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Vibrations and Intelligent Tracking Control of Single Link Flexible Manipulator

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Abstract: Residual vibrations and oscillations at the Endpoint due to flexible body motions are big challenges in control of single link flexible manipulators. This makes payloads positioning very difficult and hence less efficient and low productivity. In this paper, a hybrid intelligent control of single link flexible manipulator is proposed. Output-based filter (OBF) was designed using the signal output of the system to suppress the tip deflections and it was incorporated with both linear quadratic regulator (LQR) controller and fuzzy logic controller for set point tracking control of the system. Based on the Simulation results, it was observed that, good tracking and significant tip deflections reduction were achieved. This was measured using the time response analysis. OBF-LQR performed better and is more compatible then OBF-fuzzy.

Keywords: *Single link flexible manipulator, Output based, LQR, Residual vibration, Fuzzy.*

1. Introduction

Flexible manipulators are machines mainly used for conveying items from one place to another. These kinds of machines are used for spray painting, assembling and welding in various industries, including but not limited to nuclear plants, automotive, space exploration and aerospace [1-4]. The most important advantages of flexible manipulators over their rigid counterparts are high speed, light weight, safety operation, less cost and less energy consumption [5].

Nevertheless, due to its flexibility in nature, the flexible manipulator is associated with tip deflections, which makes precise positioning of payload difficult to achieve. To overcome this difficulty, several control techniques have been proposed over the years by various researchers. These include, hybrid controllers, feedback control feed-forward control and robust control etc.

In feed-forward control strategy, numerous input shaping schemes for tip deflections and vibration control were presented as in [3] and their performances were assessed based on level of tip deflections reduction, time response specifications and filters' robustness. A microcontroller-based input shaping technique for residual vibration control has been presented in [2], the embedded input shaping applications were proposed and their performances were compared. Command shaping strategies for vibrations suppression were presented in [6], input shaping, band stop filter and low pass filter were implemented experimentally and their performances were assessed. Vibrations elimination using an offline learning method based on an input shaping technique was presented in [7]. The method was found to be very effective and no extra sensor is needed.

In [8], an output based input shaping for vibrations control has been proposed. It was designed using the output signal of the target system. Hence in this method, problems of parameter uncertainty have been avoided.

A modified genetic algorithm for a tuned PD controller, for vibration and input tracking control was proposed in [9]. High accuracy and fast convergence have been realized. Besides, problem of premature convergence and stagnation were solved using this method.

In [10], composite fuzzy logic control strategies using PD, PID and ZVDD for input tracking and vibrations suppression were proposed. The control schemes performance was assessed based on time response analysis, input tracking and vibration reduction.

In view of the presented literatures, this paper proposes output based input shaping filter with both fuzzy logic controller and LQR controller incorporated separately, for tip deflections suppression and precise hub angle control of single link flexible manipulator.

1.1. Single Link Flexible Manipulator

The model of the single link flexible manipulator has been derived using finite element method. The system is shown in Fig. 1 and was simplified and sketched as in Fig. 2 and Fig. 3.

Fig. 1. Flexible manipulator system experimental set-up.

It has movable and non-movable coordinates. XOY is static while POQ is movable, and τ is the torque applied at the hub; V, E, I, ρ and I_h are the payload of the manipulator, area moment of inertia, young modulus, mass density per unit volume, cross-sectional area and hub inertia respectively [2, 6].

The parameters values are as shown in Table 1. Thus, the single link flexible manipulator only moves in XOY plane, and since it is long and slender, rotary inertia effect and transverse shear were neglected [11]. Elastic behavior of the system was modelled based on these assumptions using Bernoulli-Euler beam theory [4]. In addition, the manipulator is assumed torsion and stiff in vertical bending, constant cross-sectional area, and uniform material properties, to have continuous vibrations in horizontal direction with negligible effect of gravity. It is made of an aluminum with the dimension of 900 mm × 19.008 mm × 3.2004 mm [12, 13].

