Modeling and Vibration Reduction of a Flexible Planar Manipulator with Experimental System Identification

Levent Malgaca, Şefika İpek Lök, and Mehmet Uyar

Abstract—**System identification (SI) is a modeling method using experimental input-output signals without any physical properties of the system. In this study, a flexible planar manipulator is modeled with the SI method. The output is an acceleration signal of the tip point of the manipulator and the inputs are triangle and trapezoidal motion profiles. Motion parameters are set in order to reduce residual vibrations of the flexible manipulator. The mathematical model of the system is estimated with the continuous-time SI method. Simulation results are obtained by using the mathematical model. The identification and validation data are successfully matched with the experimental results.**

Index Terms—**System identification, flexible manipulator, vibration reduction.**

I. Introduction

Modeling and control of flexible manipulators have been extensively studied in recent years [1]. Vibrations of flexible manipulators can be reduced with passive or active control methods. Active vibration control uses external power, unlike passive control. Motion profiles can be used for passive vibration control. Residual vibrations can be reduced with suitable motion parameters in the study [2]-[4].

The success of control is related to the success of modeling of manipulators. There are many methods for modeling flexible manipulators such as numerical and analytical methods [5], [6].

The SI is a method that developing a mathematical representation of a physical system using simulation or experimental data. The SI can be divided into three classes: white-box, grey-box, and black-box model. All physical properties of the system are known in the white box model and the mathematical model of the system is found with Newton's laws. In the grey-box model, some properties of the system are known and the mathematical model of the system is estimated with the properties and experimental input-output data. In the black-box model, there is any information about the system. The mathematical model is estimated using only experimental input and output signals [7]-[9].

There are studies about modeling of flexible manipulators with the SI in the literature. Ziaei & Wang (2006) worked on modeling with the generalized orthonormal basis functions. They modeled a single-link flexible manipulator with simulation data and modeled a five-bar manipulator with three degrees of freedom with experimental data. They compared obtained results with traditional SI methods (ARX, ARMAX) [10]. Kapsalas *et al*. (2018) modeled a flexible beam manipulated by industrial robots with ARX model. They eliminated residual vibrations of the system with a new control method [11]. Wang and Lou (2019) studied the parameter estimation of a flexible manipulator. They found unknown parameters of the flexible manipulator using grey-box model [12].

In this study, the black-box model of the flexible manipulator is estimated by using the experimental input-output data. The inputs are trapezoidal and triangular velocity profiles. In the experiments, the motion parameters are set to reduce the residual vibrations of the flexible manipulator. The output is the measured acceleration signal. The estimated mathematical model is used for simulations with the validation data.

II. Experimental Set-Up

The single-link flexible planar manipulator considered in this study is shown in Fig. 1.

Fig. 1. Flexible planar manipulator.

The dimension of the planar manipulator is 4 × 80 × 500 mm^3. The material of the manipulator is steel with the modulus of elasticity E = 210 GPa and the density ρ=7850 kg/m^3. A sensor and a payload are placed on the manipulator. The distance of the payload from the endpoint of the manipulator is 20 mm and the distance of the sensor point from the center of the payload is 70 mm. Weights of the sensor and payload are 0.054 kg and 0.62 kg.

Fig. 2 shows the set-up used in the experiments to drive the manipulator and to measure the acceleration signals. The experimental setup includes two main sub-systems the motion control and measurement. The motion control consists of a servo motor and driver, a motion card and a PC. Mitsubishi-Electric servo motor and driver with 200 W,

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Model HC-KFS23B/ MR-J2S-20A are used. The motion control card is Adlink 8366. A SSCNET network is used to connect the motion control card and the driver. The servo driver is used for the position control mode. For the position control, the pulse signals according to the velocity profile are produced with Adlink 8366. The motion signals are produced with a Visual Basic Program.

