boldsymbol{\tau}(t) \in \mathbb{R}^m$ 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 $B \in \mathbb{R}^{N\times m}$ to the actively controlled joints. In the context of this paper, Equation (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. Figure 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.

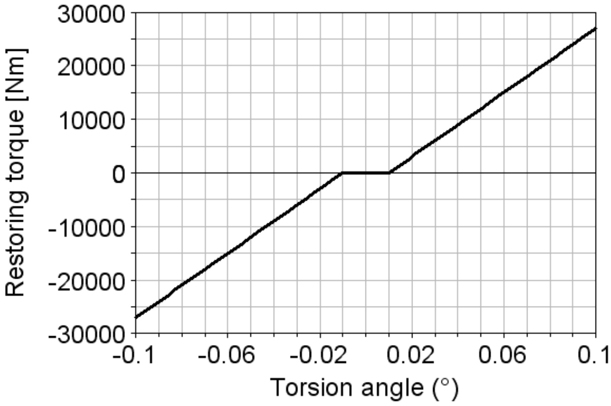

Figure 1: Modeling of the gear backlash by the relationship between joint angle and joint torque.

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 Figure 2.

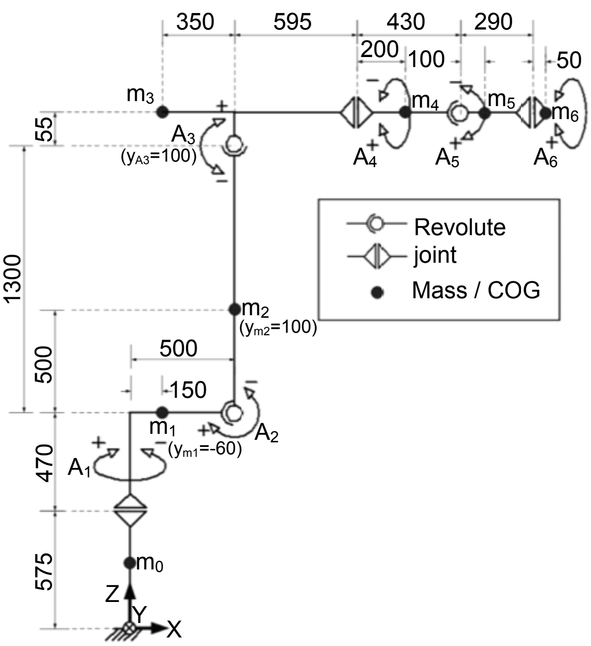

Figure 2: Example Robot.

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 Figure 2 are:

- elasticities in direction of joint motion: $3 \cdot 10^5 Nm/deg$ for the first three joints and $3 \cdot 10^4 Nm/deg$ for joints 4 and 5,
- tilting elasticities: $3 \cdot 10^7 Nm/rad$ for the first joint and $2 \cdot 10^7 Nm/rad$ for joint 2 and 3
- damping elements of $1 \cdot 10^4 Nms/rad$ for each elasticity,
- masses $m_1, \ldots, m_6$: $700kg, 400kg, 400kg, 100kg, 70kg, 200kg$ (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 to 6 are the diagonal matrices with the following entries (in kgm^2): $(100, 100, 100)$, $(130, 130, 20)$, $(30, 60, 60)$, $(3, 15, 15)$, $(1, 5, 5)$, $(0.1, 1, 1)$.

3 IMPLEMENTATIONS 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 3 Cartesian coordinates of the position, the 3 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, centre of gravity and moment of inertia are also parametrically defined. This allows a quick change of the overall kinetic behavior of the simulated robot.

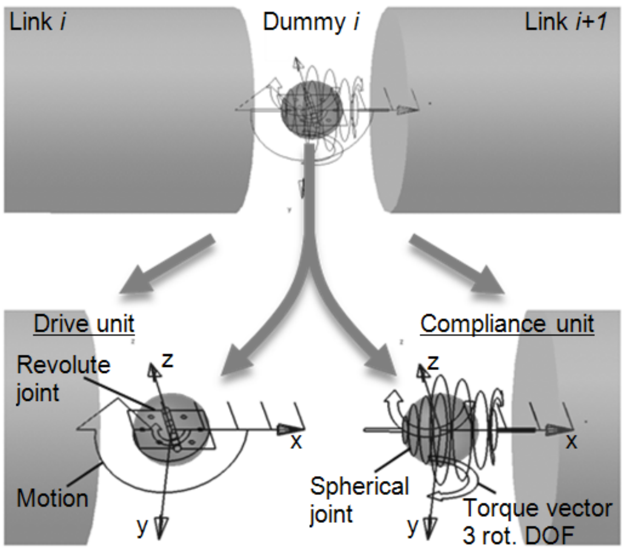

Figure 3: ADAMS setup of a joint including compliance.

