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ACTIVE VIBRATIONAL CONTROL OF FLEXIBLE MANIPULATOR USING FILTERED-X LMS ALGORITHM

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ABSTRACT

This paper describes the vibration control of a flexible manipulator using Filtered-x LMS algorithm. In this study adaptive notch filter is applied to the vibration control of a flexible manipulator model. The adaptive notch filter is designed to estimate multiple vibration mode frequencies of the flexible manipulator and to minimize the effect of vibration. The filtered-x LMS algorithm is applied to make the root strain error and the system input as close to minimization as possible. In the process, the adaptive notch filter learns to eliminate the resonant vibration frequencies of the system. The experimental results show that this presented adaptive notch filter system can suppress the vibration of the flexible manipulator and track the desired joint angles.

***Keywords*:** Active vibration control, flexible manipulator, Filtered–x LMS algorithm, DSpace, Simulink-MATLAB

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INTRODUCTION

This paper describes the vibration control of a flexible manipulator using Filtered-x LMS algorithm. In this study adaptive notch filter (Elliot, 2001; Fuller, 1996; Kuo. 1996; Peng, 2005 and Window, 1985) is applied to the vibration control of a flexible manipulator model. The adaptive notch filter is designed to estimate multiple vibration mode frequencies of the flexible manipulator and to minimize the effect of vibration.

There has been increasing interest in modeling and control of flexible manipulators in the past decades. There are a number of potential advantages stemming from the use of lightweight and high-speed flexible-link manipulators, such as faster operation, lower energy consumption, and higher load-carrying capacity for the amount of energy expanded. However, structural flexibility causes many difficulties in modeling the manipulator dynamics and guaranteeing stable and efficient motion of the manipulator end-effector. The inverse model is simply cascaded with the controlled system in order that the composed system results in an identity mapping between desired response and the controlled system output. Thus, the notch filter acts directly as the feed-forward controller in such a configuration. In the process, the adaptive notch filter adapts the inverse dynamics of the system. The performance of the steepest descent algorithm can be improved if we allow the adapting rate to change during the adapting process. The highly time-varying flexible manipulator system is shown to be controllable with satisfactory performance by applying the proposed feed forward control law. The filtered-x LMS algorithm is applied to make the root strain error and the system input as close to minimization as possible (Nakamura, 1997; Nakamura et al., 1997;Sasaki, 2012). In the process, the adaptive notch filter learns to eliminate the resonant vibration frequencies of the system. The experimental results show that this presented adaptive notch filter system can suppress the vibration of the flexible manipulator and track the desired joint angles.

FILTERED-X LMS ALGORITHM

Most practical implementations of active systems for the feedforward control of vibrations use adaptive digital filters. We shall concentrate here on the adaptation of digital filters whose outputs are formed from the weighted sum of previous inputs. Such digital filters have an impulse response which is of finite duration and are known as Finite Impulse Response, or FIR filters. If the excitation signal derived from the primary source is sampled at a fixed rate to produce the sequence $x(n)$, and this is used as the input signal for an FIR filter which acts as the controller in a feedforward vibration control system, the output sequence of the controller $y(n)$ can be written as

$$y(n) = \sum_{i=0}^{I-1} W_i(n) \cdot x(n-i) \qquad (1)$$

In this expression, n denotes the sample number, and the variables $W_i(n)$ denote the filter coefficients which weight the current and previous I-1 input samples of the signal $x(n)$. The problem of how best to adapt these coefficients can now be addressed. We choose to minimize a cost function equal to the instantaneous square of the net response:

$$J(n) = \alpha \cdot e^2(n) + b \cdot y^2(n) \tag{2}$$

where *a, b* are the weighting constants.

Expanding the operator notation, the sequence representing the net response of the mechanical system *e*(*n*), can thus be written as the sum of that present in the absence of control $d_0(n)$ and that due to the secondary actuator $d_c(n)$, so that

$$e(n) = d_c(n) + d_0(n) = \sum_{j=0}^{J-1} c_j \cdot y(n-j) + d_0(n) \tag{3}$$

where c_j is the impulse response function of the vibration transfer system.

A simple gradient descent algorithm is thus guaranteed to converge to the globally optimal solution for this problem. Such an adaptive algorithm can be written as

$$W_i(n+1) = W_i(n) - \mu(\frac{\partial J}{\partial W_i}) \tag{4}$$

Where μ is a convergence coefficient and W_i is the *i*th controller coefficient at the *n*th sample time. From the definition of the cost function *J*, the derivative in equation can be written as

$$\left(\frac{\partial J}{\partial W_i}\right) = 2 \cdot a \cdot e(n) \cdot \left(\frac{\partial e(n)}{\partial W_i}\right) + 2 \cdot b \cdot y(n) \cdot \left(\frac{\partial y(n)}{\partial W_i}\right) \tag{5}$$

The steepest descent algorithm required to adapt the coefficients of the digital controller can thus be written as

$$W_i(n+1) = W_i(n) - \alpha \cdot e(n) \cdot r(n-i) - \beta \cdot q(n-i) \tag{6}$$

in which

$$r(n-i) = \sum_{j=0}^{J-1} c_j \cdot x(n-i-j)$$

$$q(n-i) = y(n) \cdot x(n-i)$$

$$\alpha = 2a\mu, \beta = 2b\mu$$

are another convergence coefficients. This algorithm is known as the filtered-x LMS algorithm.

