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Two-Degree-of-Freedom Control of Flexible Manipulator Using Adaptive Notch Filter and Strain Feedback

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Abstract—**This paper investigates vibration control in 3-dimensional motion of a Flexible manipulator using 2-degree-of-freedom controller. The controller employs an adaptive notch filter in the feedforward and strain feedback controller in the feedback path. Experimental results show that the proposed vibration controller is effective for three-dimensional vibration control of the flexible manipulator.**

Keywords-flexible manipulator; two-degree-of-freedom control; adaptive notch filter; direct strain feedback

I. INTRODUCTION

In recent years, reduction of the weight of the links has been necessitated by the desire to the increase in operation speed, reduction in the initial cost and saving operation energy of the industrial robot arm. One of the directions taken was the reduction of the rigidity of the arm itself. This however, resulted in another need to suppress vibration due to elastic deformation [4-15]. In conventional vibration control, methods based on analytical models are generally used, but this is a problem for complex and difficult-to-model systems such as flexible manipulators. So, in this research, considering the nature of our plant, we utilize vibration control techniques which do not need analysis model directly. One of the methods is to use an adaptive notch filter as feedforward. This will have the effect of shaping the spectrum of the desired trajectory such that it will excite minimal vibrations.

The main challenge with this input shaping technique is its low convergence speed of the adaptation coefficient and the stability of the filter in the convergence process of the adaptation coefficient. To supplement this solution, we further propose strain feedback technique. Initially proposed by Luo et al. for a 1-link flexible arm who theoretically and experimentally showed that vibration can be suppressed since it increases system damping [1, 15].

Another major challenge that effects multi-link flexible manipulator which is initially vertical and undergoing three-dimensional motion is steady-state distortion which occurs due to the weight of the arm, which results in an error in the readings of the strain. Using such readings for strain feedback will lead to errors in the joint angles. A method for adaptively removing this stationary strain has not been proposed yet.

Researcher in [2] presented a 2- Degrees-of-Freedom (DOF) controller comprising of a fixed notch filter feedforward control combined with DSFB control. The results exhibited the effectiveness of the scheme when applied to a 2-link 3-DOF flexible manipulator. However, since the frequency spectrum of the notch filter is fixed, it was observed that the control performance deteriorated if the resonance frequency changed due to changes in the tip load.

In this research therefore, to guarantee performance with variable tip loads, we propose to use adaptive notch filter. To speed up the convergence of the adaptive coefficient of the adaptive notch filter and to stabilize the filter in the convergence process, we design an adaptive notch filter based on the Simplified Lattice Real Algorithm (SLRA). We also propose an adaptive stationary distortion due to self-weight of the links removal method using an adaptive notch filter. We compared the vibration suppression performance of feedforward (FF) control using adaptive notch filter and distortion feedback (DSFB) control using adaptive notch filters assessed separately against the two DOF controller combining the two techniques and we verified the effectiveness of two degree of freedom control. We also carried out experiments with variable tip load in the two degrees of freedom control like experiments in reference [2]. From the results with variable tip loads, we conclude that the proposed two-degrees-of-freedom control is effective against changing tip loads.

II. CONFIGURATION OF FLEXIBLE MANIPULATOR

Figure 1 shows a 2-link 3-DOF flexible manipulator to be controlled. A DC servomotor is attached to each of the joints. Joint1 rotates in the twisting direction, and Joint 2 and Joint 3 rotate in the bending direction. The strain is measured by a strain gauges attached to the root of each link. The joints are fitted with harmonic drives to reduce speed by a factor of 100. Link number 1 is made of steel while link number 2 is made of aluminum. The joints are assumed to be rigid while the links are flexible.

The vertical state of the flexible manipulator is assumed to be the posture at the start of the experiment, and the input is a rectangular wave with a cycle of 20 seconds during which the posture of the flexible manipulator changes. For the first 10 seconds, the posture changes as required by the joint trajectory. In the last 10 seconds, the manipulator returns to the posture at the start of the experiment, the

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posture it maintains until the end of experiment. The sampling time is set to 0.002 seconds.