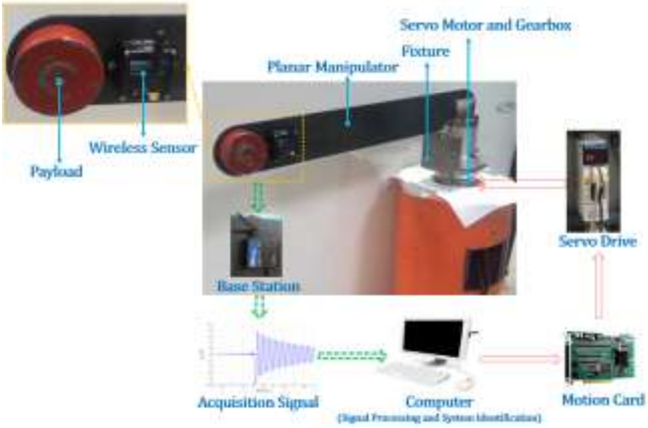
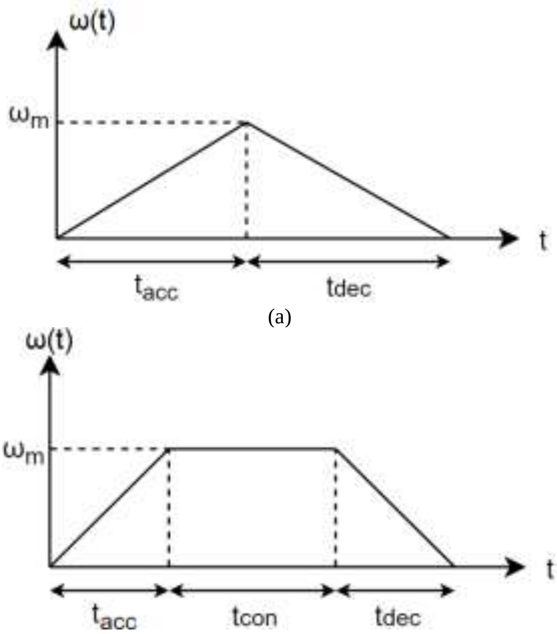


Fig. 2. Experimental set-up.

The measurement system consists of a wireless accelerometer sensor, a base station, and interface software. Microstrain sensor is used to measure the acceleration at the tip point of the manipulator. The measured signals are transferred to the PC with the Base Station. The signals are recorded with Node Commander Software. The sampling frequency of the accelerometer sensor is 617 Hz. The sensor can measure acceleration in three directions. However, the acceleration signal in the bending direction of the manipulator is considered in this study.

The residual vibration of the planar manipulator is reduced with motion profiles. Triangle and trapezoidal velocity profiles are used to drive and reduce the vibrations. Triangle and trapezoidal velocity profiles are shown in Fig. 3.



(a)

(b)

Fig. 3. (a) Triangle and (b) Trapezoidal velocity profiles.

In Fig. 3, t_{acc}, t_{con}, and t_{dec} represent acceleration, constant and deceleration time, respectively. ω_m represents the maximum angular velocity. $\theta(t)$ represents the stopping position. Time parameters are calculated according to the first natural frequency of the system. Formulations of the motion parameters are given in equation (1). In the triangle motion, the constant time is equal to zero, unlike the trapezoidal velocity profile.

$$\begin{aligned} t_{1h} &= 1/\,f_{n1}\,/\,2, \\ t_{con} &= 2t_{1h}, \\ t_{dec} &= 1t_{1h}, 2t_{1h} \\ t_{acc} &= t_m - t_{con} - t_{dec} \\ \omega_m &= \frac{\theta}{0.5t_{acc} + t_{con} + 0.5t_{dec}} \end{aligned} \tag{1}$$

The natural frequency of the manipulator is found from the free vibration response. After the motion completed, the residual response is considered a free vibration response. Applying the Fast Fourier Transform to the measured free vibration signal, the first natural frequency is calculated as f_{n1}=7.1552 Hz. The stopping position and motion time are taken as θ=60 deg and t_m =1s. For different motion profiles, the accelerations of the tip point are measured and the experimental dataset is obtained in order to model the flexible manipulator.

