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Study on dynamic modelling and vibration analysis of single-link flexible manipulator

Tek serbestlik dereceli esnek manipülatörün dinamik modellenmesi ve titreşim analizi üzerine çalışma

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Abstract

In this study, SimMechanics-based dynamic modeling and vibration analysis of a single-link flexible manipulator are studied. A flexible beam model is set up for modeling the manipulator. Transient analysis is performed to obtain the endpoint acceleration vibration responses of the manipulator moved with different motion profiles. Both the experimental and simulation acceleration results are presented for different cases. The root means square (RMS) values of the acceleration responses are calculated to evaluate the compatibility performance in verifying the simulation results with the experimental results. It has been observed that the results match each other successfully for different cases. The reliability of the SimMechanics-based dynamic modeling method of manipulators is discussed with the experimental results.

Keywords: Dynamic modeling, Flexible beam block, Single-link flexible manipulator, Vibration analysis

Öz

Bu çalışmada, tek bağlantılı esnek manipülatörün SimMechanics tabanlı dinamik modellemesi ve titreşim analizi çalışılır. Manipülatörün modellenmesi için bir esnek kiriş modeli kurulur. Farklı hareket eğrileri ile hareket ettirilen manipülatörün uç nokta ivme titreşim tepkilerini elde etmek için geçici durum analizi gerçekleştirilir. Farklı durumlar için hem deneysel hem de simülasyon ivme sonuçları sunulur. Simülasyon sonuçlarının deney sonuçları ile doğrulanmasındaki uyumluluk performansını değerlendirmek için ivme cevaplarının ortalama karekök (RMS) değerleri hesaplanmıştır. Sonuçların birbirleriyle farklı durumlar için başarılı bir şekilde eşleştiği gözlemlenmiştir. Manipülatörlerin SimMechanics tabanlı dinamik modelleme yönteminin güvenirliği, deneysel sonuçlarla ele alınmıştır.

Anahtar kelimeler: *Dinamik modelleme, Esnek kiriş bloğu, Tek serbestlik dereceli esnek manipülator, Titreşim analizi*

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1. Introduction

Robot arms use commonly in manufacturing applications for their advantages, such as short cycle time and high speed (Mariappan & Veerabathiran 2016). Robot manipulators are designed rigidly to achieve high precision, flexibility, and productivity. In order to plan the endpoint motion of robot arms and realize the position control, it is an important step to correctly design the dynamic modeling of robot manipulators. Various methods are used for the modeling and dynamic analysis of robot arms. Researchers use analytical approaches such as Newton-Euler and Euler-Lagrange methods to construct dynamic models of flexible structures. In addition, as it is known, commercial applications such as ANSYS and MATLAB/Simulink provide the opportunity to numerically model and dynamically analyze robot manipulators. For numerical analysis, Simscape based on MATLAB/Simulink is an essential toolbox used for modeling and simulation of mechanical, thermal, and fluid systems. It provides to simulate dynamically with rigid and flexible modeling of mechanical systems on the basis of a 3D model. With the proposed method, various studies on rigid robotic applications have been carried out by researchers and are summarized.

The mechanical design, dynamic analysis, and controller design of the parallel and SCARA manipulator designed with SimMechanic and CAD methods are compared (Mariappan & Veerabathiran, 2016; Tlale & Zhang, 2005). Gaber et al. (Gaber et al., 2016) developed an interface in MATLAB to animate the model and perform the position control of a 6-DOF robot arm. The designed interface is provided for communication to perform the robot control by exchanging information with the controller. With a similar approach, West et al. (West et al., 2016) developed a mechanism for the numerical modeling of a robot manipulator constructed from 7-DOF hydraulic systems and estimation of unknown parameters using a genetic algorithm. Joint torques of the dynamic model of a 5-DOF robot arm designed for use in an electric arc furnace are simulated by Esmaeili et al. (Esmaeili & Saadat, 2020). A mathematical model of a multi-link snake robot with an additional part with 6-DOF on its tail is created by Malayjerdi and Akbarzadeh (Malayjerdi & Akbarzadeh, 2019), and the detailed dynamic and kinematic analyses are obtained analytically. Dynamic equations are verified with the SimMechanics model. In Ref. (Azmoun et al., 2019), Azmoun et al. developed a dynamic model of a 4-DOF parallel robot arm that perform pick and place operation at SimMechanics. The inverse kinematics problem has been confirmed analytically, and the simulation results are compared with PID and Sliding-mode controllers. Wang et al. (Wang et al., 2017) derived a dynamic model for position control of a 3D robot arm through dependent parameters and then presented a linear model based on SimMechanics.

