Advances in Intelligent Systems Research, volume 134
2nd International Conference on Control, Automation, and Artificial Intelligence (CAAI 2017)

Adaptive Gain Tuning Feedback Control of a Flexible Manipulator

Minoru Sasaki*, Ryo Nakamura, Waweru Njeri, Kojiro Matsushita and Satoshi Ito
Department of Mechanical Engineering, Gifu University, 1-1 Yanagido, Gifu, 501-1193, Japan
*Corresponding author

***Abstract*—This paper presents vibration control of a flexible manipulator by an adaptive direct strain gain tuning feedback control. Adaptive feedback gain tuning is applied on the measured strain. These experiments compared the control performance of fixed and adaptive feedback gain control. Results show that adaptive feedback gain control has better performance in vibration control than the fixed feedback gain control.**

Keywords- adaptive gain tuning control; flexible manipulator; feedback control; vibration control; MapleSim™

I. INTRODUCTION

Currently, the high-speed operation and reduction of weight of machines and links are becoming prevalent. Along with this, the rigidity and damping of the machine are reduced, and vibration is a major problem. As the weight of the flexible manipulator also decreases, the reduction in rigidity due to the flexibility of the arm causes elastic vibration, making positioning control of the tip very difficult. Ra [1] theoretically and experimentally showed that direct feedback (DSFB) of strain is effective in a one-link flexible manipulator. Sasaki and colleagues [2] confirmed that vibration can be controlled by performing two degrees of freedom control of the inverse system and direct feedback control of distortion in a 2-link flexible manipulator. However, there is a possibility that the control performance may deteriorate with respect to changes in the model parameters such as attitude and loading. Besides adaptive control, other available methods of addressing this problems include feedforward control using adaptive notch filters and soft computing methods like neural networks. Therefore, in this study, we study the effectiveness of the vibration control on the tip load, the change of the operation speed, etc. by using the strain feedback control and adaptively varying the feedback gain.

II. CONSTRUCTION AND MODELING OF CONTROLLED OBJECTS

MapleSim™ is a modeling environment for integrated modeling and simulation of physical systems over single or multiple physical areas such as electric circuits, multi-bodies (mechanisms), 1-dimensional mechanical and heat transfer. In addition, it can work seamlessly with Maple to derive model equations, linear system analysis, optimization, etc. from pre-prepared templates. It can also be used to develop Simulink's S-function block. Furthermore, by using the automatic animation creation function of the multibody model, it is possible to visually confirm the analysis result of the multibody system. In this way, it is possible to perform the simulation at high speed and efficiently on the design target.

In the case of a rigid manipulator, the equation of motion is the equation of motion of joints and links, but in the case of a flexible manipulator it is also necessary to consider equations concerning the vibrations occurring in the arms. The tip position of the arm can be obtained by formulation of partial differential equations on position and time for elastically deforming, bending and twisting of elastically deformed, and finding a solution satisfying the boundary conditions. However, the differential equation becomes complicated and difficult to understand as the number of links increases, not to mention the possibility of making a mistake in calculation or derivation process when solving a solution, as is the case in research on most flexible manipulators. There are few studies that compare and study simulation results.

The target flexible manipulator is composed of two links and three joints, and a weight is attached to the distal end portion. Fig. 9 shows the configuration of the experimental apparatus. A strain gauge is affixed to the root of each link so that bending strain can be measured. The simulation model to be controlled is created using MapleSim™ and imported as a plant model to MATLAB.

The model of the machine area is shown in Fig. 1. FB_1 and FB_2 are flexible beams with elastic deformation and show flexible arms. R_1, R_2 and R_3 represent the respective rotary joints. RB represents the center of gravity of the rigid part, and RBF represents the rigid frame. This shows the necessary rigid parts for the configuration of the flexible manipulator used in this experiment. RB_4, RB_5, RB_6, RB_7 located one level below indicate the motor and balancer mounted horizontally to the ground. FAM_i ($i = 1, 2$) is a component that measures the force and rotational moment (three axes of x, y, z) applied to that part.