On the other hand, before control process we need the identification process. The identification can be gotten substituting $w(n) = c(n), r(n) = x(n), \beta = 0$ in the equation (4).

$$c_j(n+1) = c_j(n) + \alpha_D \cdot e(n) \cdot x(n-j) \tag{7}$$

where α_D is the convergence coefficient for the identification.

In this section, a detailed description of the materials, methods and tools used in the work is given. The components include samples, study area, experimental design, protocols, data collection and analysis. Authors may include other subsections that are relevant in their respective research areas.

For deriving the equation of the adaptive notch filter, we can modify the Filtered-x LMS algorithm.

The reference signal is defined as:

$$x(n) = A \cdot \cos(2\pi f T n + \phi) \tag{8}$$

We can calculate $y(n)$ from $4m$ pulses per one cycle of $x(n)$ using 2 sample points

$$\begin{aligned} y(n) &= w_0 \cdot x(n) + w_1 \cdot x(n-1) \\ &= w_0 \cdot A\cos(2\pi f T n + \phi) + \\ &\quad w_1 \cdot \cos(2\pi f T(n-1) + \phi) \\ &= A_0 \cdot \cos(2\pi f T n + \phi + \varphi) \end{aligned} \tag{9}$$

where

$$A_0 = \sqrt{w_0^2 + w_1^2 + 2 \cdot w_0 \cdot w_1 \cdot \cos(2\pi f T l)}$$

$$\phi = -\tan^{-1}\left(\frac{w_1 + \sin(2\pi f t l)}{w_0 + w_1\cos(2\pi f T l)}\right)$$

The sampling period T is *1/4mf* and then $y(n)$ is expressed as

$$y(n) = A_0 \cos\left(\frac{\pi}{2}\frac{n}{m} + \varphi + \phi\right) \tag{10}$$

Finally we can get the update equations as:

$$\begin{aligned} w_0(n+1) &= w_0(n) - \alpha \cdot e(n) \cdot r(n) - \beta \cdot q(n) \\ &= w_0(n) - \alpha \cdot e(n)\{\widehat{c_0} \cdot x(n) + \widehat{c_1} \cdot x(n-l)\} - \beta\{w_0 \cdot x^2(n) + w_1 \cdot x(n) \cdot x(n-l)\} \end{aligned} \tag{11}$$

$$\begin{aligned} w_1(n+1) &= w_1(n) - \alpha \cdot e(n) \cdot r(n) - \beta \cdot q(n) \\ &= w_1(n) - \alpha \cdot e(n)\{\widehat{c_0} \cdot x(n) + \widehat{c_1} \cdot x(n-l)\} - \beta\{w_0 \cdot x^2(n) + w_1 \cdot x(n) \cdot x(n-l)\} \end{aligned} \tag{12}$$

$$x(n) = \cos\left(\frac{\pi}{2}\frac{n}{m}\right) \tag{13}$$

$$\begin{aligned} y(n) = w_0 \cdot \cos\left(\frac{\pi}{2}\frac{n}{m} + \phi\right) + \\ w_1 \cdot \sin\left(\frac{\pi}{2}\frac{n}{m} + \phi\right) \end{aligned} \tag{14}$$

$$w_0(n+1) = w_0(n) - \alpha \cdot e(n) \cdot \left\{\widehat{c_0} \cdot \cos\left(\frac{\pi}{2}\frac{n}{m}\right) + \widehat{c_1} \cdot \sin\left(\frac{\pi}{2}\frac{n}{m}\right)\right\} \tag{15}$$

$$w_1(n+1) = w_1(n) - \alpha \cdot e(n) \cdot \left\{\widehat{c_0} \cdot \cos\left(\frac{\pi}{2}\frac{n}{m}\right) + \widehat{c_1} \cdot \sin\left(\frac{\pi}{2}\frac{n}{m}\right)\right\} \tag{16}$$

Figure 1 shows the block diagram of the active noise control. LPF shows the analogue low pass filter. Z^l shows the l pulse delay.

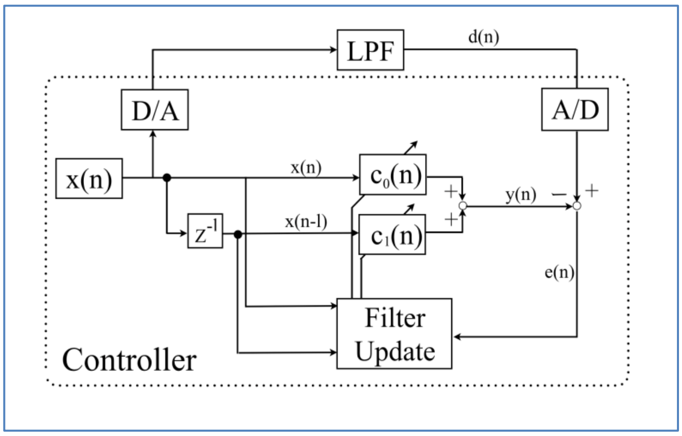

Figure 1: Block Diagram of Adaptive Notch Filter.