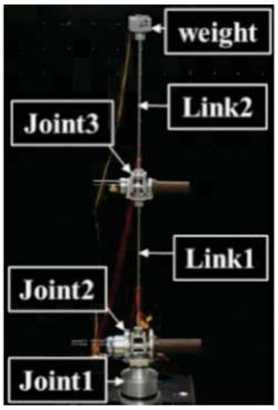


Figure 1. Flexible Manipulator.

III. Controller Design

A. Adaptive Notch Filter

Figure 2 shows the block diagram and transfer function of a second-order IIR adaptive notch filter based on the Simplified Lattice Real Algorithm (SLRA) proposed in [3].

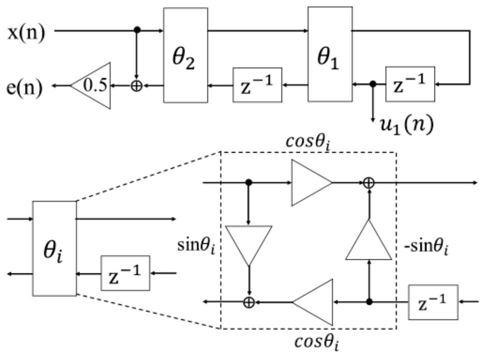


Figure 2. Adaptive Notch Filter in normalized Lattice Form.

$$H(z) = \frac{1+sin\theta_2}{2} \times \frac{1+2sin\theta_1(n)z^{-1}+z^{-2}}{1+sin\theta_1(n)(1+sin\theta_2)z^{-1}+sin\theta_2 z^{-2}} \quad (1)$$

In equation (1), θ_1 and θ_2 are the parameters that determine the notch frequency and notch width, respectively, f_N is the notch frequency, f_s is the sampling frequency, and B is the notch width. Further,

$$\theta_1(n) = 2\pi f_N/f_s - \frac{\pi}{2} \quad (2)$$

$$sin\theta_2 = \frac{1-\tan(B/2)}{1+\tan(B/2)} \quad (3)$$

Note that 0<B<π/2, and the smaller the value of B, the narrower the notch width. In this work, the value of B is 0.1.

In SLRA, by realizing an adaptive notch filter with a normalized grid type and using the state variables of the structure in an adaptive algorithm, better convergence than the gradient method can be achieved. Furthermore, since the peak gain is normalized, the filter stability is always guaranteed. The following is the coefficient update equation by SLRA.

$$\theta_1(n+1) = \theta_1(n) - \mu(n)u_1(n)e(n) \quad (4)$$

$$\mu(n) = \frac{\mu_0}{\sum_{k=0}^{n}\lambda^{n-k}[u_1(n)]^2} \quad (5)$$

The values of μ_0 and λ are determined by trial and error, and for experiments in this paper, both are taken to be equal to 1.0.

To verify the effectiveness of the designed filter, Figure 3 shows response to two different structures of adaptive notch filter when the input signal is a sine wave having an amplitude of 1 and frequency 3Hz corrupted by white noise of amplitude 0.02 peak to peak. The adaptive notch filter structure to be compared are the filter used in the conventional method constructed in a direct type and the normalized lattice, using the LMS descent method as the adaptive algorithm.

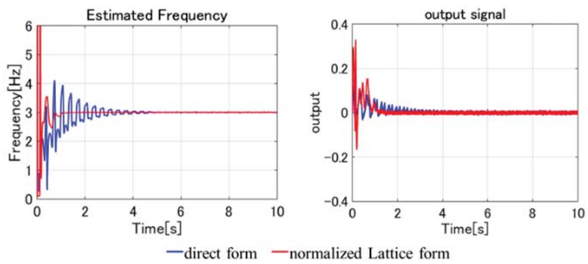


Figure 3. Simulation results.