III. System Identification

In this section, a brief introduction to continuous time SI is represented. Single input single output continuous-time system is given in equation (2).

$$\begin{aligned} y_u(t) &= G_o(p)u(t) \\ G_o(p) &= \frac{B_o(p)}{A_o(p)} \\ B_o(p) &= b_0^o + b_1^o p + \cdots + b_m^o p^m \\ A_o(p) &= a_0^o + a_1^o p + \cdots + a_n^o p^n \\ a_n^o &= 1, n \geq m \end{aligned} \tag{2}$$

$u(t)$ and $y_u(t)$ represent experimental input and output signal, respectively. $G_o(p)$ is an estimated mathematical model of the system. p is a derivative operator. $B_o(p)$ and $A_o(p)$ is numerator and denominator of the mathematical model, respectively. m and n are orders of numerator and denominator, respectively. The order of the denominator must be bigger than the order of the numerator. The mathematical model parameters are calculated using the standard least square estimation method [13], [14].

The SI procedure is shown in Fig. 4. The SI procedure consists of four steps. In the first step, experimental signals of the system are collected. In the second step, the model structure is selected such as parametric, continuous SI methods. In the third step, mathematical model parameters are estimated using criteria such as Final Prediction Error criterion (FPE), Akaike information criterion (AIC), Minimum Description Length Criteria (MDL). And fourth step is modal validation [13], [14].

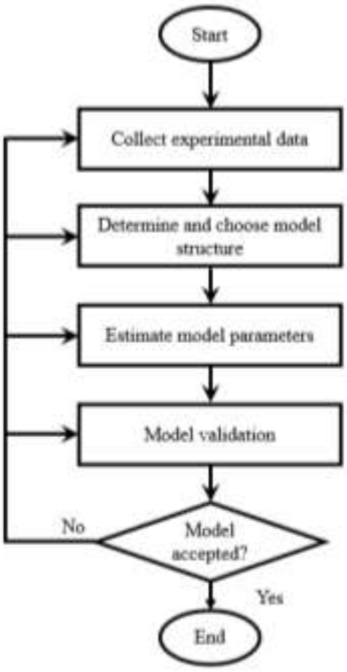


Fig. 4. SI procedure.

Two different datasets are used for the SI method. The first dataset which is an identification dataset is used to estimate models. Then, the second dataset which is a validation dataset is used to simulate the estimated model.

IV. Experimental Results

The SI method is studied for different experimental inputs and different m and n. The mathematical model is determined according to the final prediction error (FPE) criteria. The FPE criteria optimize the model complexity (the number of parameters) and goodness of fit for a specific model. The FPE formula is given equation (3)

$$FPE = \frac{1+ d/N}{1- d/N} \frac{1}{N} \sum_{t=1}^{N} \frac{1}{2} \varepsilon^2(t,\vartheta) \tag{3}$$

where d is the number of parameters, N is the number of sample and ε is the error of the estimation [7]. The fit between real data and estimated data is calculated according to equation (4)

$$fit = 100\left(1 - \frac{\|y-\hat{y}\|}{\|y - mean(y)\|}\right) \tag{4}$$

where y is real experimental data and $\hat{y}$ is estimated data. The fit value is obtained as a percentage [7].

The deceleration times of the triangle velocity profiles are taken as $t_{dec}=t_{1h}$ and $t_{dec}=2t_{1h}$ for the identification and validation dataset, respectively. For triangle velocity profiles, the FPE and fit results are given in Table I. The validation dataset is used to simulate the estimated model. In Table I, the FPE values decrease significantly up to n=3 and m=3 and then it changes too small. So, the model orders are selected as n=m=3. Success rates of the identification and validation datasets are 95.44% and 81.95%, respectively.