Figure 3 shows a sample joint able to simulate its forced motion as well as its specific compliance characteristics as it 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

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

where S is a Spline function (Akima method [1]) according to a characteristic curve including torque as a function of the torsion angle including backlash, d_k is damping coefficient, $\Delta\varphi_k$ is the torsion angle and $\Delta\dot{\varphi}_k$ the torsion velocity. The index k depicts the DOF in x, y and z direction.
For the first three robot axes compliance in all rotational directions is considered, while axes four and five only contain compliance in the direction of motion. Therefore, the spherical joints are replaced by rotational ones around z-axis and instead of Vtorques single torque elements (in ADAMS so called SForces) are used, which also base on Equation (2).
To prevent movement of the robots' kinematic in space, the base part (m_0) is connected to ground by a fixed joint at position $x = 0, y = 0, z = 0$ (cf. Figure 2). Relative to this origin, all position and orientation measurements are defined.

3.2 SimMechanics Implementation

SimMechanics is completely integrated into the Matlab/ Simulink environment and thus allows easy debugging. Fast C code can be generated for tasks with real time requirements. Although different integrators can be chosen, it is also possible to extract only the evaluation of the MBS differential equation (1).
In SimMechanics, the robot model also was set up to be fully described by easy to change parameters. The robot is divided into several blocks for each joint followed by one link, which allows easy duplication of parts of the models in the graphical user interface of Simulink.

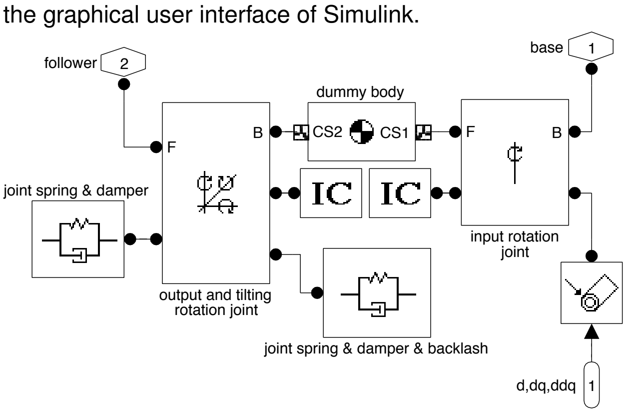

Figure 4: Joint model in SimMechanics.

Standard components for springs and dampers are attached to the joints for modeling of the tilting elasticities and modified components for the springs and dampers in direction of the axis' motion, where the backlash of the gears is taken into account (cf. Figure 4).

3.3 Comparison of the Computational Results for the Example Robot

The different implementations for the example robot were first compared for the quasi static case without gravity for constant joint angles, which basically evaluates the forward kinematics. Furthermore, the effect of the elasticities was tested with gravity for constant input joint angles. Because the elastic joints are also equipped with dampers, the equilibrium point could be used for direct comparison. In both cases, the end effector position and orientation agreed up to the tolerance of the integrator.
For a more sophisticated comparison, the standardized ISO 9283 path, cf. Figure 5, was used. Also for this case, the computational results of both implementations show good agreement. Figure 6 shows the comparison of the rigid forward kinematics path of the tool center point with the dynamic path of the elastic robot (with and without backlash) for two details of the ISO 9283 path of Figure 5, where possible deviations in the results of the model are expected to be clearly visible. As a result of gravity, a quasistatic deviation in z direction between the rigid and the compliant model can be seen for both implementations. As expected, the effect increases if backlash is taken into account. Concerning dynamics effects, the comparison of the case without backlash shows a very good agreement (cf. Figure 6, a, c). With backlash (cf. Figure 6, b, d) a small deviation between the two models can be seen especially in the left part of the circle. The reason for this deviation is expected to result from the different modeling of the angle-torque curve in ADAMS (modeled with a spline, i.e. smooth edges) and SimMechanics (modeled as a piecewise linear function, i.e. not differentiable).