SimMechanics-based modeling method is also widely used in biological studies. In another study, Stevanović and Rašuo (Stevanović & Rašuo, 2017) reported a SimMechanics-based mathematical model of a 3-DOF biological robot. In addition, a moving dynamic analysis of the mechanism is carried out. The biological arm model is modeled with a simplified 3-DOF robotic arm (Umar & Bakar, 2014). The mathematical dynamic equations of robot arms are established, and then the simulated dynamic model using computerized algorithms is compared with the SimMechanics model. For flexible structures, dynamic modeling and performing vibration analyzes of flexible structures with the FE method are widely studied. Modeling and simulation of a flexible beam are studied with both ANSYS and SimMechanics-based flexible beam element model (Uyar, 2021). Controlled and uncontrolled vibration responses are presented comparatively.

For mechanical systems, the overhead crane model is modeled by Win et al. (Win et al., 2013) using SimMechanics, and an LQR controller is applied to the system to prevent skidding. Using the experimental model of the system and the mean square root error, the most appropriate mathematical model is presented.

Studies on the modeling of SimMechanics-based robot manipulators are described above. In the studies, it was observed that modeling and dynamic analyzes on rigid robot arms were carried out. Dynamic modeling of flexible robot manipulators is a challenging process since the flexibility of flexible robot arms requires vibrations at the endpoint and position control. Therefore, various control methods are used for reducing endpoint vibrations and trajectory tracking of robot manipulators. Various control methods such as feed-forward compensation control (Abou Elyazed et al., 2016), proportional-integration-derivative (PID) control (Mailah et al., 2005), Sliding-Mode controller (Ansari-Rad et al., 2019; Azmoun et al., 2019), adaptive control (Boukattaya et al., 2011), and advance control methods (Hirukawa et al., 2007; Lavretsky & Wise, 2013; Tsay et al., 2010) have been reported to be applied in robot manipulators. In order to increase the applicability of the control method to the system, the accuracy of the dynamic model of the system is important for experimental and analytical validation. In the reference work (Malgaca & Uyar, 2019), authors built the finite element model of the flexible composite manipulator in ANSYS and performed vibration analysis. The PID control is studied for the endpoint vibration control. Although simple control methods such as PID control can be applied to the finite element analysis, modern control methods cannot be applied. The use of the SimMechanics modeling approach in the dynamic modeling of flexible robot manipulators is an important advantage in terms of applying different control methods analytically. In this study, the dynamic modeling of a flexible manipulator is modeled and analyzed in MATLAB/Simulink version 2021a based on SimMechanics. Then, the vibration analysis of the proposed model is compared with experimental studies. The evaluation of modeling and vibration analysis in the paper is organized as follows: firstly, dynamic modeling and a 3D solid model of the flexible manipulator are developed by using a block diagram and also, motion curves are determined to move the manipulator; secondly, an experimental system is built to compare the experiments with the simulation results; thirdly, the experimental and simulation results for discussion are presented and evaluated for different motion curves; and finally, the conclusions obtained from results in the paper are exhibited.

2. Dynamic modeling

SimMechanics is an important part of MATLAB/Simulink to model and to simulate the dynamic model with the dynamic forces and torques. In this section, the block diagram and dynamic 3D model of the FM are shown as the mechanical model in SimMechanics given in Figure 1.

