Application of SoildWorks® and LabVIEW®-based Simulation Technique to Gain Tuning of a 6-axis Articulated Robot

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Abstract - *Nowadays the applications of industrial robots are spreading to a great extent so that various demands for industrial manipulators are increasing. While industrial robots are coming into wide use, the control techniques of the robots are being developed as their performance is being enhanced. In this paper, for accurate gain tuning of the lab-manufactured 6-axis articulated robot (called as "RS2") with less noise, a program routine of DSA (Dynamic Signal Analyzer) for frequency response method will be programmed using LabVIEW®. Then robot transfer functions can be obtained experimentally using frequency response method with DSA program. Data resulted from the robot transfer functions are transformed into Bode plots, based on which an optimal gain tuning will be executed. Also another contribution of this paper is the proposal of SoildWorks® and LabVIEW®-based simulation technique for the gain tuning of a 6-axis articulated robot. To realize the simulation, the LabVIEW® program used in the experimental gain tuning is incorporated with SolidWorks®. The 3-D modeling of RS2 in SolidWorks® is loaded into LabVIEW®, instead of the physical robot of RS2. Moreover virtual 6 drivers are generated on the LabVIEW®, making the joint axes of 3-D model coincident with the ones of actual RS2. Then the LabVIEW® program used in the experimental gain tuning is loaded and connected to the virtual drivers. Finally SoildWorks® and LabVIEW®-based simulation is performed from axis 6 through 1 in the same manner as in the experimental gain tuning. The comparison of the simulation-based gain tuning with the experimental gain tuning can be shown to be almost the same as those of experimental gain tuning within 5% error bound. Based on the comparison, it can be suggested that the simulation-based technique of gain tuning can be applied to a 6-axis articulated robot through interlocking SolidWorks® and LabVIEW®, instead of the experimental gain tuning.*

Keywords: 6-axis Articulated Robot, SolidWorks®, LabVIEW®, Simulation-based Gain Tuning, Experimental Gain Tuning

1 Introduction

Nowadays the applications of industrial robots are spreading to a great extent so that various demands for industrial manipulators are increasing. While industrial robots are coming into wide use, the control techniques of the robots are being developed as their performance is being enhanced. For example, in order to reduce both manufacturing process and factory area, the transfer of car bodies are investigated by using 6-axis articulated robots with 6 Degrees of Freedom (DOF), instead of conveyor lines. This leads to small-scale assembly stations using 6-axis articulated robots with which can replace mass production using conveyors to meet the need of manufacturing various kinds of car in small lot. Usually 6-axis robots which are widely used for welding, spray painting and so on, have payloads from 10 kg to 300kg. In order to enhance both the control accuracy and the reliability of 6-axis articulated robot with payload of 500 kg over, the synthetic technology including design, prototyping and gain tuning should be accompanied.

As one of previous studies, Kim *et al*. [1] has presented "Prototyping and Visualization Techniques of 3-axis SCARA Robot Using DOE (Design Of Experiment) and LabVIEW®." In this paper, gain tuning using LabVIEW® has been performed for a 3-axis SCARA robot. Ahn *et al*. [2] has investigated "On Design, Prototype and Gain Optimization for Heavy Duty Handling Articulated Manipulator (HDHAM) with 6 DOF." This paper has dealt with the design of a 6-axis articulated (1/4-size lab-manufactured model for an original heavy duty handling robot [2]) robot (hereinafter called as "RS2" as shown in Fig. 1) as well as its gain tuning. But an older version of LabVIEW® programming has been used so that graphical data has been shown to be with much noise.

In this paper, for *accurate* gain tuning of RS2 with *less noise*, a program routine of DSA (Dynamic Signal Analyzer) for frequency response method will be programmed using LabVIEW®. Then robot transfer functions can be obtained experimentally using frequency response method with DSA program. Data resulted from the robot transfer functions are transformed into Bode plots, based on which an optimal gain tuning will be executed. Also another contribution of this paper is that simulation will be conducted by interlocking SolidWorks® (6-axis robot modeling) with LabVIEW®, in order to verify the experimental results of gain tuning by being compared with the simulation results of gain tuning.

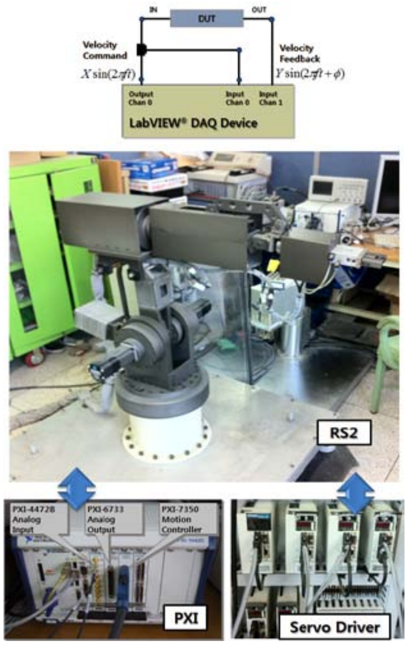


Fig.1 Configuration of RS2(6-axis articulated robot)

2 LabVIEW®-based Experimental Gain Tuning

For the higher control system of RS2, the Motion Controller of NI PXI-7350 equipment (see Fig. 1) has been used with the universal control and measurement software of LabVIEW®. Figure 2 represents a program controlling the axis of a robot. Here a value of motor encoder is received as an output robot signal for the applied voltage of an input value so that the robot signal is plotted by LabVIEW®. Upon the execution of DSA program, a robot transfer function can be obtained as a plot as shown in Fig. 3.