4 ENVISIONED APPLICATIONS

4.1 Roboforming

One planned application of the shown MBS model is the simulation of roboforming, an approach for incremental sheet metal forming developed at the LPS in Bochum [2].
In roboforming, two industrial robots form a clamped sheet metal using a geometrically simple toolkit. Due to the unspecific toolkit, almost any form can be produced by roboforming, which makes the process appropriate for the production of low piece numbers and prototypes, e.g. in the car industry.
Figure 7 shows the robot cell which consists of two robots and a clamping device. Both robots are interconnected to a cooperating robot system.
Figure 8 shows the systematic scheme of roboforming: the forming tool is driven by the master robot, while the second robot drives a supporting tool as slave. The supporting tool only has to follow the forming tool to stabilize the sheet metals back side. The robots' path is synchronized via the robots' control units.
Former tests have shown that due to the robots' kinematics and low stiffness compared to a conventional machine tool, the resulting geometry may deviate more than 1 mm from the wanted form. Therefore, the objective is to predict the deviations resulting from the low stiffness behavior of the robots and correct them via an integrated process-structure model.

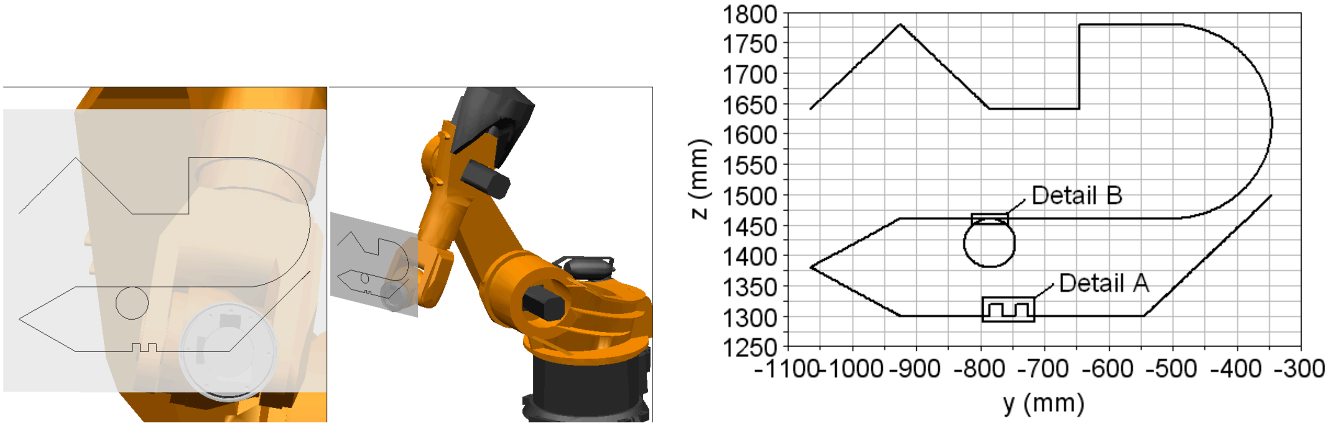

Figure 5: ISO path with details A and B, cf. Figure 6.