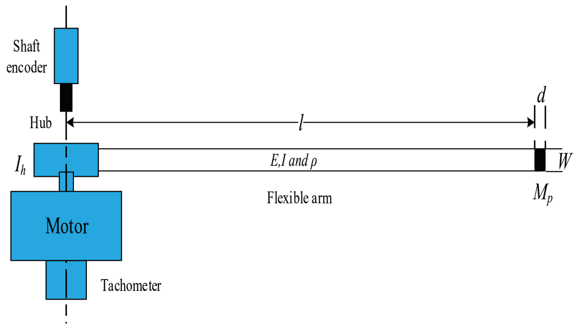

Fig. 2. A simplified outline of the single-link flexible manipulator.

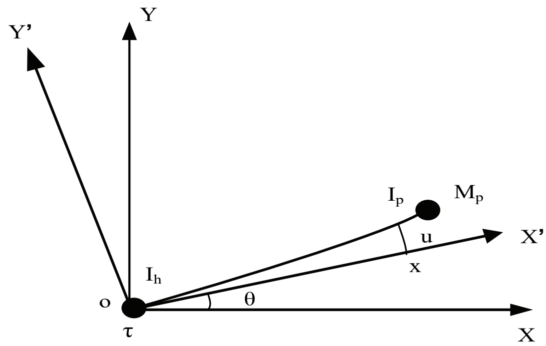

Fig. 3. Schematic of the flexible manipulator system.

Table 1. System Parameters.

Parameters	Symbols	Values	Units
Young modulus	E	71×10^9	N/m^2
Mass density per unit volume	ρ	2710	kg/m^3
Second moment of inertia	I	5.1924	m^4
Flexible link length	L	0.96	m
Flexible link width	W	0.019	m
Flexible link thickness	B	0.003	m
Hub inertia	I_h	5.86×10^{-4}	kgm^2
Moment of inertia	I_b	5.1924	kgm^2

1.2. Model of the Single Link Flexible Manipulator

In this part, model of the system was as used in [14]. And it is presented as in equation (1) and equation (2).

$$G_{hub} = \frac{-1492\times10^{-13}s^5 + 1014s^4 + 4553s^3 + 4.235\times10^7 s^2 + 2.865\times10^7 s + 1.758\times10^{10}}{s^6 + 33.37s^5 + 9.726\times10^4 s^4 + 1.164\times10^6 s^3 + 7.257\times10^8 s^2}, \quad (1)$$

$$G_{tip} = \frac{-3.553\times10^{-14}s^5 - 821s^4 - 3880s^3 - 4.315\times10^7 s^2}{s^6 + 33.37s^5 + 9.726\times10^4 s^4 + 1.164\times10^6 s^3 + 7.257\times10^8 s^2} \quad (2)$$

2. Controller Design

In this section, hybridization of LQR and Fuzzy logic controllers each with OBF are designed for both position and residual vibration control of a single link flexible manipulator as shown in Fig. 4 and Fig. 5. In each of the controller design (LQR and Fuzzy logic), the OBF was incorporated in order to suppress residual vibration of the system. The detailed design of the controllers is as follows:

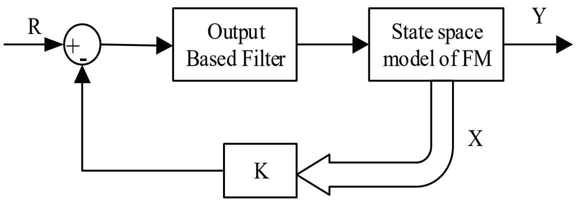

Fig. 4. Flexible manipulator LQR-OBF control system.

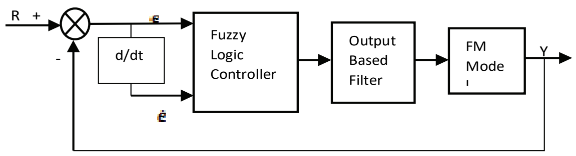

Fig. 5. Fuzzy logic controller block diagram.

2.1. Output Based Input Filter

In this technique, the filter is designed using only the signal output of the target system. Reference system which is used in the filter design, is designed based on the dynamic response of the system, output of the system was measured using simulation. The filter gains are obtained by writing a program code in MATLAB.