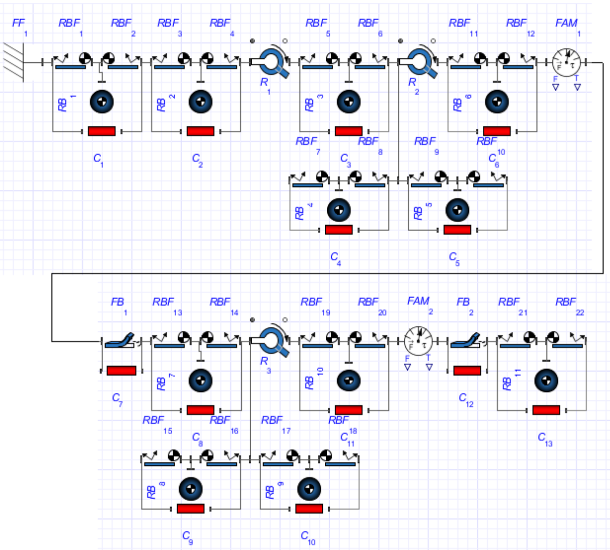

FIGURE I. MODEL OF MECHANICAL FACTOR.

TABLE I. MECHANICAL COMPONENT PARAMETER.

Figure	Type name	Parameter	Unit
	Fixed Frame(FF)		
	Revolute(R)	Damp constant[Kd]	N・m/rad
	Rigid Body Frame(RBF)	Offset[x y z]	m
	Rigid Body(RB)	Mass[M]	kg
		Moment of Inertia[I]	kg・m^2
	Force and moment(FAM)		
	Flexible Beam(FB)	Length[L]	M
		Cross section[A]	m^2
		Density[p]	g/c m^3
		Young's modulus[E]	Pa
		Modulus of Rigidity[G]	Pa
		Second moment[dly]	m^4
		Second moment[dlz]	m^4
	Cylindrical Geometry(C)		-

Since each motor is the same model, only one is explained. Fig. 2 shows the model of the electrical domain. SV_1, DC $Motor_1$, GND_1, PI_1 are servo amplifier, servo motor, Ground and PI controller respectively. LG is the Lossy Gear showing the reduction ratio of the harmonic drive. AS_1 represents an angle sensor, and the joint angle follows the target angle by angle feedback. RSS is an angular velocity sensor, which captures the angular velocity when operating by angular velocity feedback. G and Input represent signals from PC to MATLAB/Simulink via DSP board to flexible manipulator. $Pulse_1$ (In_1) becomes the target angle and is converted into the input signal by G. G is based on specifications found in [11]. Table 3.2 shows the parameters of electrical components.

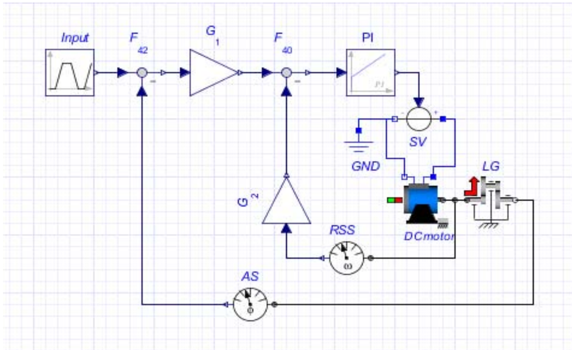

FIGURE II. MODEL OF ELECTRICAL FACTOR.

TABLE II. ELECTRICAL COMPONENT PARAMETER.

