International Journal of Mechanical Engineering and Robotics Research

ISSN 2278 – 0149 www.ijmerr.com
Vol. 3, No. 4, October 2014

Research Paper

JOINT PARAMETER ESTIMATION OF SERIAL MANIPULATORS USING RIGID BODY DYNAMICS

K N V Swamy[1]* and A Gopi Chand[2]

*Corresponding Author: K N V Swamy, ✉ Swamymtech1@gmail.com

Use of Robotic manipulators is wide spread in Mechanical Industries. Serial Manipulators take the major share in this aspect. Rigid Body dynamics is an efficient tool for estimating effect of inertial loads on joint torques and thus help in generating a better control system for robotic manipulators. In the current work, the use of Rigid Body Dynamics using the motion analysis package in commercial software (Solidworks) is used. The results are verified analytically. Rigid Body Dynamic Analysis are also performed on 3DOF planar manipulator and 3DOF spatial manipulator. The results of simulations of 3DOF spatial manipulators are taken as input for stress analysis using FEA.

Keywords: Rigid body dynamics, Motion analysis, Planar manipulator, Joint torque

INTRODUCTION

Robotic manipulators are widely being used for material handling and other applications in industry. The manipulators used for this purpose can be widely classified into two categories: 1) Serial manipulators, and 2) ParallelManipulators. Parallel manipulators, due to their robust structure, have good load bearing capacity while because of the same structure have a very low work volume. Serial Manipulators on the other have good dexterity and greater work volume but lesser strength due to their open chain structure. Thus it is always necessary to understand the forces and torques that are acting at various joints. Rigid Body Dynamics proves to be a promising solution in this regard. Rigid Body Dynamics involves the study of forces and reactions that are arising due to interaction of various bodies. During this analysis, the bodies are considered as non-deformable rigid bodies. This involves both kinematic and kinetic simulation of bodies. Many researchers have used this procedure for studying the behavior of manipulators and synthesizing the manipulator.

Vishal Abhishek *et al.* (2014) used Rigid Body Dynamics to estimate the dynamic parameters of an industrial robot KUKA KR5. Euler-Lagrangian formulation is used for this

[1] M.Tech Student, Department of Mechanical Engineering, Swarnandhra College of Engineering and Technology, Narsapur, AP, India.
[2] Professor and HOD, Department of Mechanical Engineering, Swarnandhra College of Engineering and Technology, Narsapur, AP, India.

purpose. Then the equations of motion obtained were linearized and expressed in terms of the base parameters. The numerical values of base parameters were obtained by linear regression technique applied to the points along a given planar trajectory. The obtained values are verified experimentally. Shankar and Vamsi Krishna (2014) demonstrated the use of Rigid Body Dynamics for computing workspace of a parallel manipulator. Creo 2.0 MDX module is used for this purpose. Takamitsu Matsubara *et al.* (2014) estimated inertial parameters using rigid body dynamics for modal based control of serial manipulator. The approach is focused on task specific subspace. A modern statistical supervised learning framework called covariate shift adaptation equipped with a direct importance estimation method for estimating inertial parameters is also proposed by them. Amit *et al.* (2014) did a rigid body simulation to obtain the interacting forces of various members in a wiper mechanism and then transferred these forces to FEA models for performing stress analysis. Sanjeev Soni *et al.* (2013) used ADAMS to perform kinematic analysis for computing workspace of a 3DOF medical manipulator. The obtained results are verified using D-H parameters. Patel and Gorge (2013) used kinematic analysis for workspace computation. Ling Wen *et al.* (2013) discussed the use of 5 DOF serial manipulator for various applications investigated. Various techniques for rigid body dynamics of the manipulator discussed. The 3D model of the manipulator is generated in Solidworks. Kurfess (2005) and Niku (2013) gave a lot of formulations for computing joint parameters for various types of manipulators with various cases. Ana Djuric *et al.* (2012) developed n-GDM, a generalized dynamic model computation system to compute the joint torque characteristics. This is based on n-GKM kinematic model that was developed by the same authors which can automatically generate the kinematic model based on the type of joints given as input. The model that was developed used MAPLE 12.0 math symbolic language. Burak Baykus *et al.* (2011) used rigid body dynamics to compute the interaction forces for designing a luggage door. Ngoc Dung Vuong and Marcelo Ang (2009) proposed a dynamic model considering the dynamic effects of friction when computing joint parameters. The highly non-linear nature of friction is compensated using a static friction model. Wisama Khalil *et al.* (2007) presented four methods for calculating the inertia effects of load on the joint parameters. Theingi *et al.* (2002) discussed the formulations for kinematics of a 2DOF planar manipulator formed by using a 5-bar chain. Saha (1999) discussed the constrained dynamic equations of motion of serial multibody systems consisting of rigid bodies in a serial kinematic chain. Quanzhao *et al.* (2011) performed a kinematic simulation of a 2DOF parallel manipulator using Matlab.