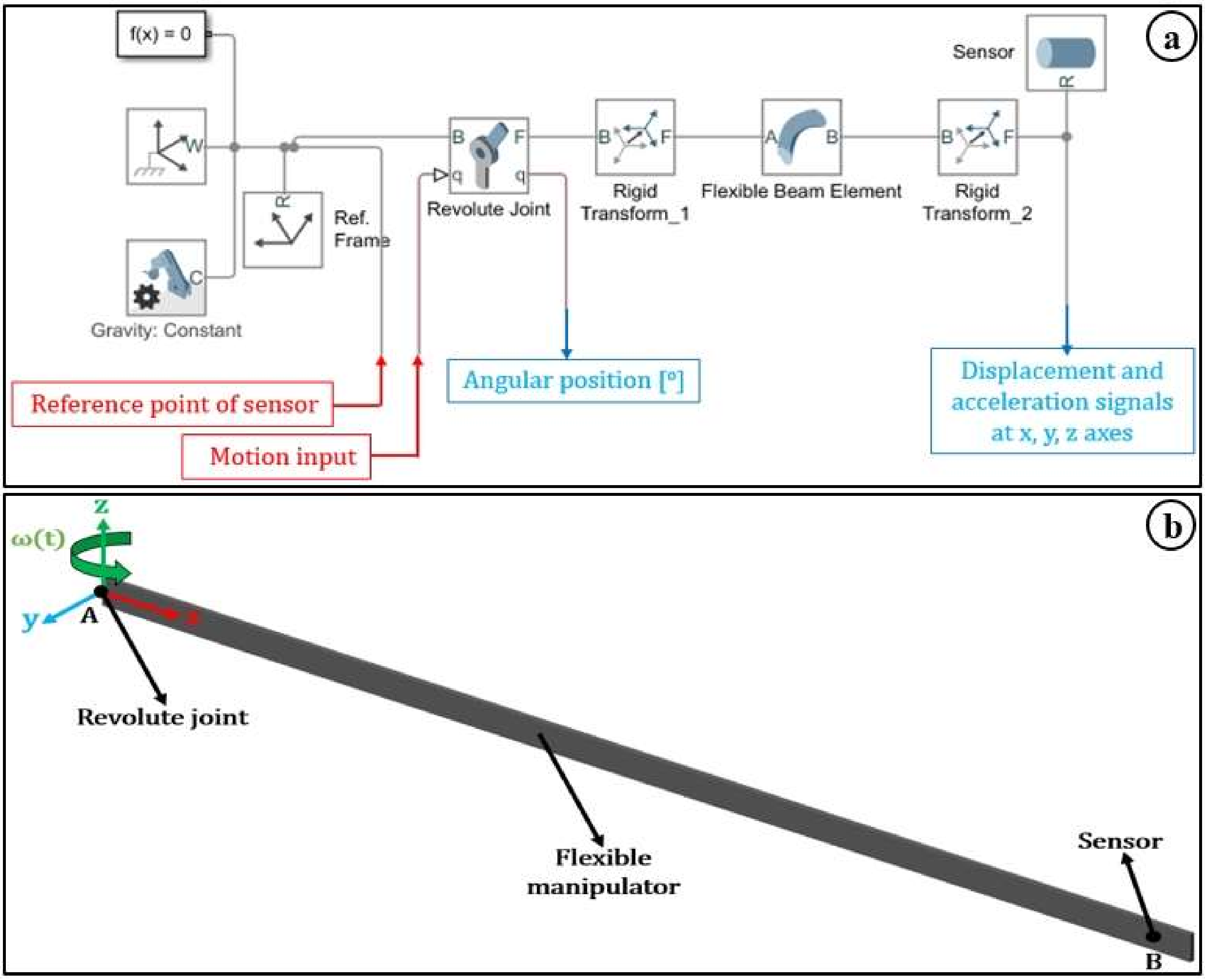

Figure 1. a) block diagram, and b) 3D model based on SimMechanics

Figure 1 indicates the block diagram and 3D model of FM. In order to create the simulation model, a flexible beam element defined in a general coordinate system is used. The flexible beam element is connected to the reference frame and the revolute joint element, which is assigned to move the manipulator. Reference frame is determined at the A point in the coordinate system. A rigid transform element is utilized to determine the sensor and actuator positions. Rigid transform 1 is used to define the position for the revolute joint at A point, while rigid transform 2 is utilized for the position of the acceleration sensor at B point. The position of the sensor is chosen as 630 mm from the root and the acceleration sensor is used to measure the acceleration signals in three directions (at x, y, z axes in the coordinate system). The sensor mass is defined as M_p=0.054 kg at the endpoint of the FM because of the weight of the acceleration sensor used in the experiment. Also, the revolute joint element in the system is utilized to measure the angular position since the angular position information in degree is obtained as a system output in the rotating joint element.

For material and physical properties, the dimension of the FM is selected as 3.2x20x640 mm^3, while its material is steel with the modulus of elasticity E=210 GPa and density of 7750 kg/m^3. Damping is defined in the flexible beam model to confirm the simulation results with the experiment. Here, system damping is used as damping ratio of 0.0002 obtained from the experimental acceleration response (Rao, 2014).