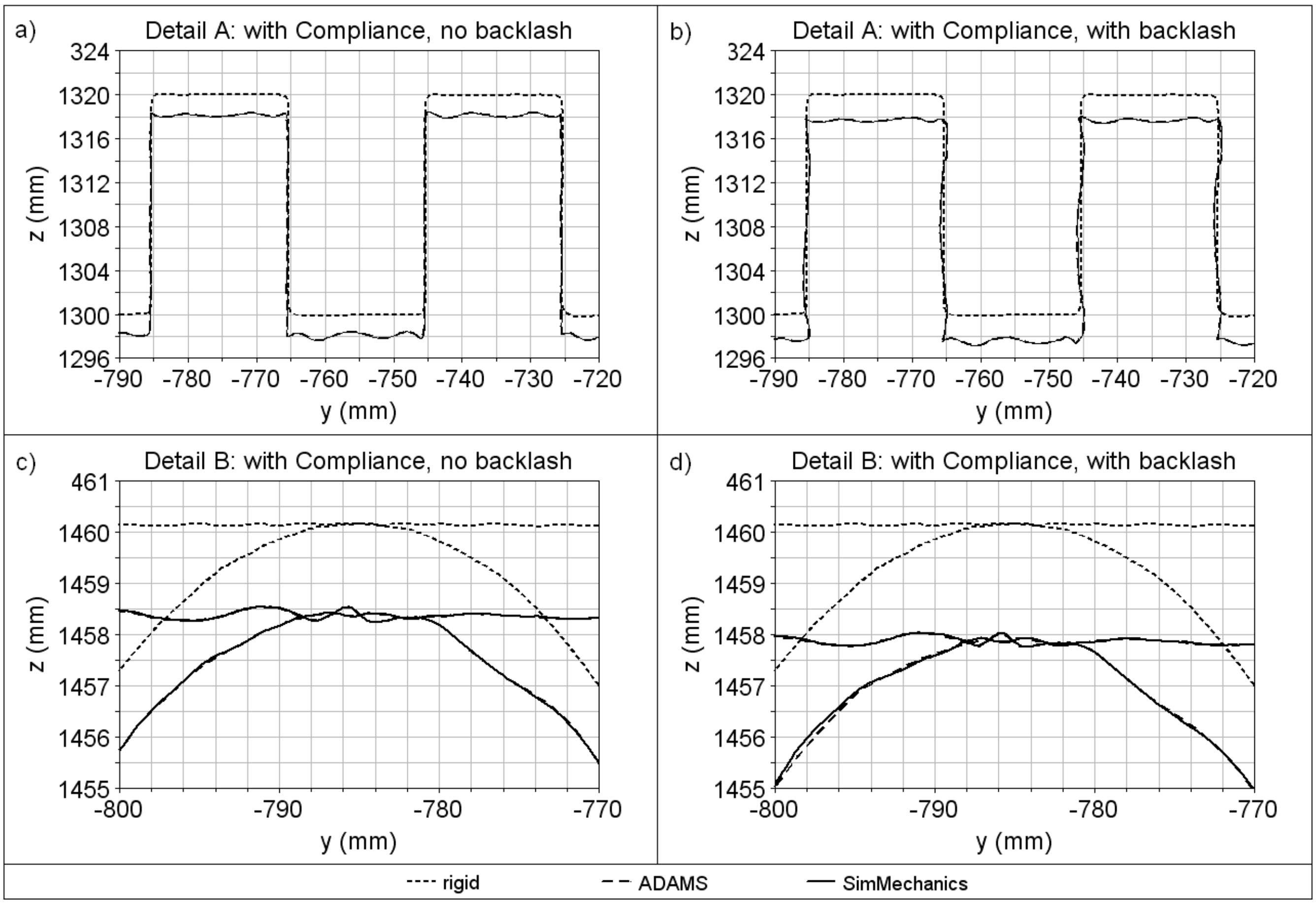

Figure 6: Comparison of the computed paths of both implementations of the robot for details of Figure 5.

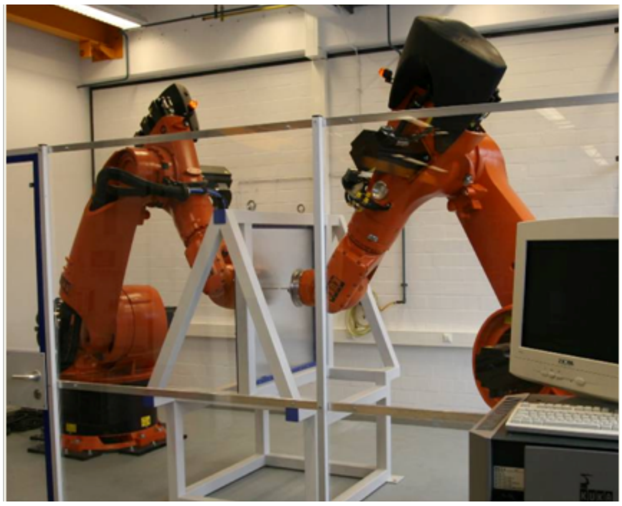

Figure 7: The robot cell.

To simulate the entire process, the multibody simulation is coupled with a finite element analysis. The finite element method (FEM) is used to determine the forces at the tool tip occurring during the forming process, while the tool path deviations due to these forces are calculated in the multibody simulation.
The requirements for such a finite element simulation are quite high. Especially realistic descriptions of the material behavior, e.g. in [3], and the treatment of complex contact phenomena have to be considered.
FEM and MBS are coupled weakly. This means, the coupling has to be iterated until the calculated deviations converge to the real value. Once, this value is known, a correction data set can be determined. In further steps, the correction data set is validated and the robots can be driven on the simulated path and reach more accurate results.