Most of the above researchers took symbolic models instead of accurate 3D models to compute the inertia effects in serial manipulators. Many of the current high end commercial modeling software are now providing the facility of Rigid Body Dynamics. In the current work an attempt has been made to use a commercial software (Solidworks) to generate the 3D models and perform Rigid

Body Dynamic Analysis. The results obtained in case of a 2DOF planar manipulator are compared with that of theoretical calculations.

PROBLEM STATEMENT

As mentioned in the previous section, the aim the current work is to demonstrate the use of commercially available modeling software to generate 3D models as well as to perform rigid body dynamic analysis. The obtained joint parameters are then transferred to FE module of the same software and FE analysis is performed on the manipulators. Three different manipulators are considered during the study. They are:

- 2DOF planar manipulator (Figure 1)
- 3DOF Planar Manipulator (Figure 2)
- 3DOF Spatial Manipulator (Figure 3)

Figure 1: 2DOF Manipulator

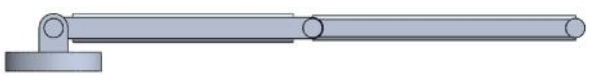
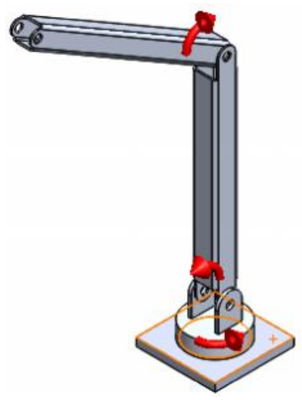


Figure 2: 3DOF Planar Manipulator

Figure 3: 3DOF Spatial Manipulator



The validity of the results is also checked using analytical formulations given by Niku (2013) for one manipulator, i.e., 2DOF planar manipulator.

ANALYTICAL MODELING OF 2DOF PLANAR MANIPULATOR

As mentioned earlier the expressions given by Niku (2013) are used to compute the joint parameters of the manipulator. The various input parameters and the expressions used are listed in this section. All the computations are performed using MathCAD.

Link 1 Length $1_1 := 130$ mm

Link 2 Length $1_2 := 132$ mm

Link 1 Mass $m_1 := 0.01808$ kg

Link 2 Mass $m_2 := 0.01693$ kg

Link 1 Angular position wrt fixed link

$$\theta_1 := \begin{pmatrix} 9.36 \\ 31.68 \\ 58.32 \\ 80.64 \\ 90 \end{pmatrix} \text{deg} = \begin{pmatrix} 0.163 \\ 0.553 \\ 1.018 \\ 1.407 \\ 1.571 \end{pmatrix}$$

Link 2 Angular position wrt link 1

$$\theta_2 := \begin{pmatrix} -9.36 \\ -31.68 \\ -58.32 \\ -80.64 \\ -90 \end{pmatrix} \text{deg} = \begin{pmatrix} -0.163 \\ -0.553 \\ -1.018 \\ -1.407 \\ -1.571 \end{pmatrix}$$

Link 1 Angular velocity relative to fixed link

$$\omega_1 := \begin{pmatrix} 17.28 \\ 25.9151 \\ 25.9265 \\ 17.3284 \\ 0.107 \end{pmatrix} \cdot \frac{deg}{sec} = \begin{pmatrix} 0.302 \\ 0.452 \\ 0.453 \\ 0.302 \\ 1.868 \times 10^{-3} \end{pmatrix} \frac{1}{s}$$

Link 2 Angular velocity relative to link 1

$$\omega_2 := \begin{pmatrix} -17.28 \\ -25.9151 \\ -25.9265 \\ -17.3284 \\ -0.107 \end{pmatrix} \frac{deg}{s} = \begin{pmatrix} -0.302 \\ -0.452 \\ -0.453 \\ -0.302 \\ -1.868 \times 10^{-3} \end{pmatrix} \frac{1}{s}$$

Link 1 Angular Acceleration

$$\alpha_1 := \begin{pmatrix} 12.959999999967 \\ 4.33954069600863 \\ -4.29372185015424 \\ -12.8952639685857 \\ -21.5136000001924 \end{pmatrix} \frac{deg}{sec^2} = \begin{pmatrix} 0.226 \\ 0.076 \\ -0.075 \\ -0.225 \\ -0.375 \end{pmatrix} \frac{1}{s^2}$$