The updating equations of the identification are

$$\hat{c_0}(n+1) = \hat{c_0} + \alpha_D \cdot e(n) \cdot x(n)$$
$$= \hat{c_0} + \alpha_D \cdot e(n) \cdot \sin\left(\frac{\pi}{2}\frac{n}{m}\right) \quad (17)$$
$$\hat{c_1}(n+1) = \hat{c_1} + \alpha_D \cdot e(n) \cdot x(n-l)$$
$$= \hat{c_0} + \alpha_D \cdot e(n) \cdot \cos\left(\frac{\pi}{2}\frac{n}{m}\right) \quad (18)$$

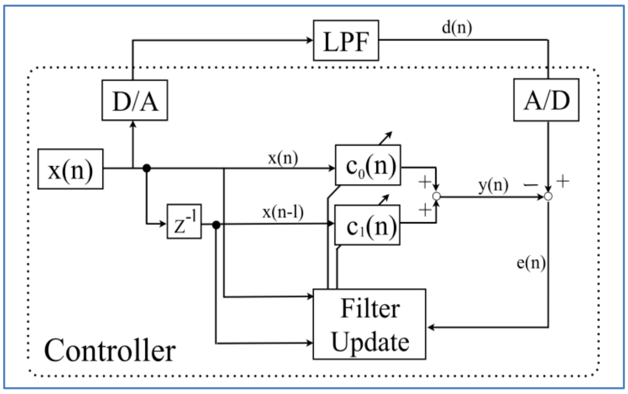

Figure: 2 Identification Block Diagram of Adaptive Notch Filter.

Figure 2 shows the block diagram of the active vibration control system. The adaptive notch filter of vibration control consists of parallel connection of the filter blocks of desired mode numbers of vibration. Now we assume the desired degree of control vibration modes $k=i, \ldots, k, \ldots, N$ and the reference signal is

$$x_k(n) = \cos\left(\frac{\pi}{2}\frac{n}{m}\right) \quad (19)$$

and the update equation is

$$y(n) = \sum_{k=1}^{N} y_k(n) \quad (20)$$

where

$$y_k = w_{k_0} \cos\left(\frac{\pi}{2}\frac{n}{m}\right) + w_{k_1} \sin\left(\frac{\pi}{2}\frac{n}{m}\right)$$

$$w_{k_0}(n+1) = w_{k_0}(n) - \alpha_k \cdot e(n)\left(\widehat{c_{k_0}} \cos\left(\frac{\pi}{2}\frac{n}{m}\right) + \widehat{c_{k_1}} \cos\left(\frac{\pi}{2}\frac{n}{m}\right)\right)$$

$$w_{k_1}(n+1) = w_{k_1}(n) - \alpha_k \cdot e(n)\left(\widehat{c_{k_0}} \cos\left(\frac{\pi}{2}\frac{n}{m}\right) + \widehat{c_{k_1}} \cos\left(\frac{\pi}{2}\frac{n}{m}\right)\right)$$

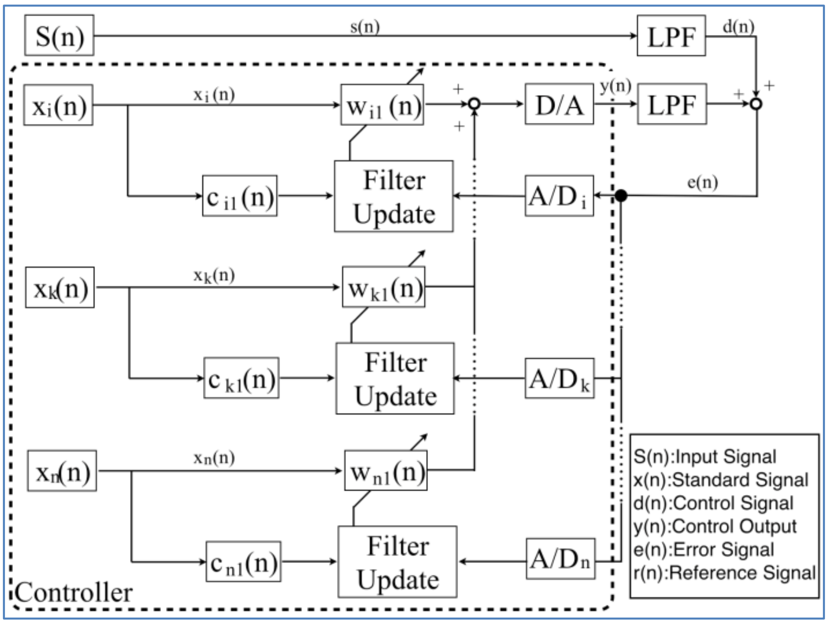

Figure 3: Block Diagram of multi-channel controller system.

EXPERIMENTAL SETUP

Table 1. System parameters.

Motor 1		Product number	V511-012EL8
		Rated torque	0.34 [N·m]
		Rated rotational speed	3000 [rpm]
		Rated output	110 [W]
Motor 2	Product number	V404-012EL8	
	Rated torque	0.13 [N·m]	
	Rated rotational speed	3000 [rpm]	
	Rated output	40 [W]	
Encoder	Output pulse number	1000 [P/R]	
Link 1	Length	0.44 [m]	
	Radius	0.005 [m]	
	Material	Stainless steel	
Link 2	Length	0.44 [m]	
	Radius	0.004 [m]	
	Material	Aluminum	
Load	Weight	200 [g]	