Figure	Type name	Parameter	Unit
	Trapezoid	Amplitude	-
		Rising	sec
		Width	sec
		Falling	sec
		Period	sec
		Offset	-
	Gain	Gain	-
	PI controller	Gain	
		Time constant	sec
	DC Permanent Magnet	Armature voltage	V
		Armature current	A
		Nominal speed	Rpm
		Resistance	Ω
		Inductance	H
		Moment of inertia	kg・m^2
	Lossy gear	ratio	-
		Loss table	-

Next, we compare the simulation result of the model created using MapleSim™ with the experimental result of the actual manipulator, and examine the validity of the created model. First, we check to what extent the model of MapleSim™ is close to actual machine. Simulation and experiment are carried out by the same experiment method, respectively, and the validity of the model is considered by comparing the strain caused by the elastic vibration, the resonance frequency, and the angular response of the joint angle.

The simulation time is 20 seconds, and the experimental method uses a step signal. As in Fig. 3 and Fig. 4, link 1 is tilted 20 degrees and link 2 is tilted 30 degrees from the vertical state. In this new position, the links are allowed 10 seconds to settle before returning to the original vertical state for 10 more seconds. Strain generated at that time is further analyzed using FFT. The physical parameter of MapleSim™ model is the same value as the actual machine. Simulation results and experimental results in this experimental method are shown in Fig. 3 to Fig. 8.

The damper value is varied as 100 [Nm / sec], 150 [Nm / sec], 200 [Nm / sec]. As a result, the power spectrum of Link 1 matched at 200 [Nm / sec], so we finished the simulation. Although the power spectrum of link 2 got bigger somewhat, since the power spectrum of link 1 separates from the value of actual machine even if trying to match here, the value of damper is decided at 200 [Nm / sec]. The results at that time are shown in Fig. 5 and 6.

From the simulation results, the initial distortion of link 1 from about 1 second to 3 seconds is very intense. The same result was obtained even if the damper value was changed. Comparing the distortion from 10 seconds to 20 seconds with the actual machine, it is clear that those associated with simulation are larger. This is so because not only the internal damping but also the friction damping due to the materials are in play, or that the damper cannot express the internal damping accurately. This distortion is reduced by making the magnitude of the angular velocity feedback gain of the electric element smaller than the present.

Currently, although it is possible to migrate MapleSim™ simulation data to MATLAB, it is not possible to transfer MATLAB data to MapleSim™. Therefore, setting of attenuation term of internal attenuation cannot be done in MapleSim™ and accurate identification cannot be performed. At the moment, there is only one way to change the value by fitting, so it cannot be completely modeled with MapleSim™. However, as shown in Fig. 7 and 8 the magnitude of the power spectrum and the resonance frequency can be adjusted to almost the same values as those of the actual machine. Therefore, it is possible to create a model that meets almost the characteristics of the actual machine other than the magnitude of the strain.

Next, this simulation model is imported to MATLAB as a plant model and simulation is performed.

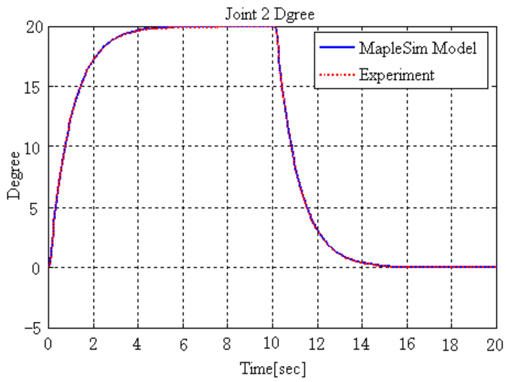

FIGURE III. ANGULAR RESPONSE OF JOINT2

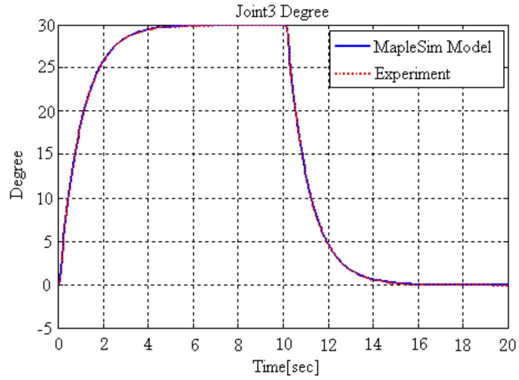

FIGURE IV. ANGULAR RESPONSE OF JOINT3.