Link 2 Angular Acceleration

$$\alpha_2 := \begin{pmatrix} -12.959999999967 \\ -4.33954069600863 \\ 4.29372185015424 \\ 12.8952639685857 \\ 21.5136000001924 \end{pmatrix} \frac{deg}{sec^2} = \begin{pmatrix} -0.226 \\ -0.076 \\ 0.075 \\ 0.225 \\ 0.375 \end{pmatrix} \frac{1}{s^2}$$

Torque at Joint 1

$$T_1 := \left(\frac{1}{3} \cdot m_1 \cdot l_1{}^2 + m_2 \cdot l_1{}^2 + \frac{1}{3} \cdot m_2 \cdot l_2{}^2 + m_2 \cdot l_1 \cdot l_2 \cdot C_2\right) \cdot \alpha_1 + \left(\frac{1}{3} \cdot m_2 \cdot l_2{}^2 + \frac{1}{2} \cdot m_2 \cdot l_1 \cdot l_2 \cdot C_2\right) \cdot \alpha_2$$

$$- m_2 \cdot l_1 \cdot l_2 \cdot S_2 \cdot \omega_1 \cdot \omega_2 - \left(\frac{1}{2} \cdot m_2 \cdot l_1 \cdot l_2 \cdot S_2 \cdot \omega_2{}^2\right)$$

$$+ \left(\frac{1}{2} \cdot m_1 + m_2\right) \cdot g \cdot l_1 \cdot C_1 + \frac{1}{2} \cdot m_2 \cdot g \cdot l_2 \cdot C_{12} = \begin{pmatrix} 0.043 \\ 0.039 \\ 0.028 \\ 0.016 \\ 0.011 \end{pmatrix} J$$

Torque at Joint 2

$$T_2 := \left(\frac{1}{3} \cdot m_2 \cdot l_2{}^2 + \frac{1}{2} \cdot m_2 \cdot l_1 \cdot l_2 \cdot C_2\right) \cdot \alpha_1 + \frac{1}{3} \cdot m_2 \cdot l_2{}^2 \cdot \alpha_2$$

$$+ \frac{1}{2} \cdot m_2 \cdot l_1 \cdot l_2 \cdot S_2 \cdot \omega_1{}^2 + \frac{1}{2} \cdot m_2 \cdot g \cdot l_2 \cdot C_{12} = \begin{pmatrix} 0.011 \\ 0.011 \\ 0.011 \\ 0.011 \\ 0.011 \end{pmatrix} J$$

SIMULATION RESULTS

As mention earlier, rigid body dynamic simulation is carried out on various manipulators. This section presents the simulation results on all manipulators considered.

2DOF Planar Manipulator

Figure 1 gives the 2DOF manipulator considered for analysis. In all the three cases the corresponding link lengths are the same. The cross section of Link 1 and Link 3 in all the cases is a box of 15 mm x 15 mm x 1 mm thick while link 2 has a cross section of 13 mm x 13 mm x 1 mm. The solid models are created in Solidworks. Joint actuation motors are applied and actuation is performed. Joint actuation profiles for 2 DOF manipulator are shown in Figures 4a and 4b. Gravity is enabled in all cases. The torques computed by executing the Rigid Body Dynamic analysis are given in Figures 5a and 5b.