To explain the basic principle of this technique, a second order system shown in equation (3) is considered as in [15].

$$G(s) = \frac{kw_n^2}{s^2 + 2\xi w_n s + w_n^2} \quad (3)$$

Let the reference system be design in a form:

$$G_r(s) = \frac{k_m w_m^2}{s^2 + 2\xi_m w_m s + w_m^2} \quad (4)$$

The filter can be design as:

$$F(s) = \frac{k_m w_m^2 s^2 + 2\xi w_n s + w_m^2}{k w_n^2 s^2 + 2\xi_m w_m s + w_m^2} \quad (5)$$

Then based on zero-pole cancelation, product of $G(s)$ and $F(s)$ will gives $G_r(s)$, therefore, adequate static gain, damping ratio and bandwidth can be achieved by choosing k_m and ξ_m respectively [15], [16]. Thus,

$$F(s) = \frac{a_2 s^2 + a_1 s + a_0}{s^2 + 2\xi_m w_m s + w_m^2} \quad (6)$$

The aim is to obtain the filter gains (a_0, a_1, a_2) so that zeros of $F(s)$ will cancel the poles of $G(s)$, and poles of $G(s)$ are identical.

The aim of the design is to find accurate filter coefficients so that the target system has zero or little vibration. Critically damped system is considered in designing a reference system which can be realized as [17]:

$$G_r(s) = \frac{w_c^2}{(s + w_c)^2}, \quad (7)$$

where w_c is the bandwidth of the system and is selected based on the time response of the system, this system has little or zero vibration.

In this paper, single link flexible manipulator is type-1 system, hence a_0 is zero and since only hub angle and tip deflection is considered, the order of the filter is reduced to fourth. Hence, reference system was designed by considering the dynamic response of the system, thus, selecting $w_c = 10$, the system is as:

$$G_r(s) = \frac{10^6}{s^4 + 40s^3 + 600s^2 + 4000s + 10^6} \quad (8)$$

Therefore, the filter gains are calculated using program in the following form:

$$\begin{bmatrix} a_1 \\ a_2 \\ a_3 \\ a_4 \end{bmatrix} = \begin{bmatrix} S_{11} & S_{12} & S_{13} & S_{14} \\ S_{21} & S_{22} & S_{23} & S_{24} \\ S_{31} & S_{32} & S_{33} & S_{34} \\ S_{41} & S_{42} & S_{43} & S_{44} \end{bmatrix} \begin{bmatrix} S_{1r} \\ S_{2r} \\ S_{3r} \\ S_{4r} \end{bmatrix}$$

Hence, the filter is obtained as:

$$F(s) = \frac{0.7952\, s^4 + 14.4578\, s^3 + 484.7298\, s^2 + 5.6805 \times 10^3 s}{s^4 + 40 s^3 + 600\, s^2 + 4000\, s + 10^6} \quad (9)$$

2.2. LQR Controller Design

LQR is a well-known design technique that provides practical feedback gains. It is a robust controller that maximizes the control performance and thus guaranteeing a good precision when regulating the tip position of the flexible link manipulator in the presence of parameter uncertainties [18]. In designing the optimal controller for the system, the main target depends on determining the optimal feedback gain matrix (*u*), so as to minimize the performance index (*J*).

$$u = -K_{lqr} x, \quad (10)$$

$$J = \int_0^\infty (x^T Q x + u^T R u) dt, \quad (11)$$

where *Q* and *R* are the symmetric, positive semi definite weighting matrices to be selected by tuning using LQR MATLAB toolbox until satisfactory behavior is obtained.

K_{lqr} is given as

$$K_{lqr} = R^{-1} B^T P, \quad (12)$$

where *P* is the solution of the following algebraic Riccati equation

$$PA = A^T P + Q - PBR^{-1} B^T P = 0 \quad (13)$$

2.3. Fuzzy Logic Controller Design

Fuzzy logic is a powerful problem solving technique with a myriad of applications in control systems [19]. The fuzzy logic controller designed in this paper has two inputs and one output, the inputs are the hub angle error (e) and its derivatives $(\dot{e})$, while the output is the fuzzy control signal generated based on decisions designed using rule base. The design involves selection of type and number of membership function, selection of rule base, inference mechanism and defuzzification process. In this design, triangular membership function is used and for both the two input and the output, 7 membership functions, negative big, (NB), negative medium (NM), negative small (NS), zero (ZE), positive small (PS), positive medium (PM), positive big (PB) were used which gives a better performance. The rule base is developed using these memberships' functions and thus, resulting 49 set of rules as shown in Table 2. A Mamdani-type fuzzy model is used which is the default inference mechanism and similarly, a default defuzification type, Centre of area was used in converting the output linguistic variable back to the crisp values. The hub angle error (e) and its derivatives $(\dot{e})$ are normalize in the range of [-3 3] while the output was normalize also to [-1.5 1.5]. The fuzzy output signal is fed to the input shaping mechanism to attenuate the resultant vibration of the system, thus guaranteeing good performance.