The left side of Fig. 3 shows the estimated value of the frequency of the unknown sine wave by the adaptive notch filter, and the right side shows the output of the adaptive notch filter. It can be confirmed that the frequency of the unknown sine wave is estimated to be 3Hz for both direct type and normalized grid type. However, while the direct type, which is the conventional method, converges to 3Hz at 5.0 seconds, the normalized grid type converges to 3Hz at 1.2 seconds. In response to this, even at the output of the filter, the normalized grid type can attenuate the sine wave faster than the direct type notch filter. From this result, it can be said that the speeding up of the convergence of the adaptation coefficient, which was the conventional problem, could be realized. In addition, the filter is guaranteed to be stable because it is configured as a normalized grid type. From the above, it can be said that the adaptive notch filter constructed based on SLRA is a filter that solves the conventional problems.

B. Steady State Strain Removal Using Adaptive Notch Filter

Adaptive notch filters are used in applications that automatically detect and remove unknown sine waves superimposed on broadband signals. In this paper, this wide band signal is regarded as steady distortion, and an unknown sine wave is regarded as a vibration component, and the signal from which the vibration component has been removed using an adaptive notch filter is subtracted from the original signal to realize the steady distortion removal. Figure 4 shows the results of steady-state distortion removal using an adaptive notch filter when the input is the distortion data of Link 2 on a real machine.

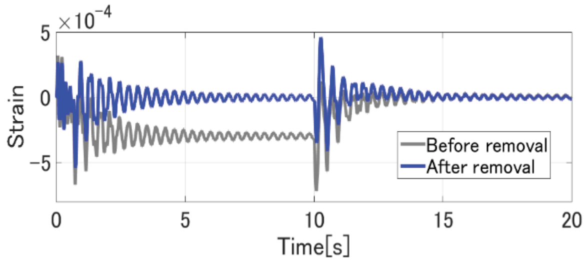


Figure 4. Removal of strain offset in Link 2.

Since the convergence value of strain is 0 at 0-10 seconds, the effectiveness of the proposed method can be confirmed. The effectiveness of steady-state distortion removal using an adaptive notch filter is verified from simulation and experiments.

IV. 2-DEGREE-OF-FREEDOM CONTROLLER DESIGN

The block diagram of 2 degrees of freedom control is shown below.

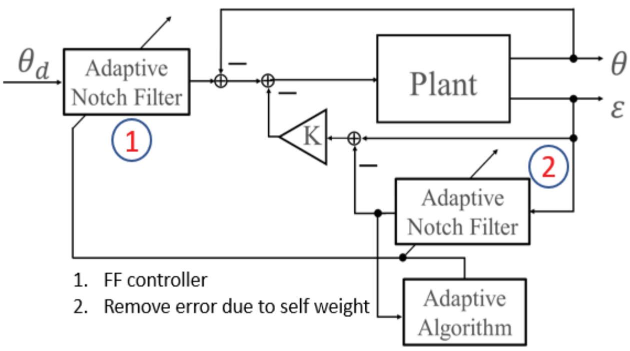


Figure 5 Block diagram of the 2-degree-of-freedom control system.

The resonant frequency of the vibration is detected from the data of distortion, and an adaptive notch filter is used for FF controller and steady-state distortion correction as label 1 and 2 in the Figure 5 respectively.

V. SIMULATION RESULTS

Using the modeling software MAPLESIM™, a plant model of the flexible manipulator to be controlled was created. After that, the plant model was imported into the control system design support system MATLAB/SIMULINK, and the performance verification of the proposed controller was performed by simulation.

A. Performance Verification of FF Control and DSFB Control

First, we verify the effectiveness of feedforward (FF) control and distortion feedback (DSFB) control using an adaptive notch filter. The simulation results are shown in Figure 6.