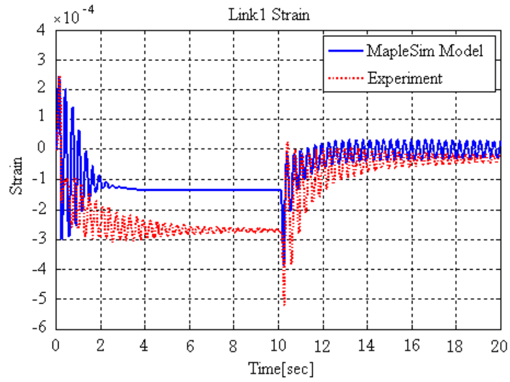

FIGURE V. TIME RESPONSE OF LINK1STRAIN.

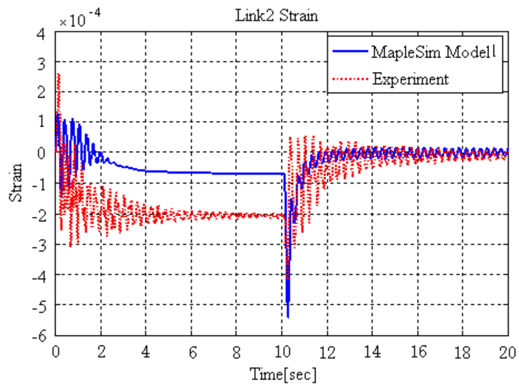

FIGURE VI. TIME RESPONSE OF LINK2 STRAIN.

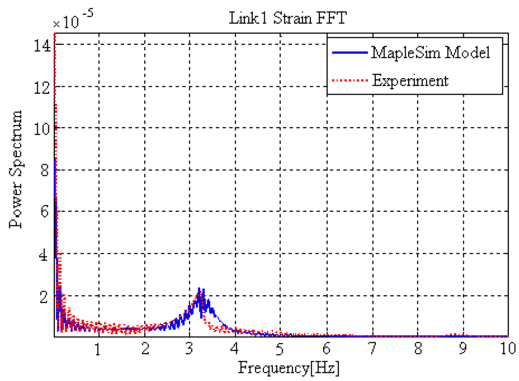

FIGURE VII. FFT ANALYSIS OF LINK1 STRAIN.

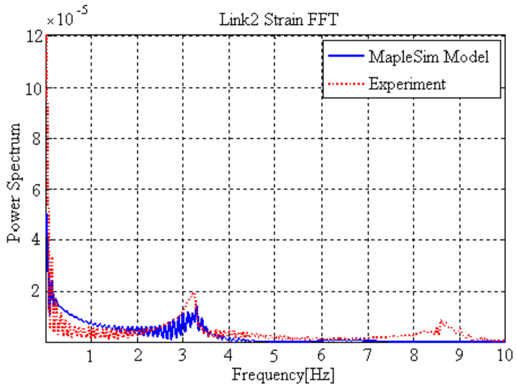

FIGURE VIII. FFT ANALYSIS OF LINK2 STRAIN.

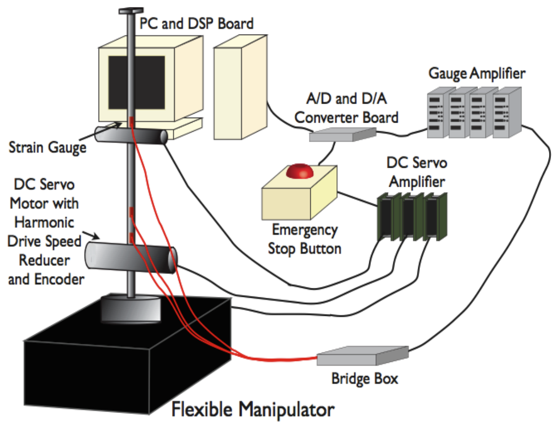

FIGURE IX. EXPERIMENTAL SYSTEM.