Table 2. Fuzzy logic rule.

$\dot{e}$/ e	NB	NM	NS	ZE	PS	PM	PB
NB	NB	NB	NB	NB	NM	NS	ZE
NM	NB	NB	NB	NM	NS	ZE	PS
NS	NB	NB	NM	NS	ZE	PS	PM
ZE	NB	NM	NS	ZE	PS	PM	PB
PS	NM	NS	ZE	PS	PM	PB	PB
PM	NS	ZE	PS	PM	PB	PB	PB
PB	PS	PS	PM	PB	PB	PB	PB

3. Result and Discussion

In this section, the single link flexible manipulator was simulated using the novel input shaping control technique to suppressed tip deflections and then LQR and Fuzzy logic controller were incorporated separately for hub angle tracking.

3.1. Simulation Results of the Flexible Manipulator with OBF

The filter was designed using the output signal of single link flexible manipulator, thus the reference system was designed as in Equation (9), based on the time response of the system. Fig. 5 shows the hub angle of the system with no overshoot and settling time of 1 sec, while Fig. 6 shows the tip deflections with maximum tip deflections of -0.03 m hence based on the literature, the filter performed excellently.

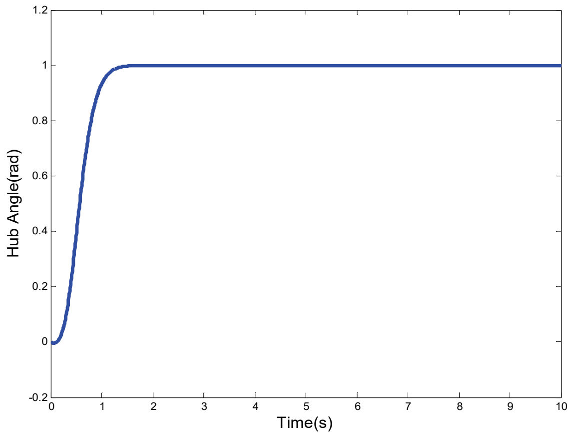

Fig. 5. Hub angle with OBF.

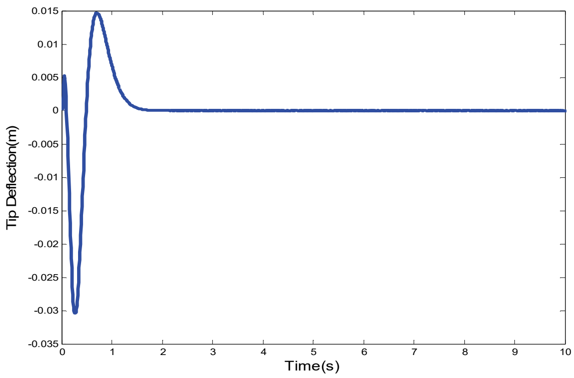

Fig. 6. Tip deflection with OBF.

3.2. Simulation Results of the Flexible Manipulator with LQR-OBF

To increase the robustness of the control algorithms, LQR was combined with the filter for both tip deflections and hub angle tracking control. The state feedback gains were obtained as K= [0.873, 63.517, 0.2389 and 0.1649]. From Fig. 7 and Fig. 8, it can be observed that a very good tracking with settling time of 1 sec and negligible overshoot were achieved. It can also be observe that, tip deflections were suppressed to a minimum (-0.03 m) as shown in Fig. 9.