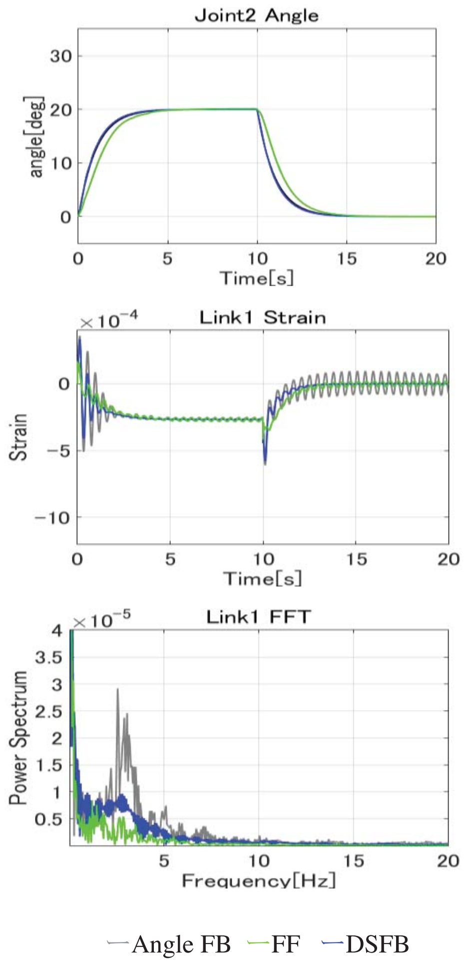


Figure 6. Simulation results.

From the simulation results, it can be confirmed that convergence to the target angle is achieved. In other words, steady-state distortion removal using the proposed adaptive notch filter can be said to be effective for convergence to the target angle in DSFB control. Also, from the strain data, vibration suppression can be confirmed in both FF control and DSFB control. In particular, FF control was able to suppress the vibration of movement from 0 to 3 [s] and 10 [s], and DSFB control has residual vibration such as 3 to 10 [s] and 13 to 20 [s] The suppression can be confirmed. In addition, in distortion FFT, FF control can cut resonance frequency components by 82% and DSFB control can cut by 67%. From the above results, it can be said that the proposed FF control and DSFB control are effective for vibration control.

B. Effectiveness of 2-Degrees-of-Freedom Control

Figure 7 shows simulation results comparing FF control, DSFB control, and two degrees of freedom (2 DOF) control whose effectiveness was confirmed in the previous section.

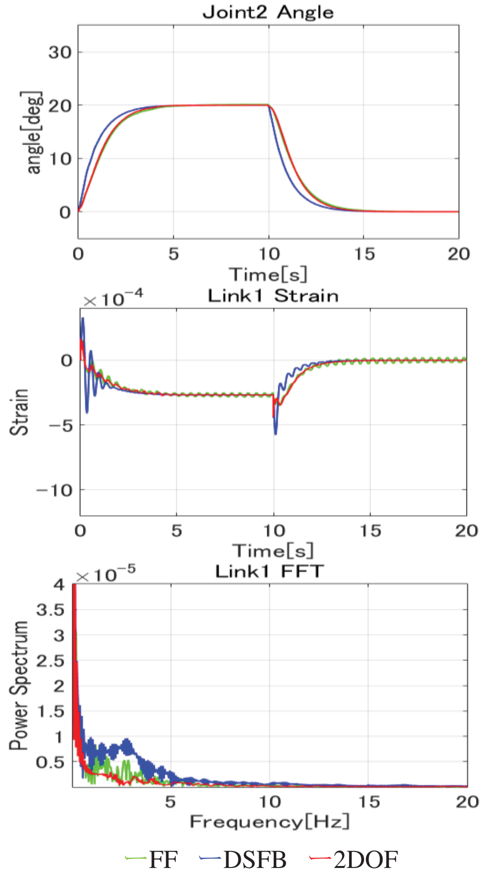


Figure 7. Simulation results.

