Mechanisms and Machine Science 46

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New Advances in Mechanisms, Mechanical Transmissions and Robotics

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This volume presents the proceedings of the Joint International Conference of the XII International Conference on Mechanisms and Mechanical Transmissions (MTM) and the XXIII International Conference on Robotics (Robotics '16), that was held in Aachen, Germany, October 26th–27th, 2016. It contains applications of mechanisms and transmissions in several modern technical fields such as mechatronics, biomechanics, machines, micromachines, robotics and apparatus. In connection with these fields, the work combines the theoretical results with experimental testing. The book presents reviewed papers developed by researchers specialized in mechanisms analysis and synthesis, dynamics of mechanisms and machines, mechanical transmissions, biomechanics, precision mechanics, mechatronics, micromechanisms and microactuators, computational and experimental methods, CAD in mechanism and machine design, mechanical design of robot architecture, parallel robots, mobile robots, micro and nano robots, sensors and actuators in robotics, intelligent control systems, biomedical engineering, teleoperation, haptics, and virtual reality.

Engineering

ISBN 978-3-319-45449-8

9 783319 454498

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ISSN 2211-0984 ISSN 2211-0992 (electronic)
Mechanisms and Machine Science
ISBN 978-3-319-45449-8 ISBN 978-3-319-45450-4 (eBook)
DOI 10.1007/978-3-319-45450-4

Library of Congress Control Number: 2016950582

Printed on acid-free paper

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The registered company is Springer International Publishing AG
The registered company address is: Gewerbestrasse 11, 6330 Cham, Switzerland

Kinematic and Dynamic Analysis of a 4DOF Parallel Robot with Flexible Links

N. Cretescu, M. Neagoe and R. Saulescu

Abstract The paper deals with the dynamic behaviour of a 4DOF parallel robot with decoupled motions, three orthogonal translations and one rotation, in a comparative approach of flexible versus rigid links, and also the influence of friction in the four active prismatic joints. The ADAMS software and its AUTOFLEX module were used to model the parallel robot and further to identify the end-effector motion errors on a representative trajectory, due to the natural flexibility of the robot links, and the variation of the actuating forces needed in the input joints with both links flexibility and active joints friction. The obtained numerical results show significant resultant errors of the end-effector from the planned trajectory, generated by link elastic deformations, and important errors of actuating forces (up to 300 %) in the assumption of both link flexibility and active joint friction. The results are useful for robot designers to optimally select the actuators and appropriate design the control system to ensure trajectory high accuracy on the robot workspace.

Keywords Parallel robot • ADAMS modelling • AUTOFLEX module • Flexible link • Friction • Analysis

1 Introduction

The parallel robots are closed kinematic chain type mechanisms, composed by a mobile platform (the end-effector) connected to the fixed base by two or more kinematic chains called limbs or legs [4]. Comparing with serial manipulators, parallel robots have the advantages of higher speeds and precision, higher loads and

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B. Corves et al. (eds.), *New Advances in Mechanisms, Mechanical Transmissions and Robotics*, Mechanisms and Machine Science 46,
DOI 10.1007/978-3-319-45450-4_48

thinness of links. As consequence, the link flexibility under heavy operational conditions can be an important factor influencing significantly the end-effector trajectory accuracy and the driving forces/torques in active joints. Furthermore, friction forces in robot joints influence directly the driving generalised forces and implicitly the design of the actuating system by appropriate choice of actuators.

The link flexibility was approached in many works [1, 2, 5–10], using different modelling methods aiming especially to develop dynamic models and to study the robot mechanism behaviour in the assumption of elastic deformations of robot links. A dynamic finite element analysis of a planar fully parallel robot with flexible links is developed in [9]. By formulating and solving a set of linear ordinary differential equations of motion, the influence of mechanism configurations at high speed motions on the elastic vibrations was highlighted. A numerical kinematical and dynamical modelling in rigid and flexible links hypothesis was presented in [1, 2], using a simplified CAD model developed in ADAMS software and analysed as flexible link system in ADAMS AutoFlex module.

The dynamic behaviour a flexible space robot with joint friction was analysed in [6] by developing the dynamic equations using Jourdain's velocity variation principle and the single direction recursive construction method, concluding that the Coulomb friction model is limited in describing the nonlinear features of friction. Furthermore, an active controller of a flexible space robot considering joint friction was designed, studied and validated using ADAMS software [5]. A review of the main principal methods used in literature for kinematical and dynamical analysis of flexible mechanical systems is presented in [10].