Figure 4a: Joint 1 Actuation

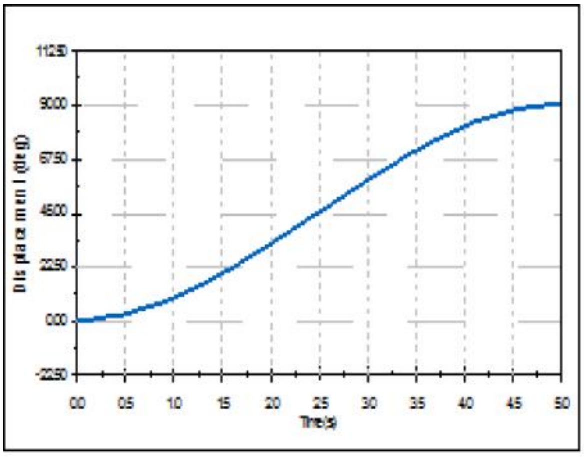


Figure 4b: Joint 2 Actuation

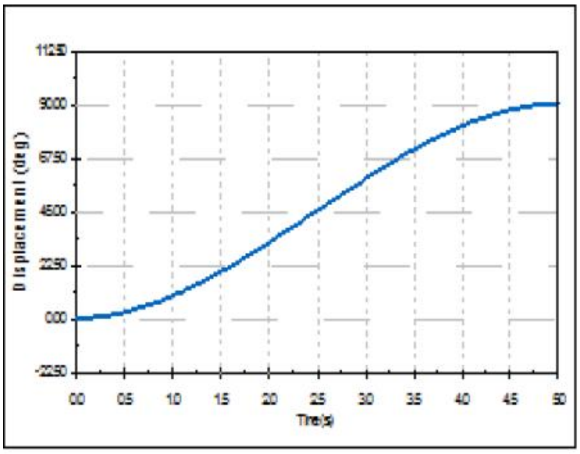


Figure 5a: Resulting Joint 1 Torque

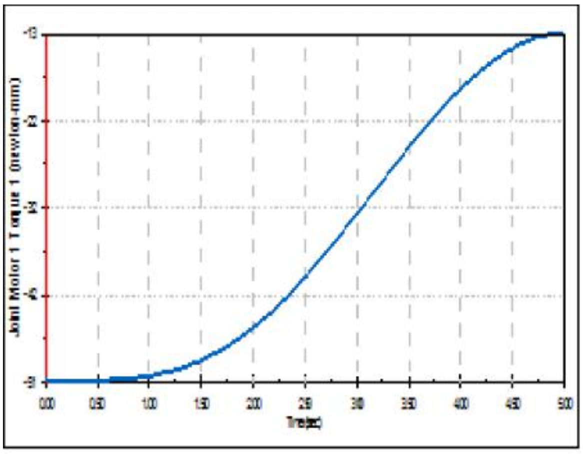
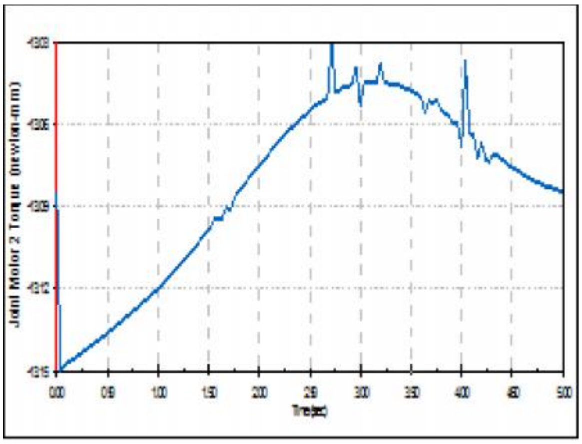


Figure 5b: Resulting Joint 2 Torque



The comparison between calculated joint torques and the torques obtained through simulation are presented in Figures 6a and 6b. From the comparison, it can be seen that there is not much difference between calculated values and simulation results indicating that the simulations can be relied upon. An average deviation of 15% is observed between the computed values and simulation results.

3DOF Planar Manipulator

For 3DOF manipulator, joint actuation profiles are shown in Figures 7a, 7b and 7c. The

Figure 6a: Joint 1 Torque Comparison

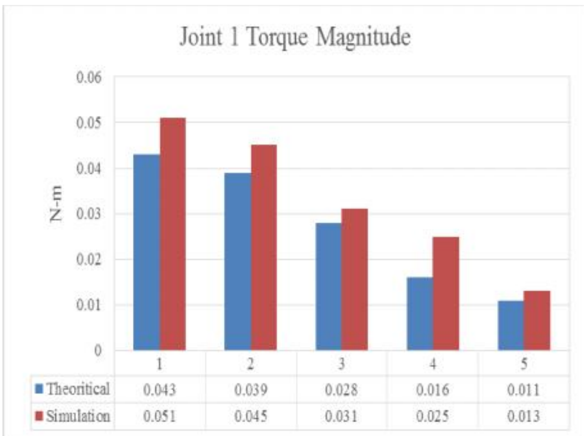


Figure 6b: Joint 2 Torque Comparison

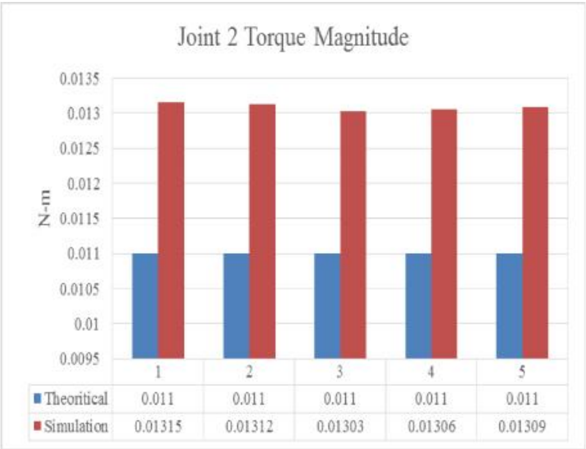
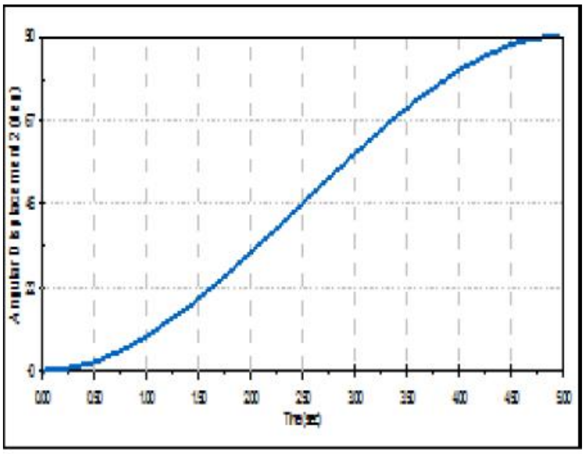