In order to move the FM, the angular velocity curve given in Figure 2 is created with time and motion parameters.

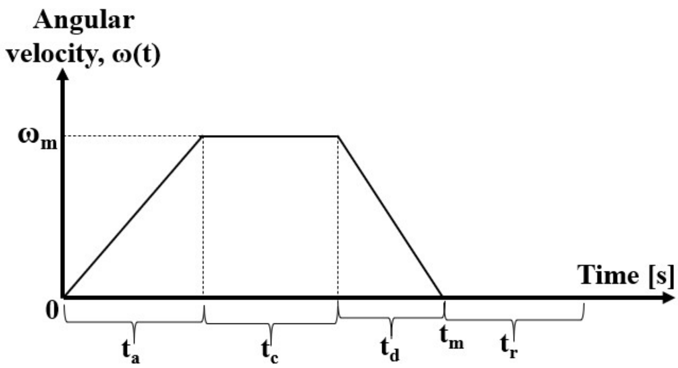

Figure 2. Angular velocity curve

The motion curve is selected as a trapezoidal velocity profile which consists of four parts: acceleration, constant, deceleration, and residual, separately. As seen from Figure 2, t_a, t_c, t_d, and t_r motion parameters are represented as acceleration, constant, deceleration and residual time parameters, respectively. t_m is the motion time. ω_m denotes the maximum angular velocity. Time parameters are selected in seconds while ω_m is in rad/s. Motion and time parameters are determined as described in Refs. (Malgaca et al., 2017; Malgaca & Uyar, 2019).

To find the motion and time parameters, the frequencies of the FM are used. Modal analysis is achieved to obtain the natural frequencies of the FM. Experimentally, natural frequencies are found with the experimental modal analysis by obtaining the frequency-amplitude plot from the free vibration responses at the tip point, and, in simulation, natural frequencies are calculated by using the time responses obtained from SimMechanics. After the Fast Fourier Transform (FFT) is applied to the free vibration responses obtained from the experiment. Experimental vibration and frequency response is shown in Figure 3.

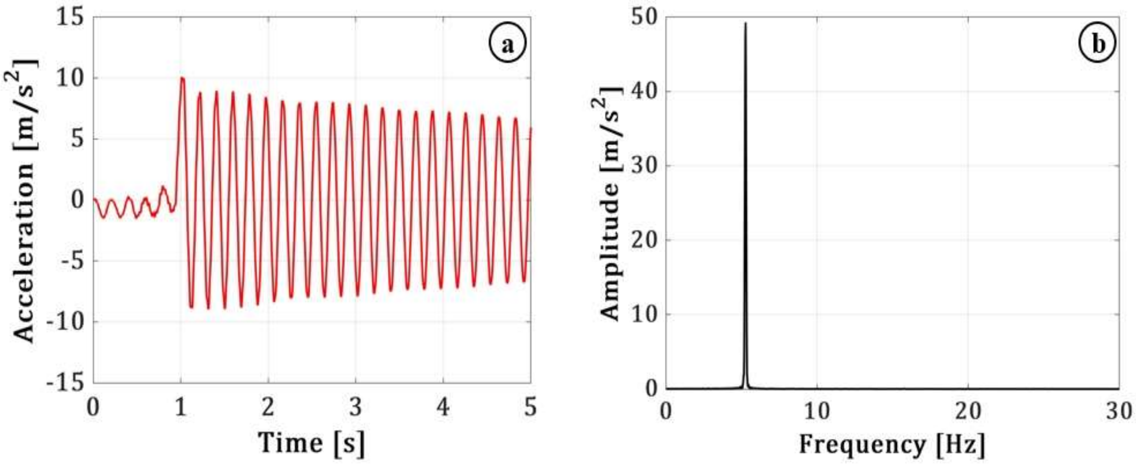

Figure 3. a) vibration and b) frequency responses

Modal analysis results for first natural frequencies are calculated as 5.23 Hz for the experiment and 5.23 Hz for the simulation, respectively. As seen from modal analysis results, it is observed that the results of the experimental and simulation natural frequencies are successfully matched well. The accuracy of the SimMechanics model is experimentally confirmed with the modal analysis results for the first natural frequency.