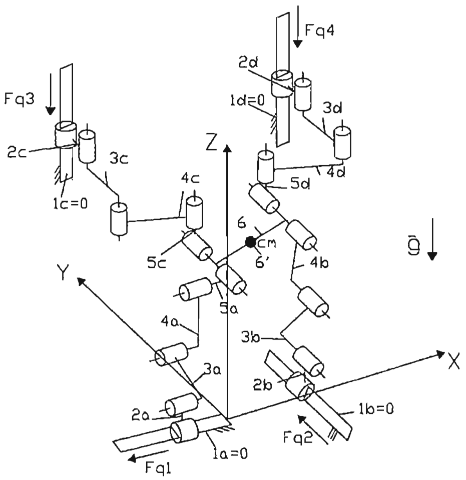
The paper aims at presenting representative results on the influence of the link flexibility and active joint friction on the dynamic behaviour of parallel robots, based on a case study of the 4DOF Isoglide4 manipulator [3] by approaching the robot modelling in ADAMS software and ADAMS Autoflex module to highlight their effect on the end-effector motion accuracy and the driving forces.

2 Problem Formulation

The paper deals with the modelling and simulation of the Isoglide4 parallel robot with decoupled motions [3], Fig. 1, in the assumption of flexible links 3a, b, c, d and 4a, b, c, d and considering friction in the four prismatic active joints q1…q4.

This parallel robot (Fig. 1) is composed by four arms (a, b, c and d), containing each 3 revolute joints with parallel axes, and connected to the end-effector 6 through revolute joints. And additional load 6' is added in the centre of mass (cm) of the mobile platform 6. The end-effector has three decoupled translational motions (along X, Y and Z axis) and one coupled rotational motion (on Y axis) obtained through differential motion of the two vertical linear drivers. This robot is included in a parallel mechanism family proposed in literature [4] as parallel tool machine, raising multiple issues on the link flexibilities and joint frictions.

Fig. 1 Kinematical scheme of the Isoglide4 parallel robot

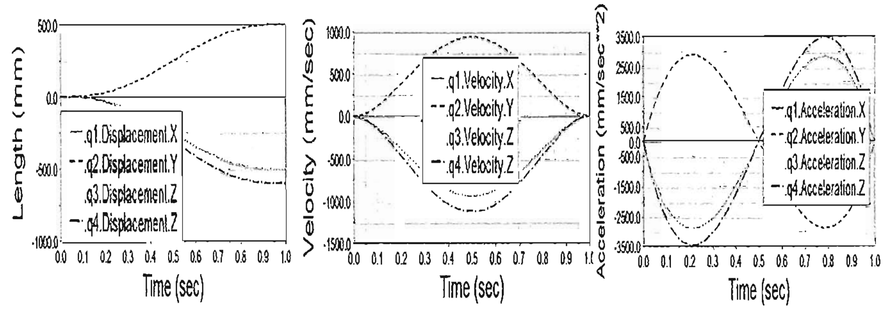


This study is based on the CAD model developed in the ADAMS software considering the following assumptions:

- the robot links are modelled using simple shape steel bodies: cylinders and parallelepipeds, with physical properties systematized in Table 1. The masses of links 5a, c, d are not significant and thus neglected;
- the gravity acts in the negative sense of the Z axis;
- a supplementary mass 6′ of 10 kg is used as robot load;
- using ADAMS AutoFlex module, the links 3 and 4 of each arm are transformed into flexible links; their natural frequencies up to 1000 Hz are considered in simulations;
- the open loop control is applied in the parallel robot simulations;

Table 1 Geometric and mass parameters (according to Fig. 1)

Lengths		Masses	
$l_{2a} = l_{2b} = l_{2c} = l_{2d}$	130 mm	$m_{2a} = m_{2b} = m_{2c} = m_{2d}$	17.10 kg
l_{3a}	677 mm	m_{3a}	26.90 kg
l_{3b}	711 mm	m_{3b}	28.65 kg
l_{3c}	752 mm	m_{3c}	22.81 kg
l_{3d}	638 mm	m_{3d}	23.58 kg
l_{4a}	792 mm	m_{4a}	31.98 kg
l_{4b}	698 mm	m_{4b}	27.99 kg
l_{4c}	630 mm	m_{4c}	28.99 kg
l_{4d}	702 mm	m_{4d}	28.97 kg
l_6	300 mm	m_6	17.00 kg
l_5	120 mm	m_5	0 kg



a b c

Fig. 2 Motion generated in the active joints q1, q2, q3 and q4: **a** displacement, **b** velocity, **c** acceleration