The joint angle response shows that the target angle is followed in 2DOF control. In other words, steady-state distortion removal using the proposed adaptive notch filter is also effective in 2DOF control. Furthermore, based on the strain data, 2DOF control is a control that has both the features of suppression of start-up vibration that is a feature of FF control and suppression of residual vibration that is a feature of DSFB control. Comparison between FF control and DSFB control therefore, it can be said that 2 DOF control combining FF control and DSFB control is effective for vibration control because it is superior to the two controllers individually.

VI. Experimental Results

This section presents experiential results obtained by using Feedforward (FF) control using adaptive notch filter, strain feedback (DSFB) control with steady state strain removal using adaptive notch filter and the two degrees-of-freedom controllers combining the above two controllers (2DOF). The control exercise was carried out on a real flexible manipulator, and the effectiveness of the 2DOF control is verified by comparing the vibration suppression performance of each controller. Experiments were done considering changes of motion angle, changes of motion speed, and changes in tip load. We verified the robustness of each controller and affirmed the effectiveness of 2 DOF control. Experiments confirmed that the proposed 2 degrees of freedom control is effective for the change of tip load which results in changes of resonance frequency.

Figure 8 shows experimental results comparing FF control, DSFB control, and 2DOF control.

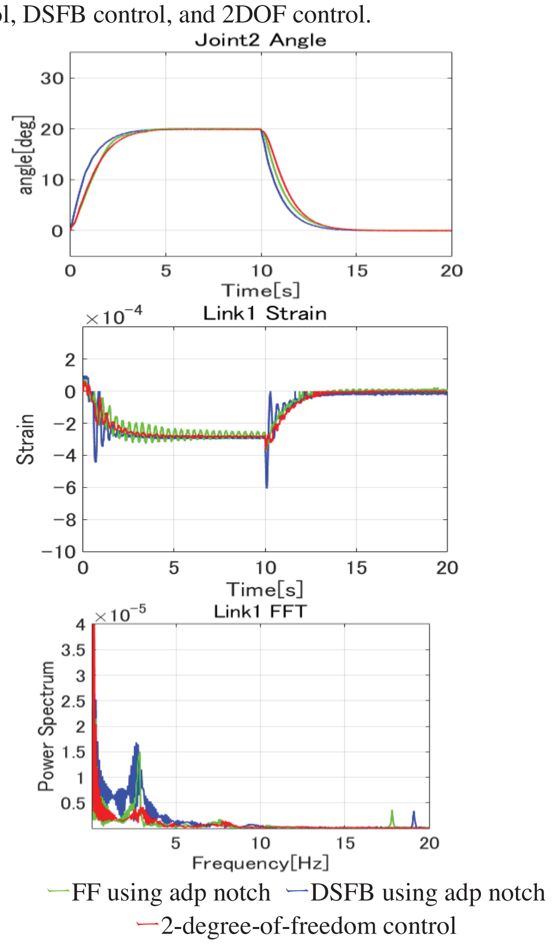


Figure 8. Results of Experiment.

From the joint angle response, the joint angles in the three control systems; FF control, DSFB control and 2DOF control converge to the target joint angle. In other words, it shows that stationary distortion removal using an adaptive notch filter is effective. From the strain data, it can be confirmed that FF control and DSFB control have the features of vibration suppression of residual movement and residual vibration suppression as well as simulation. Further, it can be observed that 2 DOF control has the features of FF control and DSFB control. From the strain spectrum FFT, the resonance frequency component can was reduced by 87%, and it is understood that it has better control performance than FF control and DSFB control.

To investigate the response of individual controllers with variable loading, a weight of 100 grams was attached to the tip, and the operation angles for Joint 1, Joint 2, Joint 3 were 20 degrees, 20 degrees, 30 degrees respectively. Figure 9 shows the experimental results.