III. DESIGN OF CONTROL SYSTEM USING FEEDBACK ADAPTIVE LAW

In this section, we first describe the adaptive law of the feedback gain and design the control system. Next, we simulate the simulation model in the previous scenarios and verify the validity of the designed control system.

Theoretically and experimentally, it has been proved that DSFB (Direct Strain Feedback) is an effective direct feedback distortion technique for 1 link flexible robot arm [1]. In addition, Sasaki and colleagues show that direct feedback control of strain is effective for the same 2-link flexible manipulator that is the object of this time [7]. However, control performance may deteriorate due to parameter changes such as posture change and leading load change. To guarantee this, it is necessary to adaptively change the feedback gain. Therefore, the following integral gain adaptive law is used as a feedback gain tuning method.

$$\dot{k}(t) = \alpha[\varepsilon(t,0)]^2 \qquad (1)$$

$\alpha>0$ is an appropriate constant, $k(t)$ is the feedback gain, and $\varepsilon(t,0)$ represents the distortion. Letting $k(0)$ be the initial value $k(t)$ which is always positive. This equation continues to raise the feedback gain unless the vibration decays to zero. Therefore, since the feedback gain integrates the distortion signal, there is a steady offset in the strain sensor, or even if noise accompanies it, the vibration gradually increases after the vibration stops gradually, so finally the whole control system may diverge. Therefore, we introduce a normal number β to yield the improved gain adaptive law as follows.

$$\dot{k}(t) = \alpha[\varepsilon(t,0)]^2 - \beta\cdot k(t) \qquad (2)$$

As can be seen from this equation, as the value of strain converges, the gain decreases. Therefore, problems of stationary offset and noise can be solved. In steady state, the β is chosen such that feedback gain will not increase. The above equations (1) and (2) are basically considered to be further simplification of the Simplified Adaptive Control (SAC) described in references [12] and [13].

Fig. 10 shows a block diagram of the adaptive gain feedback controller used this time. Adaptive algorithm is the above integral gain adaptation law. As the distortion converges to 0, the gain also converges to 0. In addition, PI control is added to the controller for angle error to follow the target angle.

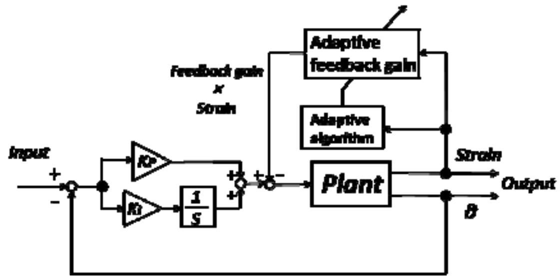

FIGURE X. BROCK DIAGRAM OF THE SYSTEM.

IV. CONTROL EXPERIMENT

The experiment involved moving link 1 at an angle of 10 degrees and link 2 at an of 30 degrees using a step signal for 10 seconds and restoring the links back to the vertical position for 10 more seconds. The end effector was loaded with a load of 100g. The results were compared with those obtained using a fixed feedback gain of 0.45 obtained by trial and error from previous work. Fig.11 and 12 shows angular response, time response of strain and gain.

As shown in Fig. 11 and 12, it is confirmed that the gain is adaptively changed and the vibration can be suppressed even at the high speed operation and the change of the tip load.

V. CONCLUSION

Vibration control of the flexible manipulator was performed using the feedback gain adaptive law, and the control performance with the case of the fixed gain was compared. It was confirmed that the gain was adaptively changed with respect to the change in the operation speed and the tip load, and vibration control was performed. Also, compared to the case of fixed gain, the adaptive gain can further suppress vibration. Therefore, the proposed control system is robust against fluctuation of parameters and is effective.