- the numerical simulations are carried out considering a representative linear trajectory in the Cartesian space between two points, using a fifth degree polynomial movement low in each active joint (Fig. 2, q1 and q3 have identical motion lows), which allow the end-effector maximum acceleration reaching 5.5 m/s^2, while the linear actuators develop a maximum acceleration of 3.5 m/s^2 and a maximum velocity of ~1 m/s; the strokes of the driving motions along the X (q1), Y (q2) and respectively Z (q3) axis are each of 500 mm and the coupled rotational motion along Y axis is done by the difference between the motions q3 and q4 (the q4 stroke equals 600 mm;
- the coefficient of friction in active joints are 0.016 (static) and 0.01 (dynamic).

Starting from these data, a comparative analysis on the kinematic and dynamic behaviour of the Isoglide4 parallel robot with flexible vs. rigid links, in both assumptions of considering and neglecting the friction in the active joints, is performed in the next chapters. The motion errors on a planned trajectory, due to the link flexibility, are investigated; the influence of friction and link flexibility on the driving forces is also approached in the paper.

3 Effects of Links Flexibility on Robot Behaviour

Based on the CAD simplified rigid link model developed in the ADAMS software (Fig. 3a), the flexible link robot model (Fig. 3b) is obtained using ADAMS AutoFlex module.

The links elasticity influence on the robot kinematic behaviour is highlighted in Fig. 4 by drawing the time variation of the resultant motion (displacement—Fig. 4a, velocity—Fig. 4b and acceleration—Fig. 4c) of the mobile platform mass centre (cm, Fig. 1) in relation to the ideal trajectory achieved by the robot with rigid links. The results show that the elasticity has a significant impact on the end-effector

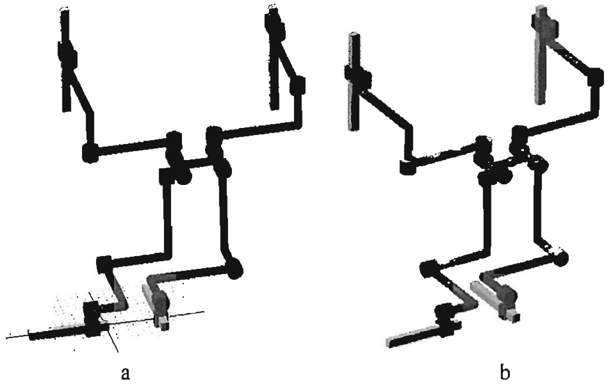


Fig. 3 ADAMS model of parallel robot in the initial position on the selected trajectory: **a** rigid links model and **b** flexible links model

motion, causing an oscillating evolution of the kinematic parameters relative to the planned trajectory and hence significant displacement, velocity and acceleration errors. Thus, for the considered trajectory (Fig. 2) the maximum resultant displacement error reaching worth ~45 mm is recorded at the trajectory ends (Fig. 4a) due to inertial effect. The maximum resultant errors of the velocity on the trajectory reach values up to 15 mm/s (Fig. 4b), and the resultant acceleration records errors up to 7500 mm/s^2 (Fig. 4c), i.e. acceleration maximum relative errors of ~125 %. Larger errors are registered for the angular motion of the mobile platform, e.g. velocity relative errors up to 175 % (Fig. 4d).