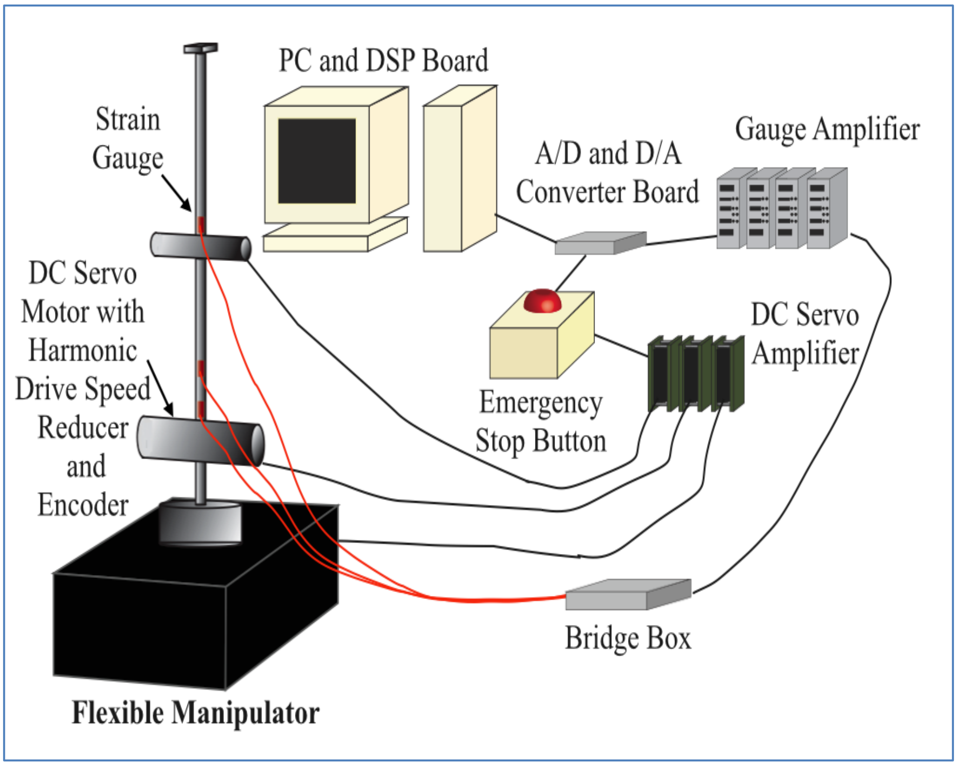

Figure 4(a) Experimental system.

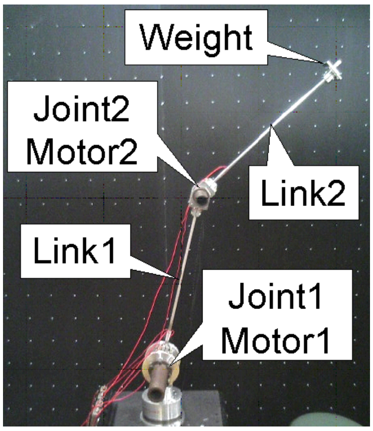

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Figure 4(b) The flexible manipulator.

The experimental system consists of highly flexible links as shown in Figures 4(a) and (b) whose parameters are shown in Table 1. High performance drives were assembled consisting of PWM amplifiers that operate in speed feedback mode, DC servo motors with optical encoders and harmonic drive speed reducers. The digital controller consists of a dSPACE^{TM} system based on the PowerPC. Sixteen channels of 16 bit A/D and D/A and 6 counters are also provided as shown in Figure 5. In earlier experiments on this test-bed, the authors designed a PD controller. The 4th degree Chebyshev low pass filter's cutoff frequency is

60Hz. The convergence coefficient for the identification α_D is used for 0.01 by trial and error. The identified model of the manipulator was derived and there was good agreement between experiment and model. Figures 7 show the time response of the identified models and FFT analysis result. The experimental results and the identified results match closely. The above analysis demonstrates that a linear model can approximate the actual system reasonably well and is suitable for defining the new output and designing the controllers.