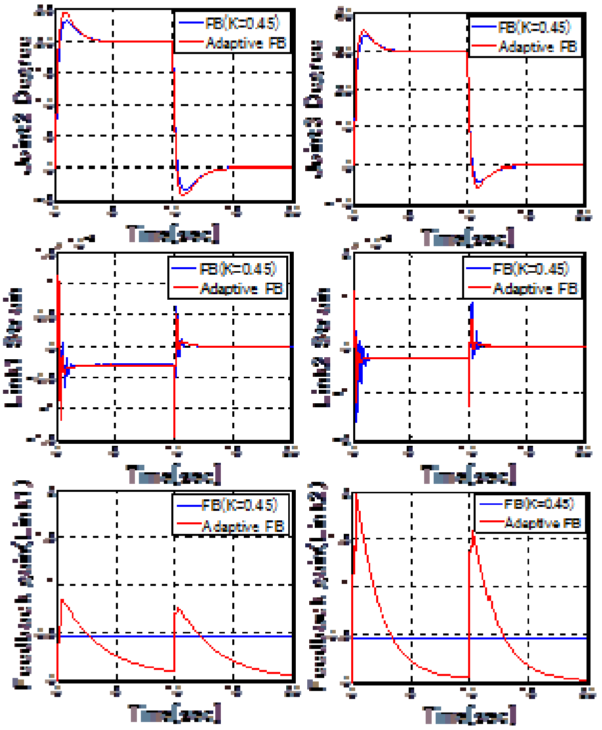

FIGURE XI. MOVEMENT SPEED IS TWICE.

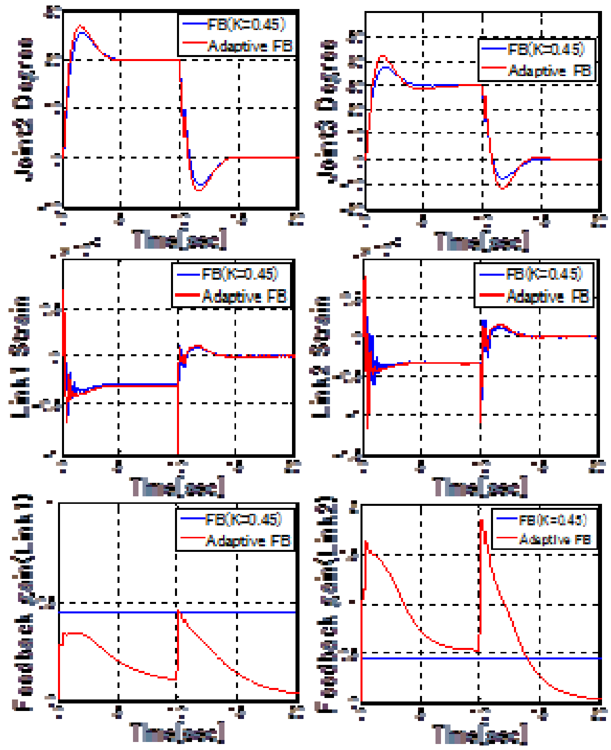

FIGURE XII. TIP WEIGHT +100[G].

REFERENCES

[1] Luo Zheng-Hua, “Theoretical and Experimental Study on Control of Flexible Robot Arms Using Direct Strain Feedback”, Transaction of Society of Instrument and Control Engineers, vol.28-1, pp. 67-76, 1992.

[2] Minoru Sasaki, Tomoya Wada, Kenji Funato, Satoshi Ito, “Two-degrees –of-freedom control of two-link flexible manipulator”, The 23rd Mechanical Dynamics Symposium on Electromagnetic Force, pp. 201-206, 2011- 05. Journal of Japan AEM Society, Vol. 12, No. 1, p. 1024, 2003.