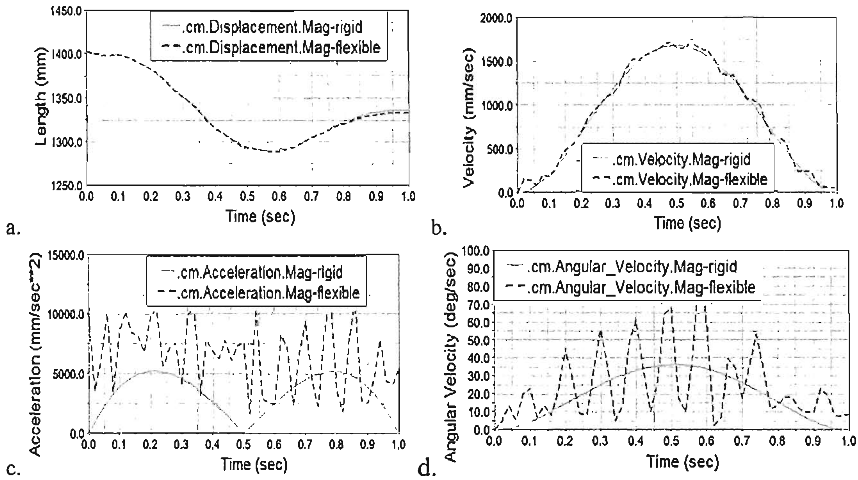
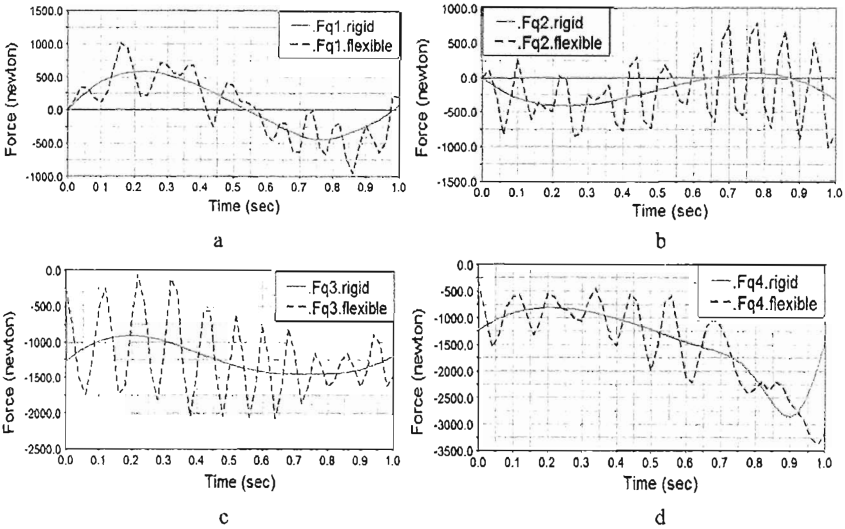


Fig. 4 End-effector motion magnitude (the length of the resultant vector) on the planned trajectory, in rigid (*red—continuous line*) and flexible link hypothesis (*blue—dashed line*): **a** the resulting displacements, **b** the resulting linear velocities, **c** the resulting linear accelerations, **d** the angular velocities



a

b

c

d

Fig. 5 Driving forces needed in the active joints: **a** q1, **b** q2, **c** q3 and **d** q4, in rigid links hypothesis (*red—continuous line*) and flexible links hypothesis (*blue—dashed line*) (color figure online)

The links elasticity influence on the robot dynamic behaviour is determined by analyzing the evolution of the axial forces in the active joints (q1…q4) and their errors in relation to the ideal case of rigid links. The obtained results (Fig. 5) show a relatively high frequency oscillatory regime of active forces, with negative impact on the robot operation due to the additional rapid varying loads on the linear actuators. It can be remarked that all four actuators are affected by the links elasticity effects to a similar extent, the driving force relative errors registering maximum values of approximately 100 % (Fig. 5).

4 Influence of Friction on Driving Forces

The joint friction influences the robot dynamic behaviour in both assumptions of rigid and flexible links, having a major impact on the driving forces in the active joint, as Fig. 6 shows. The normal forces in the active prismatic joints, transmitted to the base link, generate additional resistant friction forces for the linear actuators and thus changing the magnitude of the driving forces. In the case of rigid links robot, the driving forces with friction are registering significant absolute errors in relation with the ideal joints assumption for the active joints q1 (up to 475 N, Fig. 6a, b) and q2 (up to 700 N, Fig. 6c, d), and friction has less influence on the other two vertical actuators (Fig. 6e–h).