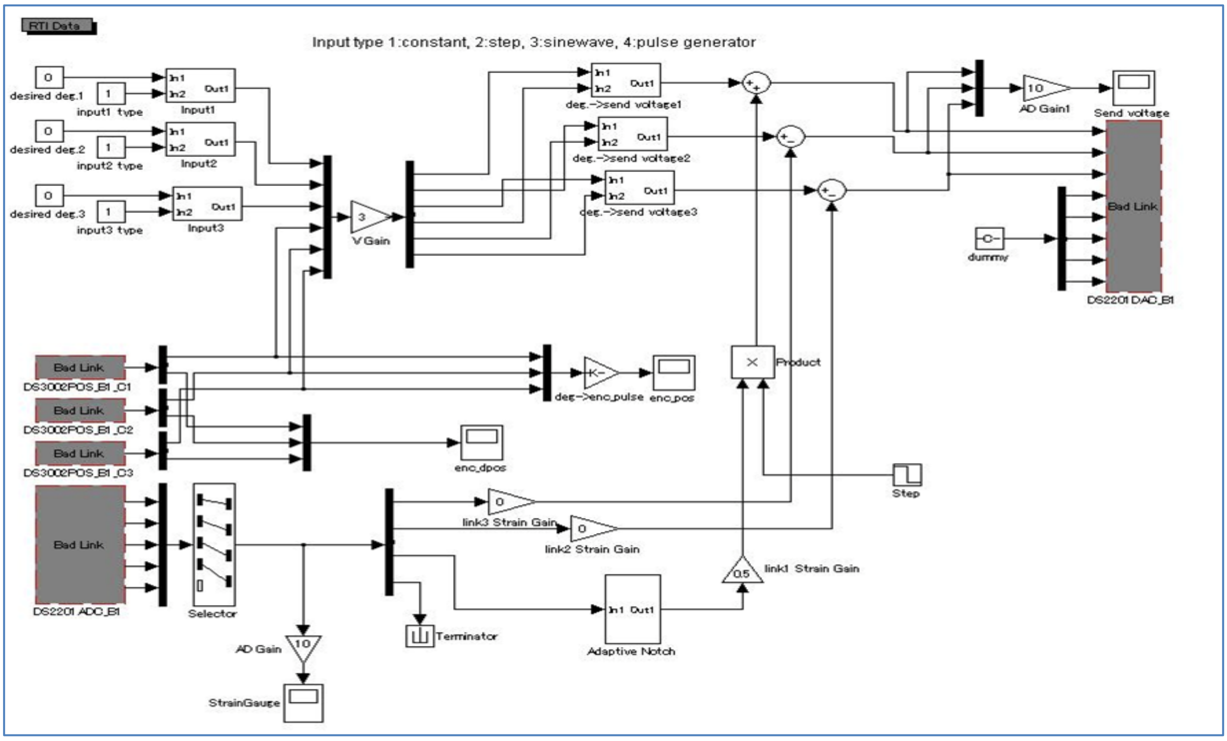

Figure 5: Block diagram of the experimental system**.**

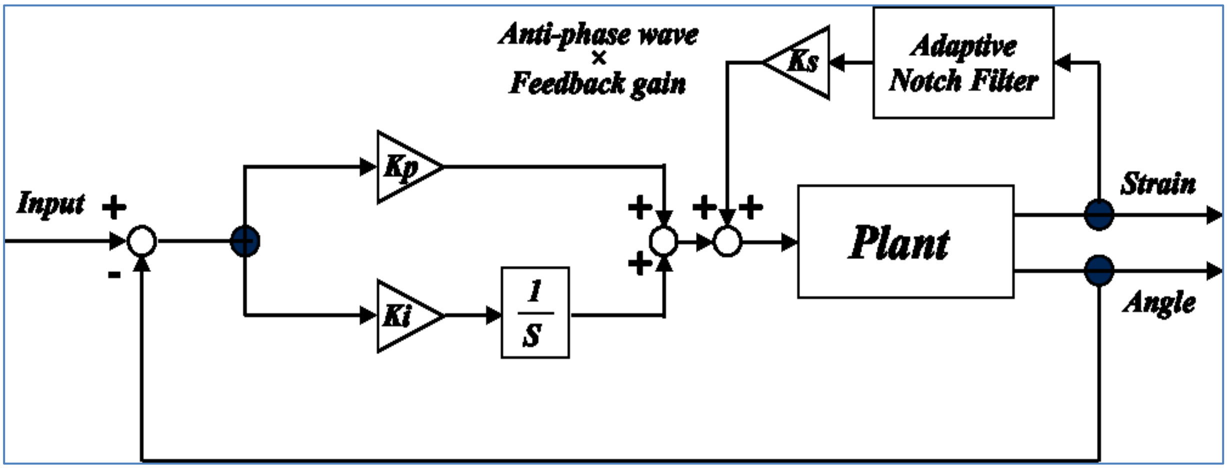

Figure 6: Block Diagram of Adaptive Notch Filter with PI controller