TABLE I: Identification Results

n	m	FPE	Fit (%) identification Triangle $t_d=t_{1h}$	Fit (%) validation Triangle $t_d=2t_{1h}$
2	1	0.7755	85.85	62.33
2	2	0.5246	88.37	65.93
3	2	0.2822	91.47	77.99
3	**3**	**0.08067**	**95.44**	**81.95**
4	3	0.08076	95.44	81.95
4	4	0.07748	95.54	81.33

All coefficients of the mathematical model of the manipulator are found successfully. The estimated mathematical model is given in equation (5).

$$G(s) = \frac{Y(s)}{U(s)} = \frac{b_3 s^3 + b_2 s^2 + b_1 s + b_0}{s^3 + 95.95 s^2 + 2041 s + 1.84x10^5} \tag{5}$$

The numerator coefficients of the model are not given in the paper. The natural frequency of the estimated model can be calculated with the roots of the denominator. The natural frequency of the estimated model is 7.0080 Hz. The natural frequency of the estimated model is approximately the same as the natural frequency of the experimental system. The SI method is compared with other methods such as the finite element method and it is found to be successful.

The experimental, identification and validation results for triangle and trapezoidal motions are shown in Fig. 5-8.

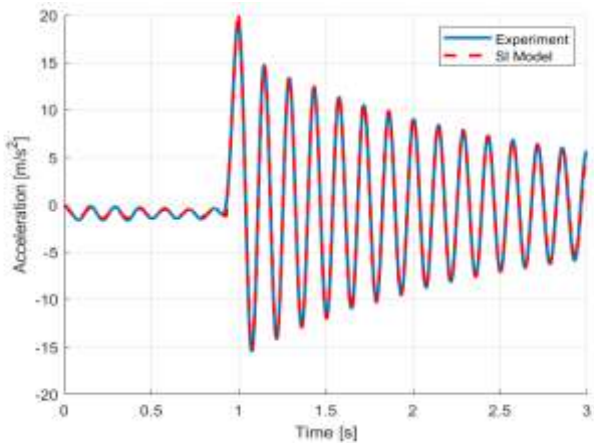


Fig. 5. Triangle velocity response for $t_{dec}=t_{1h}$.

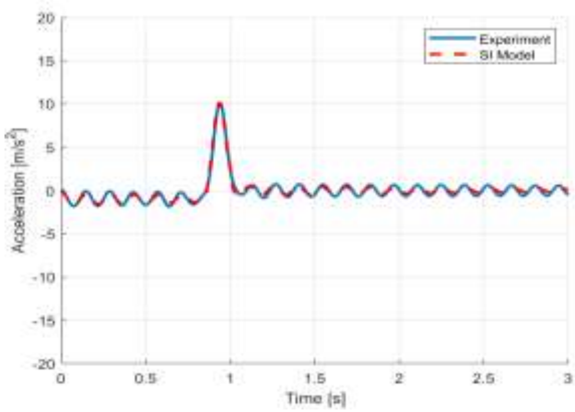


Fig. 6. Triangle velocity response for $t_{dec}=2t_{1h}$.

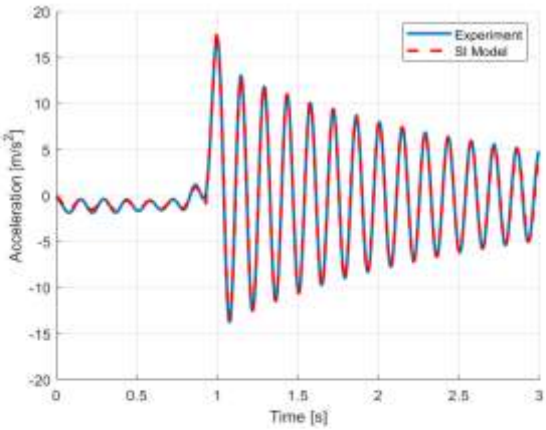


Fig. 7. Trapezoidal velocity response for $t_{dec}=t_{1h}$.