The links flexibility increases in some extent the impact of friction forces on the driving forces, but keep the same frequency profile of active forces variation

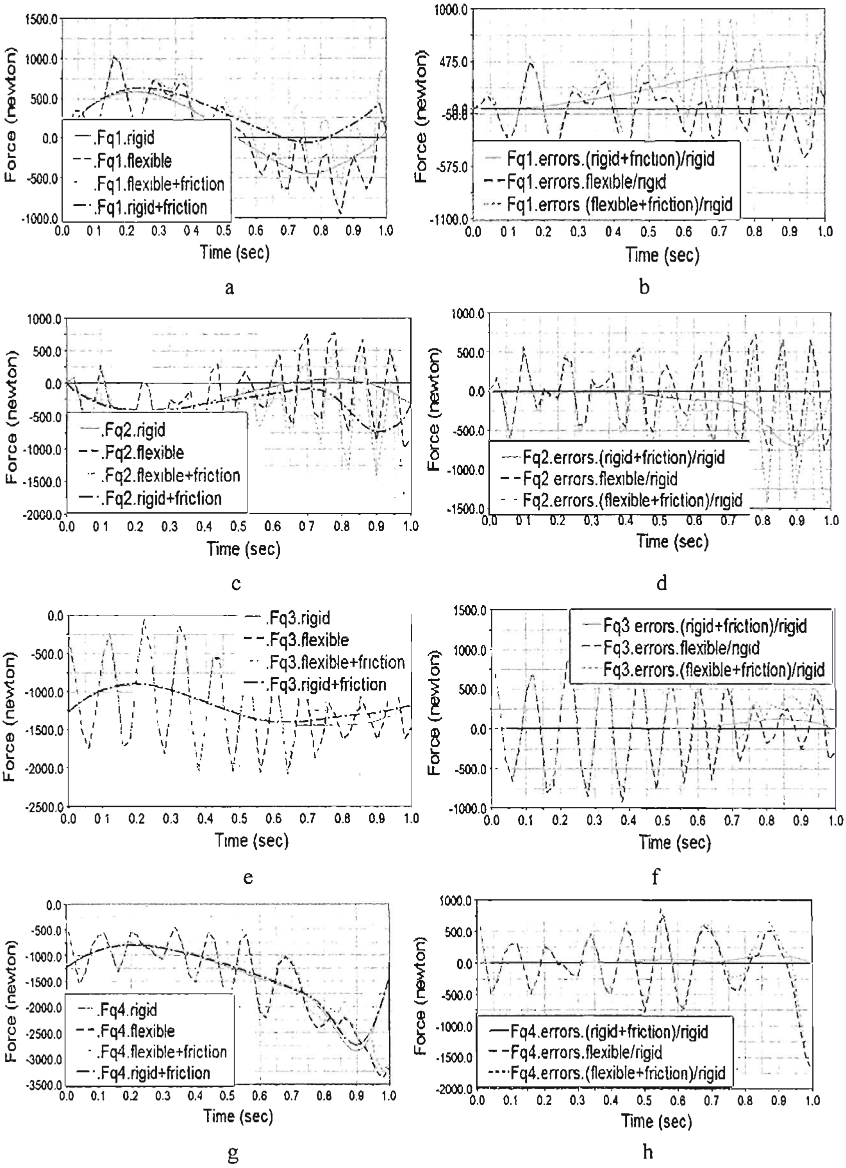


Fig. 6 **a**, **c**, **e**, **g** Driving forces: *red*—rigid link hypothesis, *blue*—flexible link hypothesis, *dark blue*—rigid link hypothesis with friction in active prismatic joints, *pink*—flexible link hypothesis with friction in active prismatic joints; **b**, **d**, **f**, **h** absolute errors of active forces, relative to the rigid links case: *green*—rigid links and joint friction, *blue*—flexible links, *red*—flexible links and joint friction (color figure online)

comparing with the no friction assumption. Comparing with the rigid link robot without friction, it can be highlighted that the driving forces are doubled when only the elasticity is considered and are tripled if the joint friction occurs, mainly for the active joints q1 (Fig. 6a) and q2 (Fig. 6c).

5 Conclusions

This comparative study of the Isoglide4 parallel robot with flexible links and friction in the four active prismatic joints in relation with its ideal variant (rigid link and no friction assumption), allows us to draw the following conclusions:

- the link flexibility has a significant influence on the robot trajectory accuracy, large variations of the end-effector displacements, velocities and especially accelerations can occur from the planned motion trajectory;
- the link flexibility has an important influence on the time variation of driving forces, increasing both the forces magnitude and frequency;
- the joint friction generates relevant additional resistance forces and thus increases the driving forces.

According to the presented results and conclusions, the designers of parallel robots should develop deep knowledge on the kinematic and dynamic behaviour of the robot with flexible links and joint friction in order to identify the best solutions for a high accuracy operation and appropriate selection of the actuators according to the real power and force requirements. Also, a future work will aim at comparing the simulation results with real robot measurements.

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