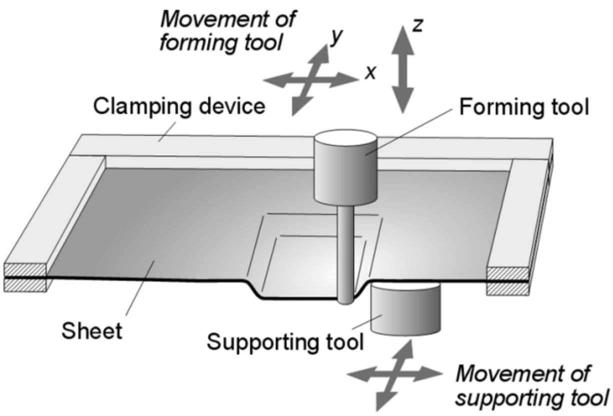

Figure 8: Principle of roboforming.

4.2 High Speed Cutting

The major fields of cutting applications for industrial robots are prototyping, cleaning/ pre-machining of cast parts and finishing of middle tolerance components. Typical milling operations on cast parts are deburring and removing of risers, which are left from casting. These operations take place mostly in noisy, dusty and unhealthy places, and are often done manually or with costly cutting tools on hydraulic presses. For such operations on voluminous and heavy cast parts with complicated lines of burries and undercuts, the robot system can be an economical machine concept. The problem of milling applications with industrial robots is the occurrence of high forces due to the cutting operation which leads to a static and dynamic deflection of the tool centre point. Due to the slender structural parts, the gear compliance and several rotational axes, the deflection is much higher compared to standard machine tools. The high deflection finally results in an undesirable low accuracy and surface quality of the work piece.

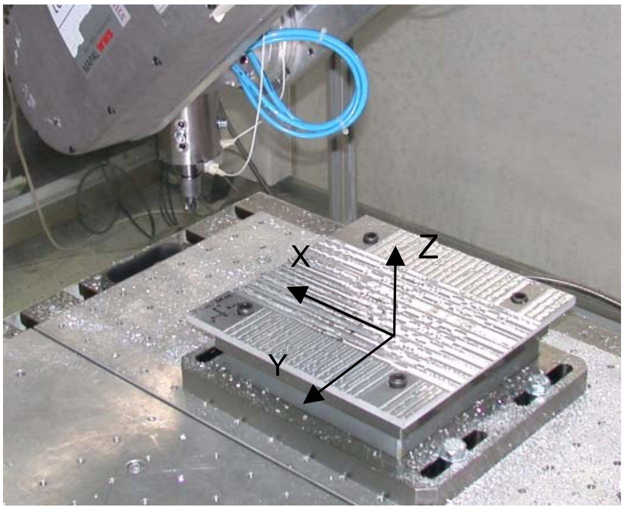

Figure 9: Experimental setup for measuring the cutting forces.

However, by increasing the cutting speed up to the high speed cutting area, the force can be reduced significantly. In a milling test on an industrial robot, the cutting force at a spindle speed of 20.000 and $40.000 min^{-1}$ was recorded. The forces were measured with a Kistler 3component load cell (Type: 9255A). The milling operation in Aluminum 3.1325 was end milling of a straight line in negative x-direction with a tool diameter of $16mm$, a depth of cut $3mm$ and a feed velocity of $8000mm/min$.

Figures 10 and 11 shows the static and dynamic forces normal to the feed direction (y direction) measured with the experimental setup shown in Figure 9. It can be seen that the static forces decrease by 37% when the spindle speed is increased from 20.000 to $40.000min^{-1}$ [4]. Due to the force reduction, the static deflection of the milling path can be reduced as well, which helps to apply industrial robot to work piece operation with smaller tolerances.

In an ongoing project, the cutting process is coupled to the MBS model of the industrial robot to predict and compensate deviations caused by the elasticity of the robot [5]. Once the deviations can be predicted by the model of the robot and the cutting process, by a model based optimal control approach the deviations can be compensated by offline modification of the robot trajectory.