Undamped natural frequency results are utilized to determine the motion parameters as described in Ref.(Malgaca & Uyar, 2019). In the vibration analysis of FM, three different stopping positions for the trapezoidal motion curve are defined as 10, 30 and 60 degrees. Motion time is taken as t_m=1 s. Motion and time parameters are calculated as listed in Table 1.

Table 1. Motion parameters for trapezoidal velocity curve

Motion curves	θ [º]	t_a [s]	t_d [s]	t_m [s]	ω_{max} [rad/s]
C_{1A}		0.7131	0.0956		
C_{1B}		0.6175	0.1912		
C_{1C}	10	0.5219	0.2868	1	0.2930
C_{1D}		0.4263	0.3824		
C_{1E}		0.3307	0.4780		
C_{2A}		0.7131	0.0950		
C_{2B}		0.6175	0.1912		
C_{2C}	30	0.5219	0.2868	1	0.8791
C_{2D}		0.4263	0.3824		
C_{2E}		0.3307	0.4780		
C_{3A}		0.7131	0.0950		
C_{3B}		0.6175	0.1912		
C_{3C}	60	0.5219	0.2868	1	1.7582
C_{3D}		0.4263	0.3824		
C_{3E}		0.3307	0.4780		

In Table 1, time and motion parameters are given for three stopping positions of the trapezoidal velocity curve. Motion curve is applied to the revolute joint element to move the manipulator in simulation and to drive the manipulator by using the servo motor and driver in the experiment.

3. Experimental system

In this study, the experimental set-up is used to verify the simulation results based on SimMechanics as shown in Figure 4.

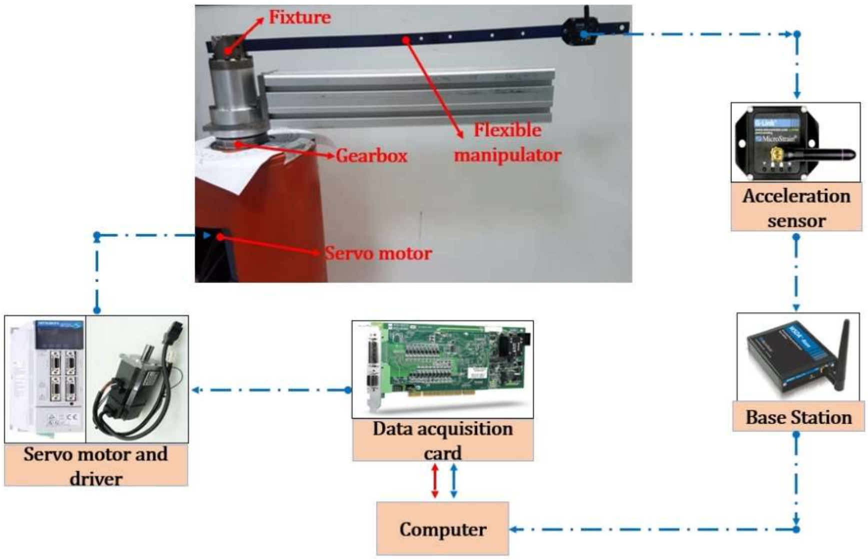

Figure 4. Experimental and measurement system

In the experimental and measurement system, there is a single-link flexible manipulator, an acceleration sensor and base station, a data acquisition card (DAQ), a personal computer (PC), a servo motor, and driver. The acceleration sensor providing wireless-based data communication is located at a distance of 20 mm from the tip point of the FM. The Servo motor and driver of Mitsubishi Electric company with 200 W are used in the experiment. The servo motor is connected to the FM with the gearbox via a Fixture. The gearbox of Harmonic Drive company is utilized with a gear ratio of 100 for the servo motor. In order to drive the FM, the motion card of Adlink PCI-8366 which is communicated with the servo driver in serial by the SSCNET network, is used. And, motion card is programmed by using Visual Basic (VB) commands. VB program is prepared to create the motion profile. In the VB program, pulses are produced by using the velocity values corresponding to each time step by the time and motion parameters of the trapezoidal motion profile given in Table 1. The pulses generated to move the manipulator are sent synchronously to the servo driver via VB. The servo driver and motor are connected to each other with SSNET communication protocol.