Figure 7: Joint Actuation Profiles and Resulting Torque Profiles

(a) Joint 1 Actuation Profile



(b) Joint 2 Actuation Profile

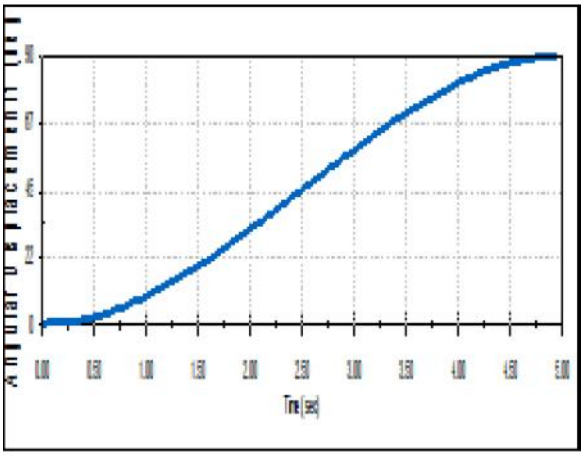
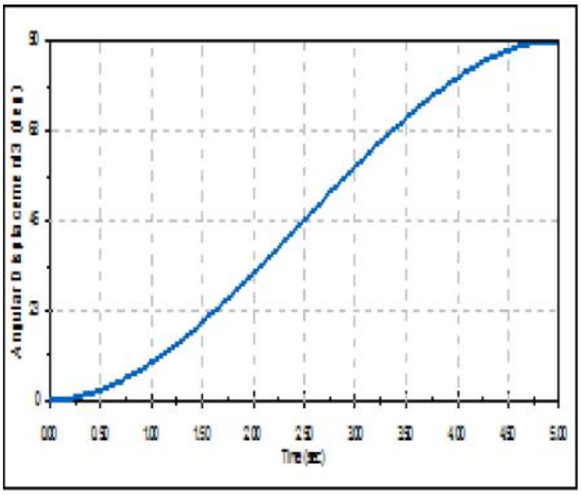
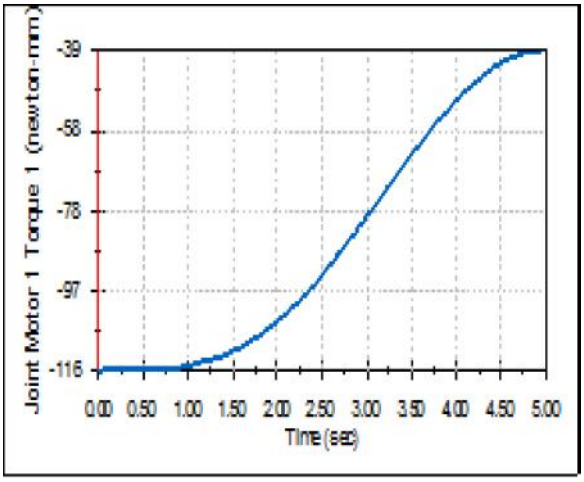


Figure 7 (Cont.)

(c) Joint 3 Actuation Profile



(d) Joint 1 Resulting Torque



(e) Joint 2 Resulting Torque

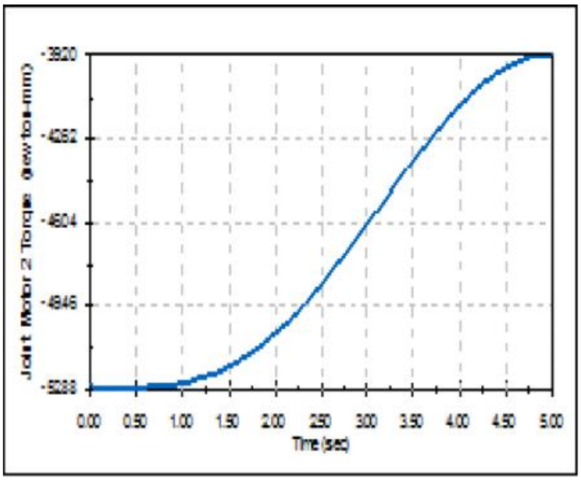
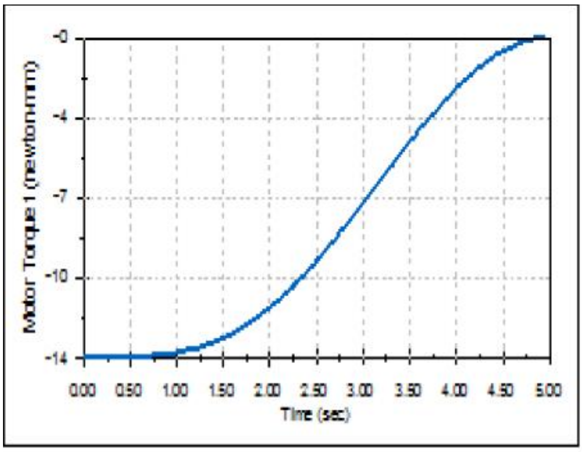