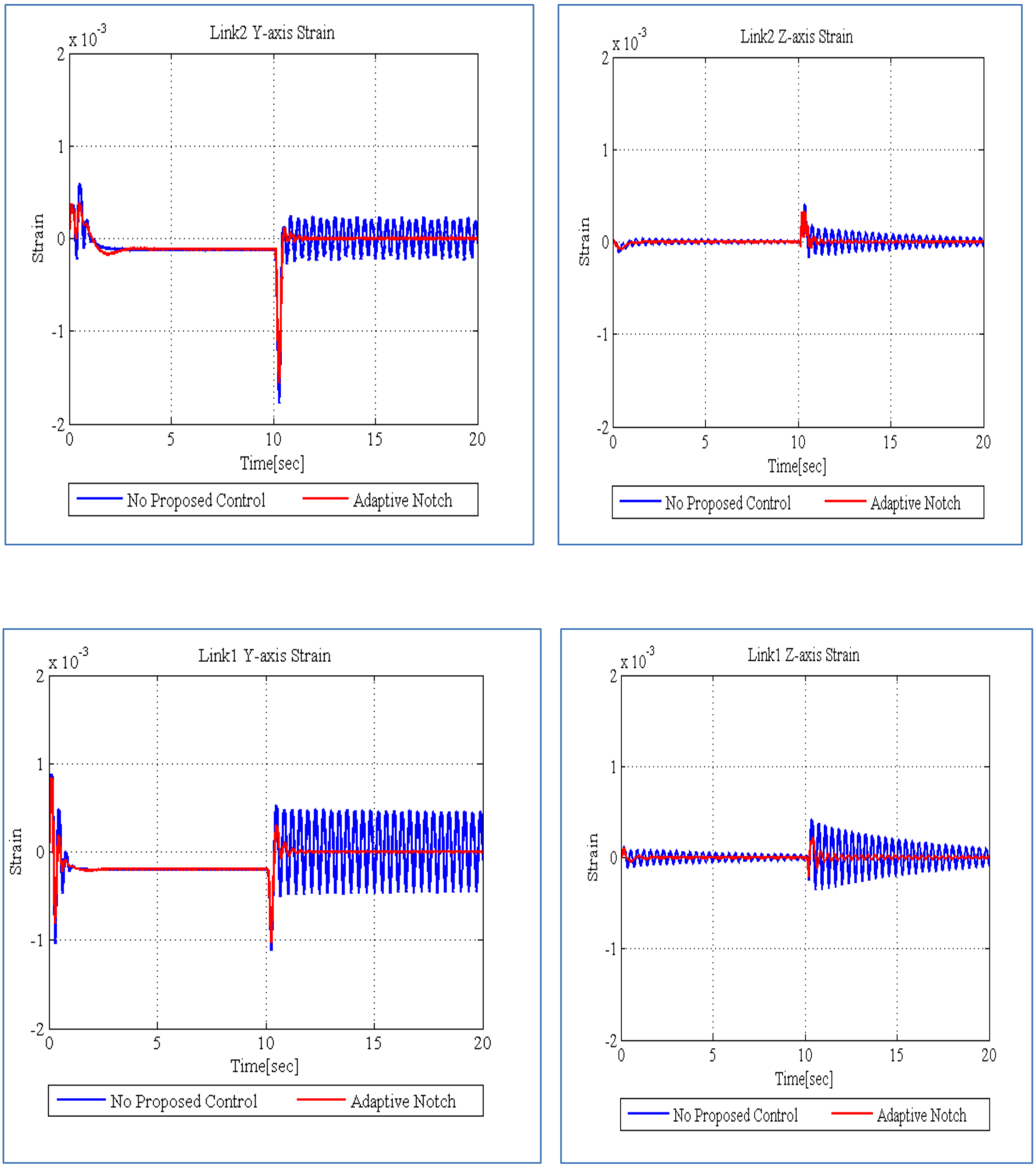

Figure 7: Time Response of each link's strain.

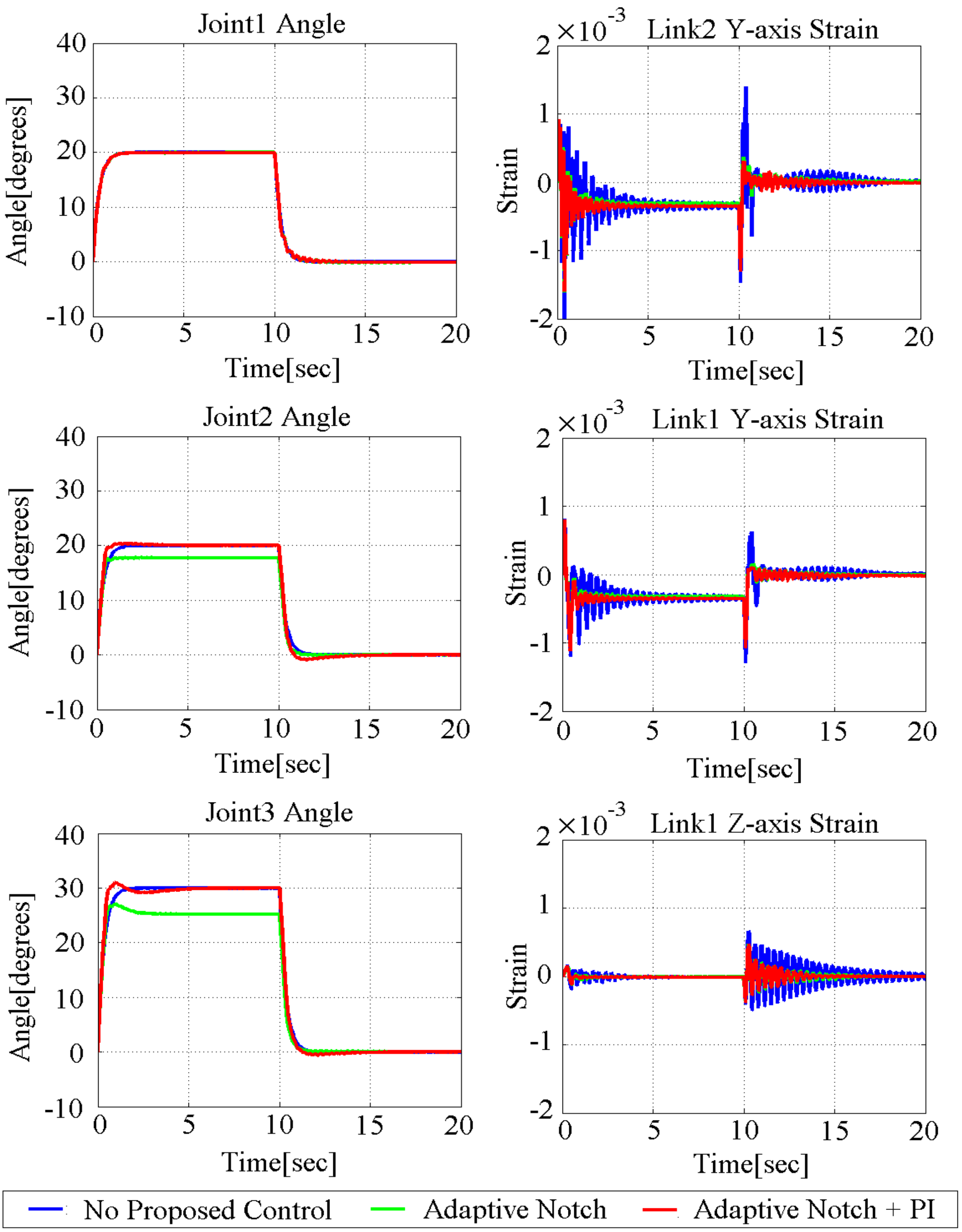

Figure 8 Time response of the joint angles and the link strains with and without control.