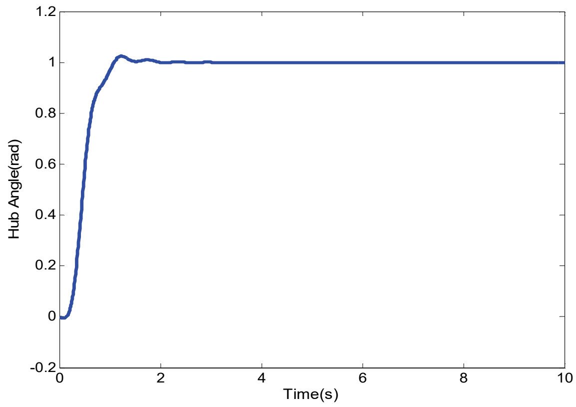

Fig. 7. Hub angle with LQR-OBF.

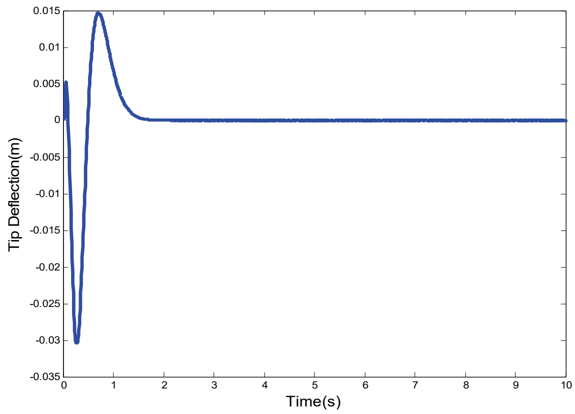

Fig. 8. Tip deflection with LQR-OBF.

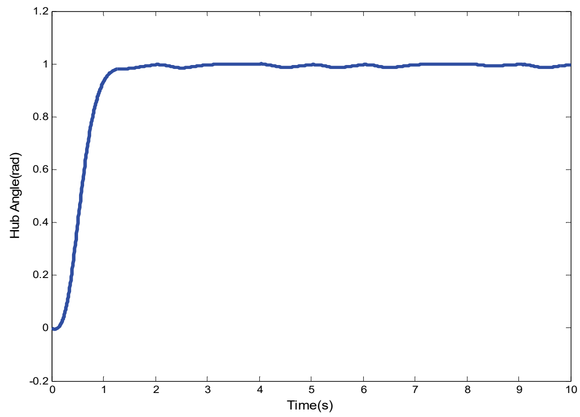

Fig. 9. Hub angle with Fuzzy-OBF.

3.3. Simulation Results of the Flexible Manipulator with Fuzzy-OBF

In addition, fuzzy logic controller was also incorporated with output-based filter for tracking and tip deflections suppression. This was achieved using the ranges of -3 to 3 for both error and derivatives of error while -1.5 to 1.5 for the output variables. As shown in Fig. 9 and Fig. 10, good tracking and tip deflections suppression were achieved. Thus, it can be observed that settling time is still around 1 sec and maximum tip deflections is -0.03 m. But comparing the performance of the two control algorithms, LQR-OBF are more compatible than Fuzzy-OBF.

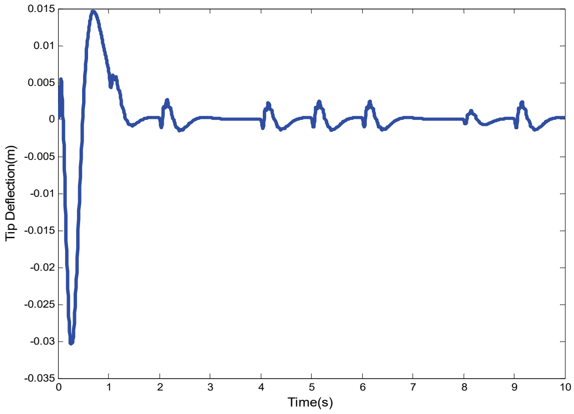

Fig. 10. Tip deflection with Fuzzy-OBF.

4. Conclusion

This paper has presented a hub angle tracking and tip deflection suppression of the single link flexible manipulator, using Fuzzy-OBF and LQR-OBF control algorithms. Performances and compatibility of the two algorithms were compared. Based on the simulation results, it was observed that a very good tracking and tip deflections suppression was achieved in both case, but LQR-OBF is more compatible hence performed better.

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