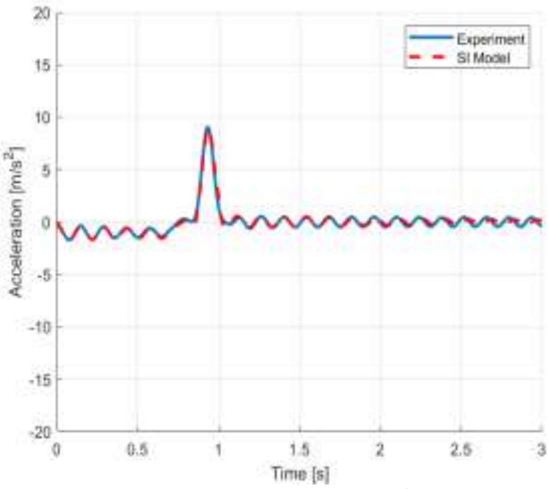


Fig. 8. Trapezoidal velocity response for $t_{dec}=2t_{1h}$.

TABLE II: RESULTS FOR TRIANGLE AND TRAPEZOIDAL MOTION

		t_{dec}	RMS (m/s²)		Reduction ratio (%)	
			Exp	SI	Exp	SI
Uncontrolled	Triangle	t_{1h}	7.241	7.238	-	-
Controlled	Triangle	$2t_{1h}$	0.495	0.294	93.15	95.93
Uncontrolled	Triangle	$3t_{1h}$	2.891	2.635	54.79	58.78
Uncontrolled	Trapezoidal	t_{1h}	6.395	6.391	-	-
Controlled	Trapezoidal	$2t_{1h}$	0.340	0.303	94.67	95.26
Uncontrolled	Trapezoidal	$3t_{1h}$	2.662	2.371	58.38	62.91

Triangle velocity responses for $t_d=t_{1h}$ and $t_d=2t_{1h}$ are shown in Fig. 5 and 6. Trapezoidal velocity responses for $t_d=t_{1h}$ and $t_d=2t_{1h}$ are shown in Fig. 7 and 8. It is observed that the identification and validation results are successfully matched with the experimental results.

Vibration responses given in Fig. 5, 6, 7 and 8 of the manipulator can also be obtained by using the finite element method [2], [4].

Furthermore, the residual vibrations are successfully reduced by calculating the motion parameters based on the dynamic properties of the flexible manipulator. It is observed that when the deceleration time is selected as t_{1h} or $3t_{1h}$, the vibration response can be called as an uncontrolled response and when the deceleration time is selected as $2t_{1h}$, the vibration response can be called as a controlled response. Six cases with motion profiles are studied with the SI method. For the experiment and the SI model, the RMS and reduction ratio results are given in Table II.

The root mean square (RMS) results presented in Table II are calculated from the residual vibration signals with the following equation [15].

$$RMS = \sqrt{\frac{1}{n}\sum_{i=1}^{n} x_i^2} \tag{6}$$

The reduction ratios are presented to evaluate the vibration suppression. The reduction ratios can be calculated from the RMS values of the uncontrolled and controlled responses. As seen from Table II, when the controlled cases are considered with the triangle motion, the reduction ratios are 93.15% and 95.93% for the experimental and SI model vibration responses, respectively. When the controlled cases are considered with the trapezoidal motion, the reduction ratios are 94.67% and 95.26% for the experimental and SI model vibration responses, respectively. It is observed that the reduction ratios of the mathematical model also match with the experimental ones.

V. CONCLUSION

In this study, the modeling of the single-link planar manipulator is studied by the SI method. The mathematical model of the flexible manipulator is successfully estimated by using experimental data. The mathematical model represents the relationship between angular velocity driven by the motor and acceleration signal at the endpoint of the manipulator. The results of the mathematical model show that the motion parameters are effective for vibration suppression on the flexible manipulator.

CONFLICT OF INTEREST

The authors declare no conflict of interest.

AUTHOR CONTRIBUTIONS

L. Malgaca supervised the study and reviewed the paper. Ş. İ. Lök analyzed the experimental results and wrote the paper. M. Uyar obtained experimental data. All authors have approved the final version.

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