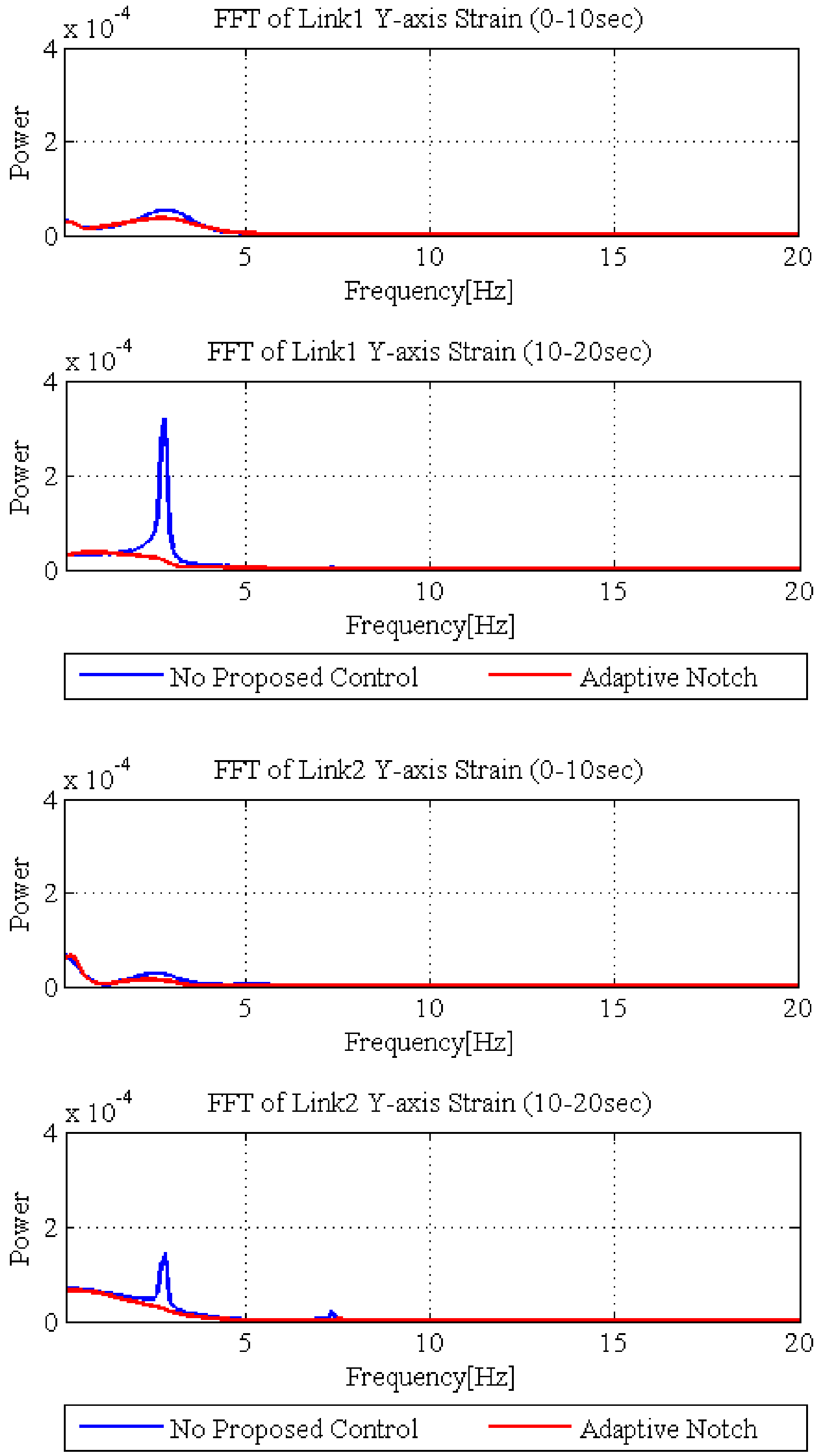

Figure 9 (a) FFT analysis of each link strains.