[3] Luo Zheng-Hua, Aikoh Sakawa, “On expansion of DSEB's flexible multi-link arm to control, Proceedings of the 10th Japan Robotics Society”, pp. 1183-1186, 1992.

[4] Shunhiro Asai, Haruku Murasawa Minoru Sasaki, Satoshi Ito, “Flexible Manipulator Control Using Neural Network”, Journal of Japan AEM Journal 16 (3), pp. 214-220, 2008-09-10.

[5] Murota Takahito, Sho Kume, Minoru Sasaki, Satoshi Ito, “Control of Two Link Flexible Manipulator by Immune Adaptive Learning Neuro Controller”, Proceedings of Robotics · Mechatronics Conference 2010, "1A1-E17 (1)" - "1A1 - E 17 (4) ", 2010.

[6] Minoru Sasaki, Tomoya Wada, Kenji Funato, Satoshi Ito, “Two-degree-of-freedom control of a two-link flexible manipulator”, Proceedings of the 23rd Mechanical Dynamics Symposium on Electromagnetic Forces, pp. 201-206, 2011- 05.

[7] Minoru Sasaki, Hiroyuki Shimazaki, Satoshi Ito,“Modeling and control of a flexible manipulator using symbolic mathematical processing”, Proceedings of the Robotics and Mechatronics conference 2010, "1A1-E18 (4)", 2010.

[8] Bar-Kana I. and Kaufman, H., “Global stability and performance of a simplified adaptive algorithm”, Int. J. Control, 42-6 (1985), pp. 1491-1505.

[9] Shimizu Yoshimi, Minoru Sasaki, Tokuji Okada, “Hand Position Control of a Two-DOF Planar Flexible Manipulator Based on Extension of Dynamics”, Transactions of the Society of Instrument and Control Engineers, Vol.44 (5), pp. 389-395, 2008-05-31 .

[10] Suguru Kino, Toshiyuki Murakami, Kohei Ohnishi, “Vibration Suppression Control of Flexible Manipulators Using Acceleration Sensor”, IEICE Technical Committee materials. IIC, Industrial Measurement Control Study Group 1997 (40), pp. 67-72, 1997-10- 27.

[11] Atsushi Konno, Masaru Uchiyama, Yutaka Kitoh, Masato Murakami, “Vibration Suppression Control of 3D Flexible Manipulator by Acceleration Directive”, Journal of the Robotics Society of Japan, Vol.12 (7), pp. 88-96, 1994-11-15.

[12] Aikoh Sakawa, Fumitoshi Matsuno, Yoshiki Ohsawa, Toshihisa Abe, “Modeling of flexible manipulator with three degrees of freedom and vibration control using acceleration sensor”, Journal of the Robotics Society of Japan, Vol.6 (1), pp. 42-51, 1988.

[13] Kousaku Takahashi, Kazuhiro Shimizu, Shinichi Hirai, “Flexible Arm Tip Position Control by High-Speed Visual Feedback”, Proceedings of Society of Instrument and Control Engineers System Integration Division conference, pp.178 - 179, 2004.

[14] Hidefumi Wakamatsu, Kousaku Tkahashi and Shinichi Hirai, “Dynamic Modeling of Linear Object Deformation based on Differential Geometry Coordinates”, Proc. IEEE Int. Conf. On Robtics and Automation, pp. 1040-1045, Barcelona, April, 2005.

[15] Ryota Yamashina, Toshiki Hayashi, Tetsuro Yabuta, “Learning control of one degree of freedom flexible arms using a neural network”, Proceedings of the Robotics Society of Japan Conference (CD-ROM), 21st, 1C16, 2003.

[16] Jun Arakawa, Toshio Fukuda, “Flexible Robot Arm Control: 3rd Report, Optimal Vibration Suppression Control and Sensitivity Analysis of Three Degrees of Freedom System”, Transactions of Society of Mechanical Engineers of Japan Vol.56 (529), pp. 2446-2453, 1990-09-25.