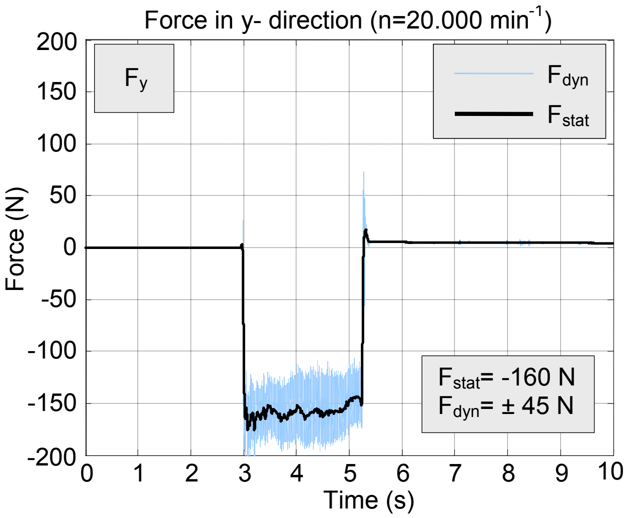

Figure 10: Cutting forces at lower speed.

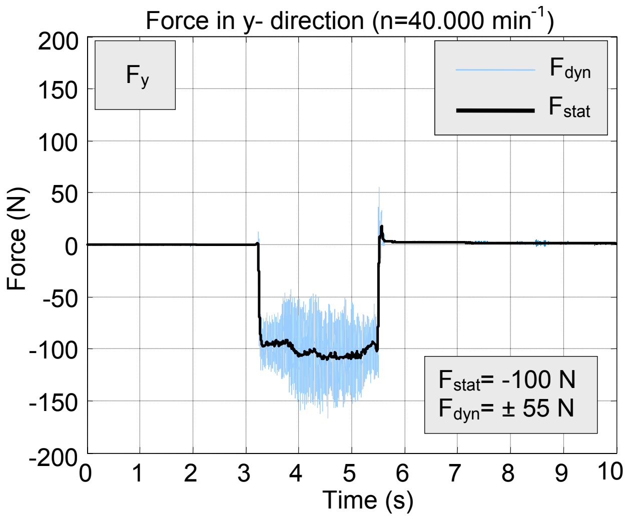

Figure 11: Cutting forces at higher speed.

5 SUMMARY AND OUTLOOK

An industrial robot with elastic joints has been modeled. The main rotation axes are extended by springs and dampers. The backlash of the gears is taken into account. Additional spring and damper elements are used to model the tilting axis.
The model has been implemented in ADAMS and SimMechanics. The computational results for both implementations show good agreement; computation times are comparable. The validation of the computational models with experimental results is in progress.
The next step is to compensate the deviations occurring during roboforming and high speed cutting. Different approaches for the compensation are currently developed. In the case of roboforming, no oscillations in the contact forces occur. Therefore, compensation will be done by iterative mirroring of the deviation with respect to the desired path. In high speed cutting, highly oscillating contact forces occur. A model based optimal control approach for the compensation of deviations will be investigated. Therefore, an object oriented implementation that computes derivative information [6] which can be used for the optimal control approach, will be set up.

6 ACKNOWLEDGEMENT

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7 REFERENCES

[1] Akima, H., 1970, A new method of interpolation and smooth curve fitting based on local procedures. Journal of the Association for Computing Machinery, 17(4):589–602

[2] Meier, H., Smukala, V., Dewald, O., and Zhang, J., 2007, Two point incremental forming with two moving forming tools. SheMet ’07, Proceedings of the 12th International Conference on Sheet Metal, Apr 01.-04., Palermo, Sicily, Italy, Trans Tech Publication Ltd., Switzerland ISBN: 0-87849-437-5, 599–605

[3] Vladimirov, I. N., Pietryga, M. P., and Reese, S., 2007, On the modelling of non-linear kinematic hardening at finite strains with application to springback comparison of time integration algorithms. Int. J. Numer. Meth. Engrng, Published online, DOI: 10.1002/nme.2234

[4] Abele, E., Weigold, M., and Kulok, M., 2006, Increasing the accuracy of a milling industrial robot. Production Engineering Vol. XIII/2 (2006), 221–224

[5] Stelzer, M., von Stryk, O., Abele, E., Bauer, J., and Weigold, M., 2008, High speed cutting with industrial robots: Towards model based compensation of deviations. *Proceedings of Robotik 2008, Munich, Germany; to appear*

[6] Höpler, R., Stelzer, M., and von Stryk, O., 2004, Object-oriented dynamics modeling for legged robot trajectory optimization and control In: Proc. IEEE Intl. Conf. on Mechatronics and Robotics (MechRob), 972–977