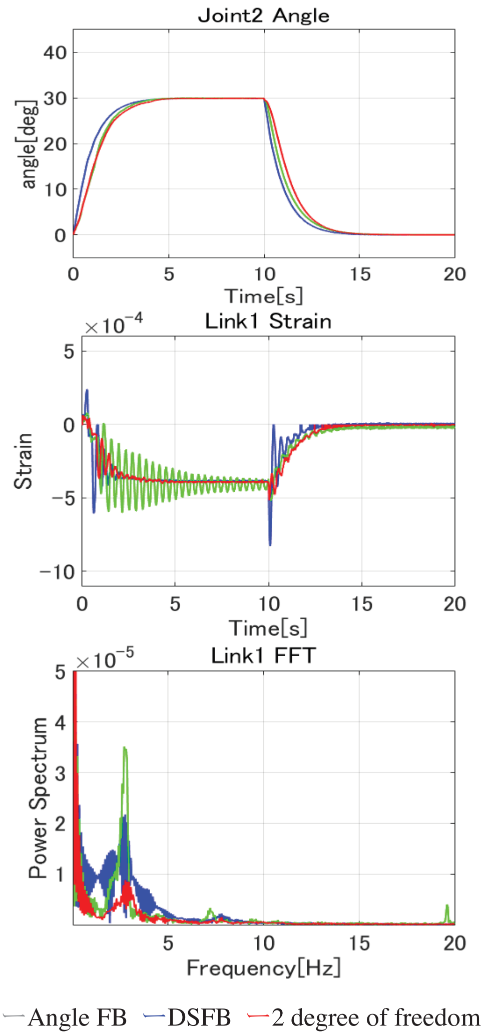


Figure 9. Experimental results.

From Fig. 9, the three controllers converged to the target angle. In other words, steady-state strain removal using an adaptive notch filter can be said to be robust to changes in the tip load. Further, regarding strain as well, both transient and residue vibration were suppressed. From spectrum FFT of strain, FF control reduced strain power by 22% of resonance frequency component and DSFB control reduced strain power by 57%, whereas 2DOF control reduced strain power by 92%. From the above, it can be said that the proposed 2DOF control is robust to changes in the tip load.

In the two-degree-of-freedom control described in reference [2] having fixed notch filter and the two-degree-of-freedom control proposed in this research, Figure 10 shows the results of normal operation experiments and Figure 11 shows the experimental results when the tip load is changed.

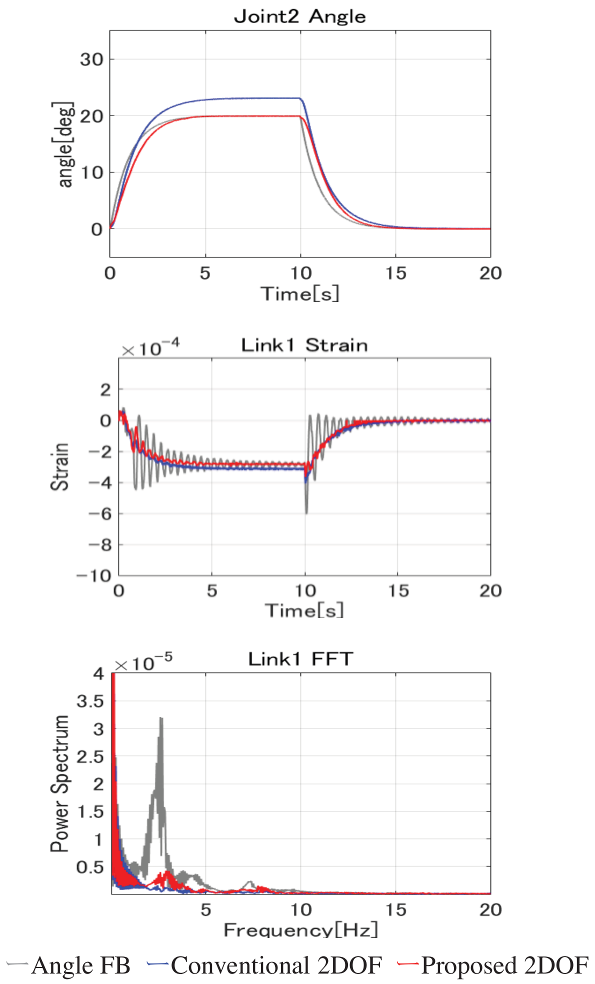
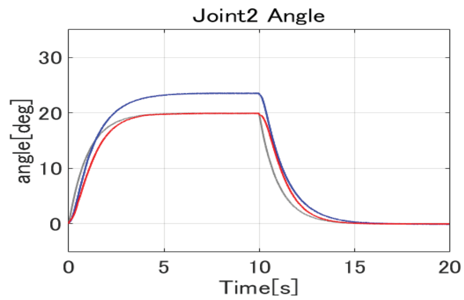