[17] Jun Arakawa, Toshio Fukuda, “Control of Flexible Robot Arm: 4th Report, Control Experiment on Three Degrees of Freedom System”, Transactions of Society of Mechanical Engineers of Japan, Vol.57 (539), pp. 2313-2320, 1991-07-25 .

[18] Z. Mohamed, J. M. Martins, M. O. Tokhi, J. Sa da Costa, M. A. Botto, "Vibration control pf a very flexible manipulator system", Control Engineering Practice 13 (3), pp. 267-277, 2005-03.

[19] Jun Konno, Masaru Uchiyama, "Experiment on Variable Gain Vibration Suppression Control of Three Dimensional Flexible Manipulator", Transactions of Society of Mechanical Engineers of Japan, Vol.61 (591), pp. 4345-4350, 1995-11.

[20] Luo Zheng-Hua, Yamamoto Toru, "Strain Direct Feedback Control of Flexible Robot Arm by Gain Adaptation", Transactions of Society of Mechanical Engineers of Japan, Vol.59 (566), 1993-10.

[21] Kaneko Makoto, "Flexible Arm Feature", Journal of the Robotics Society of Japan, Vol.6, No. 5, pp. 415-466, 1988.

[22] Fumitoshi Matsuno, Special Issue on "Flexible Manipulator", Journal of the Robotics Society of Japan, Vol. 12, No. 2, pp. 169-230.1994.

APPENDIX

TABLE III. PARAMETERS OF FLEXIBLE MANIPULATOR.

Servo moter1 (Joint1)	Type	V850-012EL8(Sanyo Co.Ltd)	
	Rated armature voltage	80	V
	Rated armature current	7.6	A
	Rated power	500	W
	Rated spindle speed	2500	Rpm
	Rated torque	1.96	N・m
	Moment of inertia	0.60×10^{-3}	kg・m^2
	Mass	4.0	Kg
Servo moter2 (Joint2)	Type	T511-012EL8(Sanyo Co.Ltd)	
	Rated armature voltage	75	V
	Rated armature current	2	A
	Rated power	100	W
	Rated spindle speed	3000	Rpm
	Rated torque	0.34	N・m
	Moment of inertia	0.037×10^{-3}	kg・m^2
	Mass	0.95	Kg
Servo moter3 (Joint3)	Type	V404-012EL8(Sanyo Co.Ltd)	
	Rated armature voltage	72	V
	Rated armature current	1	A
	Rated power	40	W
	Rated spindle speed	3000	Rpm
	Rated torque	0.13	N・m
	Moment of inertia	0.0084×10^{-3}	kg・m^2
	Mass	0.4	Kg
encoder	Reduction ratio	1/100	P/R
	Spring constant	1.6×10^{4}	
Harmonic drive –joint1	Type	CSF-40-100-2A-R-SP	
	Reduction ratio	1/100	
	Spring constant	23	N・m/rad
	Moment of inertia	4.50×10^{-4}	kg・m^2
Harmonic drive –joint2	Type	CSF-17-100-2A-R-SP	
	Reduction ratio	1/100	
	Spring constant	1.6×10^{-4}	N・m/rad
	Moment of inertia	0.079×10^{-4}	kg・m^2
Harmonic drive –joint3	Type	CSF-14-100-2A-R-SP	
	Reduction ratio	1/100	
	Spring constant	0.71×10^{-4}	N・m/rad
	Moment of inertia	0.033×10^{-4}	kg・m^2
Link1	Material	Stainless steel	
	Length	0.44	M
	Radius	0.0005	M
Link2	Material	Aluminum	
	Length	0.44	M
	Radius	0.004	M
Strain Gauge	Type	KGF-2-120-C1-23L1M2R(Kyowa Electric Instrument Co. Ltd.)	