Figure 7 (Cont.)

(f) Joint 3 Resulting Torque



3DOF Spatial Manipulator

The configuration of this manipulator is shown in Figure 3. For this, Joints 1 and 2 are actuated through 90° for 5 sec in CW and CCW directions respectively while the joint 3 is actuated through a distance of 60° for 5 sec in CW direction. Two cases are considered during simulation: (i) without any end effector load, (ii) with end effector load. The end effector load is considered as 1 N acting vertically

Figure 8: Joint Torque Estimation for 3DOF Spatial Manipulator in No Load and Loaded Condition

(a) Joint 1 Torque with No Load

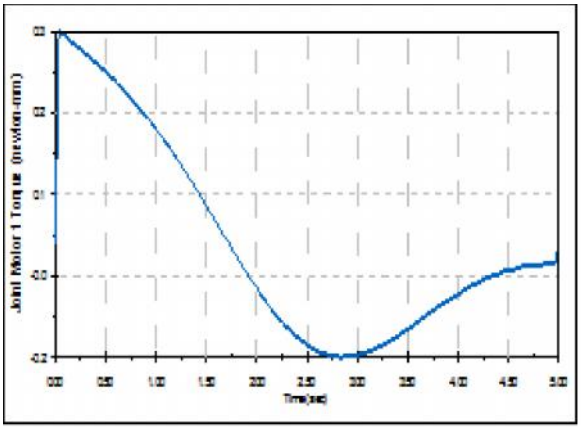
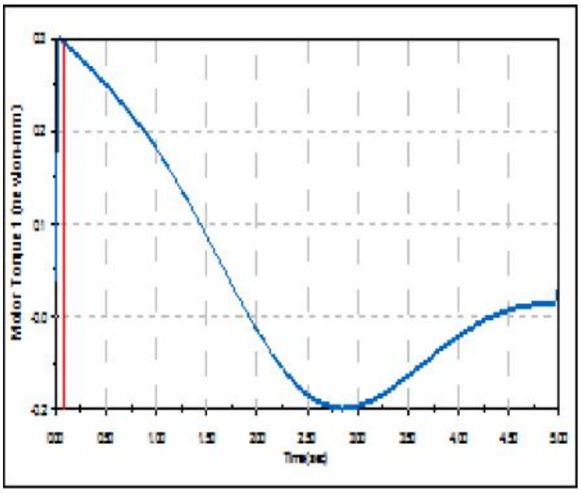
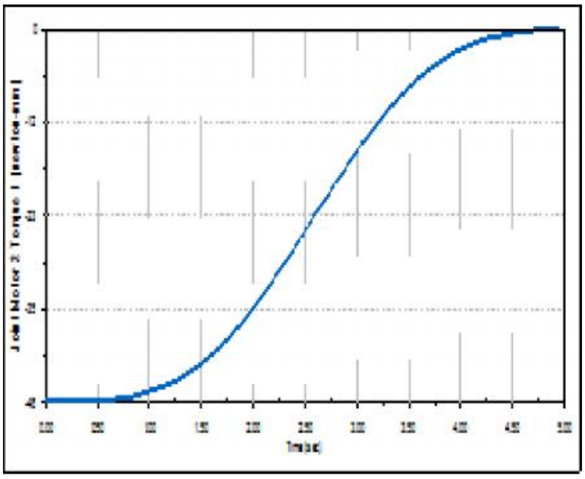


Figure 8 (Cont.)