Figure 10. Results of Experiment (Tip weight +0 grams).



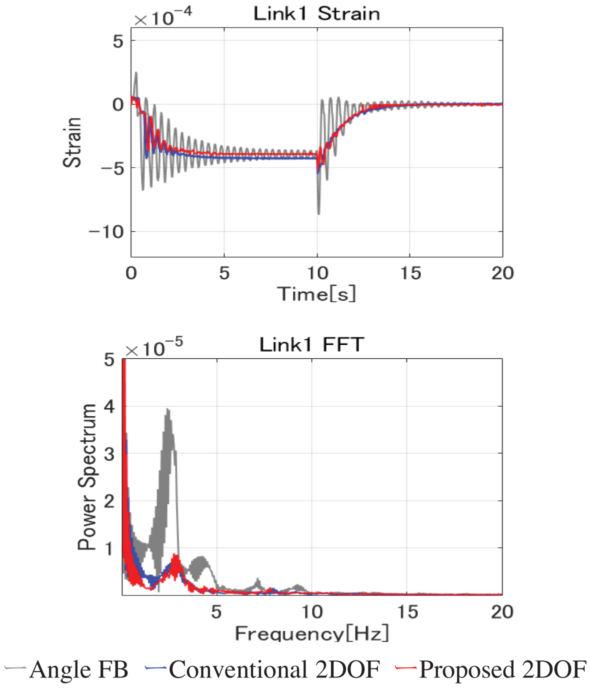


Figure 11. Results of Experiment (Tip weight +100 grams).

Regarding joint angle response, in the case of conventional two-degree-of-freedom control, the joint angle error increases from 3.17 degrees to 3.63 degrees. This is due to the increase in steady-state strain caused by the addition of load to the tip. On the other hand, in the proposed two-degree-of-freedom control, no angular error occurs in both normal operation experiments and tip load change experiments due to steady-state strain removal using an adaptive notch filter. Furthermore, the proposed method suppresses vibration more at 1 to 3 seconds. This is because the resonance frequency changes due to the change of the tip load, and the change can be adapted by the proposed method. From the strain FFT, the conventional method cuts the 86% resonant frequency component in the tip load change experiment, while the proposed method cuts 92%. From the above, it can be said that the two degree of freedom control system created in this work is effective for the change of the resonance frequency.

VII. CONCLUSIONS

In this research, the adaptive notch filter is configured based on SLRA to speed up of convergence of the adaptation coefficient and to stabilize the filter in the convergence process. Further, we proposed an adaptive steady-state strain removal technique using an adaptive notch filter and showed its effectiveness. After that, we constructed a control system with two degrees of freedom comprising of a notch filter-based feedforward controller and direct strain feedback controllers. We performed simulations and experiments and compared the proposed controller with individual control techniques to demonstrate its strengths for three-dimensional motion of a 2-link flexible arm. Lastly, compared the proposed controller with a similar conventional controller having fixed notch filters and their response to changing tip loading. The 2 DOF controller performed better than the conventional controller and the improvement is attributed to the adaptation algorithm and the correction of the error due to self-weight of the links. It was concluded that the proposed controller was effective for vibration control and trajectory tracking even in situation having varying loads.

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