During the movement of the manipulator, vibrations occur at the endpoint, which is considered the free point. The endpoint acceleration signals are measured synchronously with the wireless accelerometer. Acceleration data is transmitted to the base station by the wireless communication protocol. After the data is processed, the acceleration signals are transmitted to the computer via the WSDA base station and then recorded to the PC via the Node Commander program of Microstrain company. The sampling frequency of the sensor is selected as 512 Hz and signals are filtered with a cut-off frequency of 20 Hz by using the low-pass Butterworth filter.

The FM moves from a rest position at t=0 s to a stopping position at $t=t_m$. After completing the movement of FM, the residual section begins at $t=t_m$ and completes at $t=t_r$. For three different motion curves, acceleration signals at the endpoint of the FM are obtained during the time from the rest position to the residual position.

4. Results and discussions

The experimental and simulation results are obtained for three different motion curves. For motion time t_m=1 s, example vibration responses for C_{1A-1B}, C_{2A-2B} and C_{3A-3B} motion curves are shown in Figure 5.

Figure 5 presents the experimental and simulation results for example motion curves. When the acceleration responses are examined, it is clear that the acceleration amplitudes are high at t_m=1 s when the manipulator completes its movement. While the endpoint acceleration responses are obtained, the vibration responses of the manipulator are obtained by subtracting the rigid body motion curve from the flexible body motion curve. Therefore, it is obvious that high amplitude acceleration vibration responses are obtained in the stopping position due to the inertia of the manipulator. As seen from Figure 5, the vibration amplitudes for the motion profile C_1 vibrate with a maximum and a minimum of approximately ±4 m/s^2, while these values for C_2, C_3 are maximum ±12 m/s^2, and ±24 m/s^2, respectively. It is clear that maximum vibration amplitudes are obtained for C_{1A}, C_{2A} and C_{3A} in all three different cases.

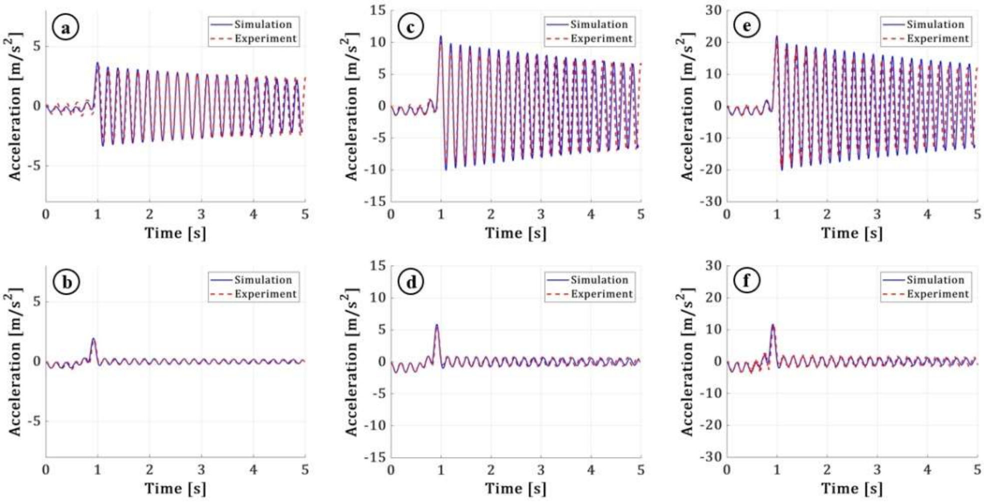

Figure 5. Vibration time responses for a-b) C_{1A-1B}, c-d) C_{2A-2B}, and e-f) C_{3A-3B}

As seen from Figure 5, it is observed that experimental and simulation vibration responses matched each other well in motion profiles with both maximum and minimum vibration amplitudes. For all cases, root means square (RMS) values of the acceleration responses are computed in order to find the Prediction Error Criteria (PEC) which is a criterion that checks the compatibility of the reference model for a specific model. The reference model is selected as experimental studies while the specific model is defined as simulation method based on SimMechanics. In this study, PEC is determined by the Percent Error Rate (PER) of the RMS values of the acceleration responses in the experiment and simulation. RMS values are calculated for the experimental and simulation results and listed in Table 2.