(b) Joint 1 Torque with 1 N End Effector Load



(c) Joint 2 Torque with No Load



(d) Joint 2 Torque with 1 N End Effector Load

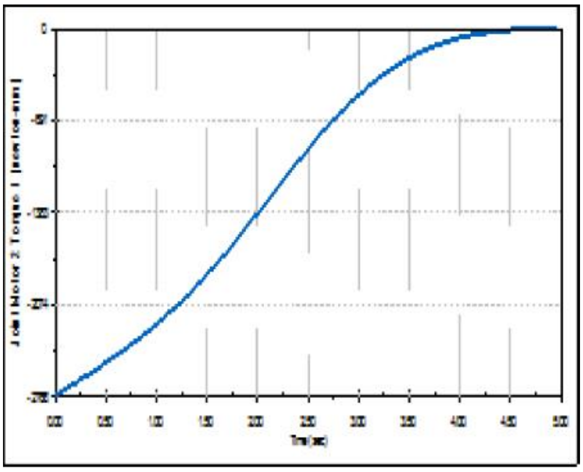
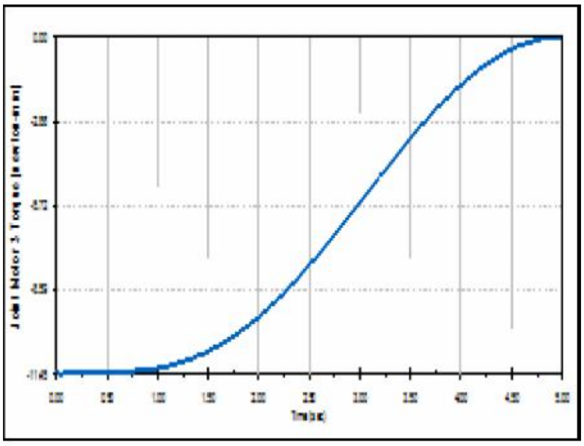


Figure 8 (Cont.)

(e) Joint 3 Torque with No Load



(f) Joint 3 Torque with 1 N End Effector Load

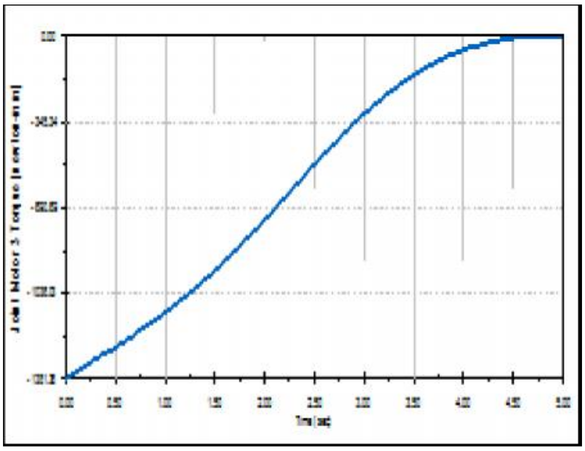


Figure 9: Stress Plots for 3DOF Spatial Manipulators

(a) Stress Plot When there is No Load Acting Max Stress of 1.15 MPa Predicted

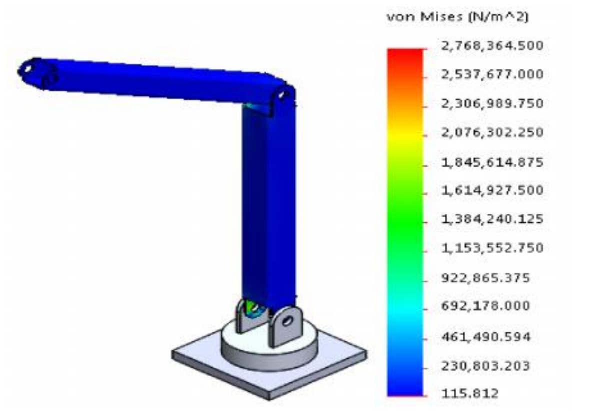
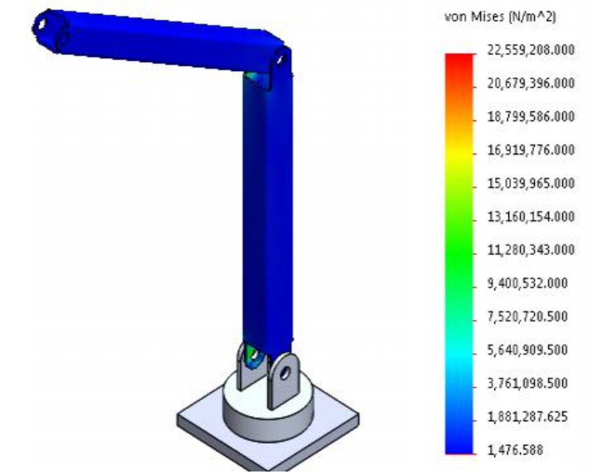


Figure 9 (Cont.)

(b) Stress Plot When a Load of 1 N is Acting Max Stress of 22.5 MPa Predicted



downward. Gravity is enabled during simulations. The result of the Motion simulation is then used to calculate stresses. A comparison of joint torques and link stresses are shown in Figures 8 and 9.