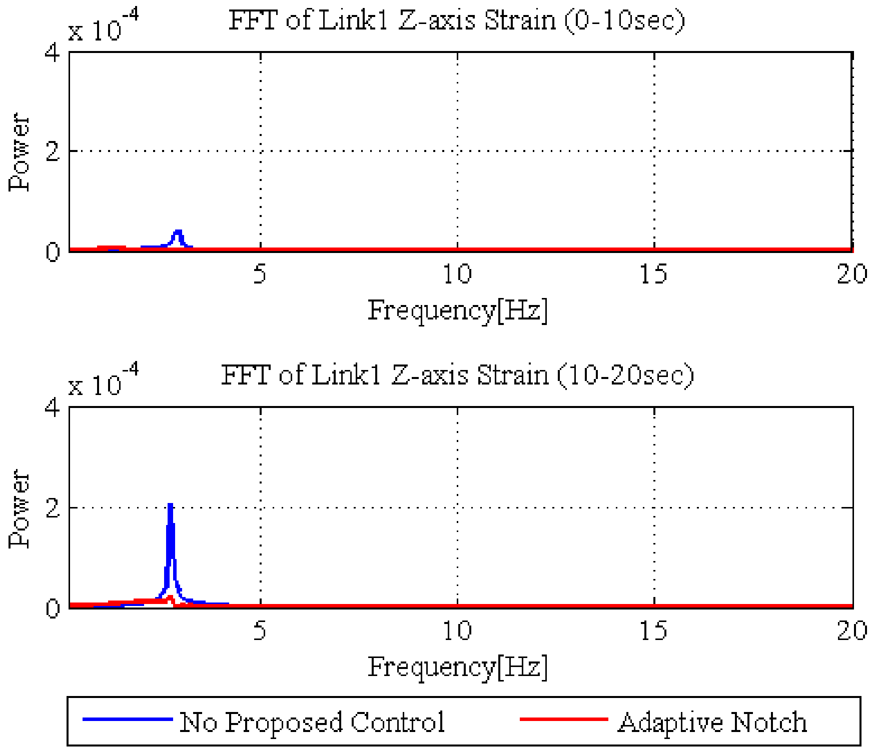

Figure 9(b) FFT Analysis of Link1 Z-axis Strain.

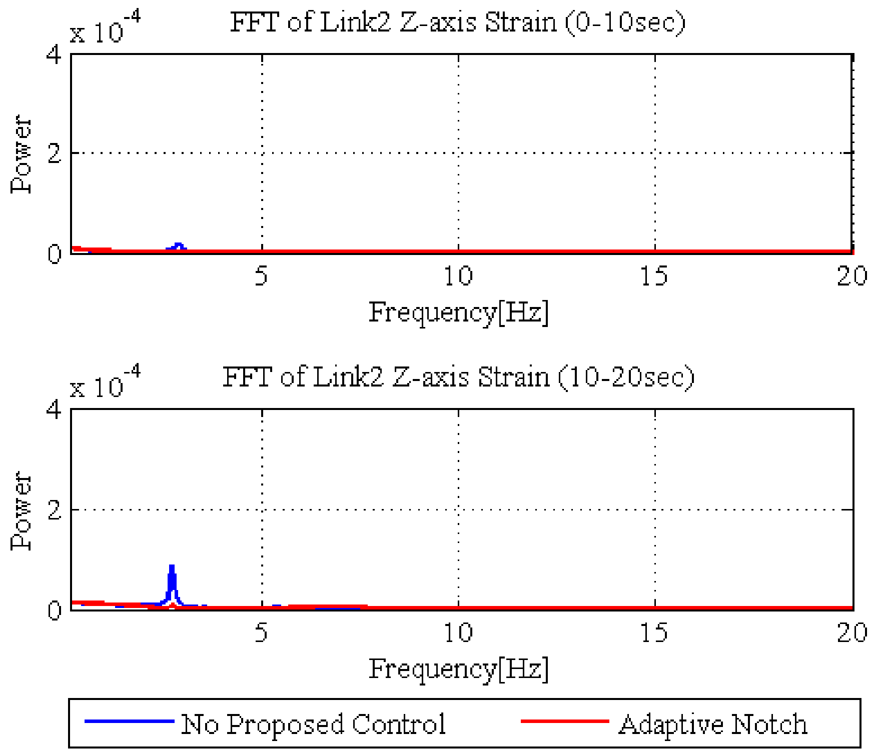

Figure 9(c) FFT Analysis of Link2 Z- axis Strain.

RESULTS AND ANALYSIS

We applied the adaptive notch filter based on the filtered-x LMS algorithm to vibration control of the flexible manipulator and evaluated its effectiveness by analyzing the rate of convergence, mis-adjustment rejection bandwidth and tracking capabilities. Figure 6 shows the block diagram of the feed-forward control using the adaptive notch filter. Figure 8 shows the time response of the joint angles and root strains of the arm. Figure 9 shows the power spectrum of the link 1 and 2 root strains. The root strains from 0 to 10 seconds and 10 to 20 seconds have different peaks before control with adaptive notch filters. After controlling with the proposed adaptive notch filters the resonant peaks completely eliminate. The 1st natural frequency of the flexible manipulator is 6.7Hz, 2nd one is 17.5Hz, 3rd one is 38.5Hz. The sampling frequency is 0.002Hz. This control system can suppress the vibration of the flexible arm within a short time in comparison with the conventional joint angle controller and can track the desired joint angles. Experimental results for the vibration control of a flexible arm are presented and verified that the proposed control system is effective at controlling the motion of the flexible manipulator. Experimental results show the filtered-x LMS adaptive notch filter feed forward control system can be used effectively for the vibration control of 3D motion of the flexible manipulator.

CONCLUSION

This paper describes vibration control of a flexible manipulator using an adaptive notch filter based on filtered-x LMS algorithm. The flexible arm is defined as low stiffness of a robot arm. The adaptive notch filter is used for a second order all-pass filter. We carried out the vibration control experiments using the adaptive notch filter. From the experiments, we succeeded in eliminating approximately 82.1% of strain in comparison to flexible manipulators without vibration control. The experimental results show the good control performance of 3D motion control of the flexible manipulator using an adaptive notch filter based on filtered-x LMS algorithm.

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