Table 2. RMS values

Motion curves	RMS Values [m/s^2]	
	Simulation	Experiment
C_{1A}	1.5235	1.4417
C_{1B}	0.2124	0.1618
C_{1C}	0.6546	0.6485
C_{1D}	0.3308	0.3587
C_{1E}	0.6795	0.6073
C_{2A}	4.2101	3.7849
C_{2B}	0.6878	0.6078
C_{2C}	1.5822	1.5015
C_{2D}	0.7832	0.7480
C_{2E}	1.4314	1.3527
C_{3A}	6.8244	6.7530
C_{3B}	1.2474	1.1427
C_{3C}	3.0072	2.8751
C_{3D}	1.5211	1.4532
C_{3E}	2.7267	2.5978

In Table 2, RMS values are presented to evaluate PER values of experimental and simulation results. For PER values, RMS values for experimental vibration responses are considered as reference values. For three different motion curves, PER values are calculated and presented in Figure 6.

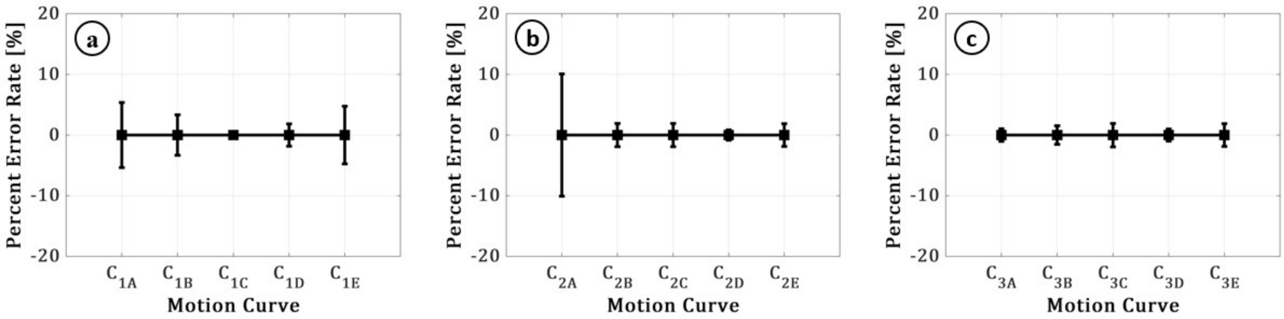

Figure 6. Percent error rates of RMS values for a) C_{1A-E}, b) C_{2A-E}, and c) C_{3A-E}

Figure 6 shows PER values of all motion curves for the simulation and experimental studies. For C_{1A-E}, PER values are found as 5.36%, 3.32%, 0.40%, 1.83%, and 4.74%, respectively.

While the maximum PER value for C_{2A} is obtained as 10.10%, it is also observed that it is the highest PER value for all cases, and when all motion curves are compared, the minimum PER values are found for the C_3 motion curves according to the other motion curves. For all cases of the C_3 motion curve, the experimental results are successfully matched well with the simulation vibration responses. If the 10% value of PER is accepted as the reference value for the accuracy of the simulation model, it has been observed that the simulation model is in good agreement with the experiments for all velocity profiles. Briefly, the proposed modeling method based on SimMechanics is verified with the experiments for three different stopping positions and five different motion curves for each position.

5. Conclusions

In this work, the dynamic modeling of a single-link flexible manipulator is investigated in order to confirm the proposed modeling method with experimental studies. The simulation model based on SimMechanics is designed in MATLAB/Simulink. Motion curves for different stopping positions are defined to move the manipulator. Acceleration vibration responses at the endpoint of the FM are obtained with simulations and experiments. The simulation results are successfully verified with experiments. Also, the proposed method for different stopping positions and cases is supported by experimental results.

The accuracy of the modeling approach of the SimMechanics-based dynamic modeling method is increased by experimental studies. Therefore, since the simulation and experimental vibration results are successfully matched with each other, the proposed method leads to its use in mechanical systems such as flexible manipulators. It is advantageous to use the proposed approach in obtaining dynamic models of complex structures that are analytically modeled. Moreover, while control methods applied to finite element analysis are limited in commercial applications such as ANSYS, different and modern control methods can be applied to dynamic models in MATLAB.

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Author contribution

Mehmet UYAR: Research concept/design, experimentation, data analysis, processing, literature search, drafting manuscript, critical revision, and final version of the manuscript.

Declaration of ethical code

The author declares that the methods and materials used in this study do not require ethical committee approval and/or legal-specific permission.

Conflicts of interest

The author declares that there is no conflict of interest.

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