CONCLUSION

In the current work, Rigid Body Dynamic (RBD) Simulations are used to compute the inertial parameter effects. The simulations are carried out using Solidworks. Initially, a simulation is executed on a 2DOF manipulator. The results are compared with that of theoretical calculations. MathCAD software is used for this purpose. By comparing simulation and analytical results, it is observed that an average error of 15% exists and the results are acceptable. Latter, simulations are carried out for planar 3DOF and spatial 3DOF manipulator. The RBD simulation results, in case of spatial 3DOF manipulator, are used as input for calculating stresses in links of the manipulator using FEA. Based on the stress analysis, it is found that the stress is mostly at the joints of Link 2 of spatial manipulator.

REFERENCES

1. Amit A Nimbalkar and B E Narkhede (2014), "FEA Analysis of An Electric Wiper Mechanism", *International Journal for Scientific Research & Development*, Vol. 2, No. 5, pp. 275-278.
2. Ana Djuric, Riyadh Al Saidi and Waguih ElMaraghy (2012), "Dynamics Solution of n-DOF Global Machinery Model", *Robotics and Computer-Integrated Manufacturing*, Vol. 28, No. 5, pp. 621-630.
3. Burak Baykus, Elmas Anli and Ibrahim Ozkol (2011), "Design and Kinematics Analysis of a Parallel Mechanism to be Utilized as a Luggage Door by an Analogy to a Four-Bar Mechanism", *Engineering*, Vol. 3, No. 4, pp. 411-421.
4. Kurfess T R (2005), "Lagrangian Dynamics", *Robotics and Automation Handbook*, Chapter 1, pp. 1-18.
5. Ling Wen, Yu Zhang, Lufeng Luo and Cong Zhang (2013), "Five Degree of Freedom Manipulator Motion Simulation Based on Virtual Environment", *Modern Mechanical Engineering*, Vol. 3, No. 1, pp. 34-38.
6. Ngoc Dung Vuong and Marcelo H Ang Jr. (2009), "Dynamic Model Identification for Industrial Robots", *Acta Polytechnica Hungarica*, Vol. 6, No. 5, pp. 51-68.
7. Patel Y D and George P M (2013), "Kinematic Analysis and 3D Workspace Development of 3DOF Parallel Manipulator with a Rotary Base", 1st International & 16th National Conference on Machines and Mechanisms (iNaCoMM 2013), pp. 672-679, IIT, Roorkee.
8. Quanzhao Tu, Xiafu Peng, Jiehua Zhou and Xunyu Zhong (2011), "Kinematics Simulation and Analysis of 2DOF Parallel Manipulator with Highly Redundant Actuation", URL: www.scirp.org/journal/paperdownload.aspx? paperid=28000
9. Saeed B Niku (2013), "Dynamic Analysis and Forces", Chapter 4, pp. 147-177, Industrial Robotics, Wiley Publications.
10. Saha S K (1999), "Dynamics of Serial Multibody Systems Using the Decoupled Natural Orthogonal Complement Matrices", *Journal of Applied Mechanics*, Vol. 66, No. 4, pp. 986-996.
11. Sanjeev Soni, Kuldeep Singh, Sanjeev Verma, Dinesh Pankaj and Amod Kumar (2013), "Kinematic and Dynamic Analysis of a Surgical Tool Manipulator Towards Robotic Surgery", 1st International & 16th National Conference on Machines and Mechanisms (iNaCoMM 2013), pp. 987-991, IIT, Roorkee.
12. Shankar N V S and Vamsi Krishna P (2014), "Workspace Computation Using Motion Analysis", *International Journal of Mechanical Engineering and Robotics Research*, Vol. 3, No. 1, pp. 198-203.
13. Takamitsu Matsubara, Hiroaki Takada and Kenji Sugimoto (2014), "Task-Adaptive Inertial Parameter Estimation of Rigid-Body Dynamics with Modeling Error for Model-Based Control Using Covariate Shift Adaptation", IEEE/ASME International Conference on Advanced Intelligent Mechatronics (AIM), pp. 476-482.
14. Theingi Chuan Li, I-Ming Chen and Jorge Angeles (2002), "Singularity Management

of 2DOF Planar Manipulator Using Coupled Kinematics", 7th International Conference on Control, Automation, Robotics & Vision (ICCARV 2002), Singapore.

15. Vishal Abhishek, Abdullah Aamir Hayat, Arun Dayal Udai and Subir Kumar Saha (2014), "Identification of Dynamic Parameters of an Industrial Manipulator", The 3rd Joint International Conference on Multibody System Dynamics the 7th Asian Conference on Multibody Dynamics, BEXCO, Busan, Korea.

16. Wisama Khalil, Maxime Gautier and Philippe Lemoine (2007), "Identifcation of the Payload Inertial Parameters of Industrial Manipulators", IEEE International Conference on Robotics and Automation - ICRA'07.