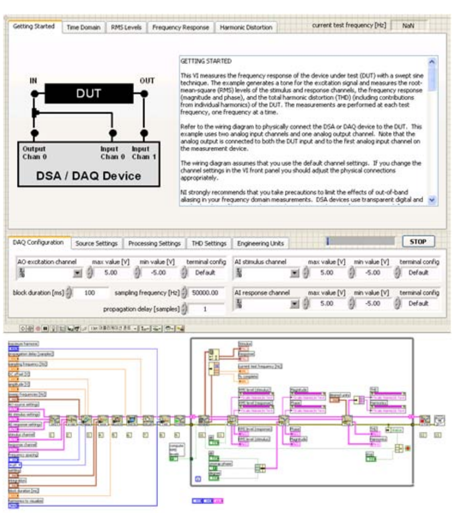


Fig. 2 LabVIEW® programing

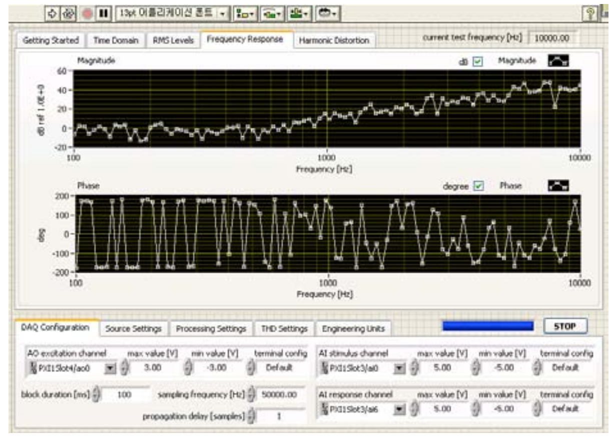


Fig. 3 Robot signal response

The faster joint velocity in robot control, the more deviation from the designated path of end-effector. In turn, this results in the vibration of robot mechanism, depending on changes in joint speed. To cope with this problem, the robot's response can be greatly improved by setting PID gain values so as to be suited to robot characteristics.

For tuning of a proportional gain (K_v), the LabVIEW® DAQ (Data AcQuisition) equipment is connected with the 6-th (*i.e.*, the last) axis motor driver nearby the end-effector of robot. First, an arbitrary value of proportional gain has been set for the motor driver. Then an appropriate value of the sine wave amplitude X is selected according to ref. [3]. At this time, an integration effect has been eliminated by setting the integration time constant at 1000 [4]. Finally frequency response test is conducted as follows: A sine wave of 0.5 V_{rms} (root mean square of voltage) from 2Hz through 500Hz is applied to the speed command pin of a servo driver as a source wave form from PXI-6733 of LabVIEW® DAQ; a Bode plot ($G_c(s)$) of a closed loop can be extracted using the programmed DSA; the closed loop transfer function $G_0(s)$ can be obtained by using the open loop transfer function $G_c(s)$ in Eq. (1).

$$G_o(s) = \frac{G_c(s)}{1 - G_C(s)} \quad (1)$$

Then the open loop transfer function, $G_0(s)$, can be converted to the Bode plot by using LabVIEW® DAQ.

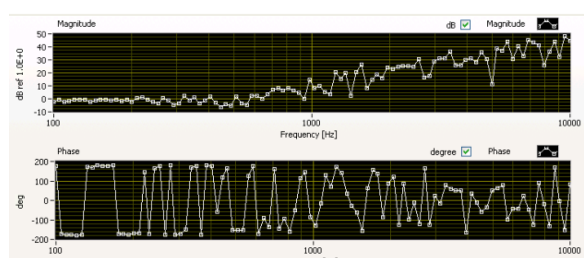


Fig. 4 Bode plot of open loop transfer function

In Fig. 4, the extracted Bode plot of open loop transfer function leads to the gain margin of -15dB and the phase margin of -91.3 degree. In general, according to Nyquist stability[5], gain margin should be -6dB ~ -20dB, while phase margin should be larger than 45 degree. In this case, if we put the gain margin to be -6dB, we can obtain the new proportional gain of velocity control loop K'_v as follows

$$
\begin{aligned}
&20\log x = (\text{-6dB})\text{-}(\text{-15dB}) \\
&x = 10^{\frac{-6+15}{20}} \\
&\therefore K'_v = 2.8\times 50 = 141
\end{aligned}
\tag{2}
$$

Figure 5 shows a newly extracted Bode plot of open loop transfer function, $G_0(s)$, when the new proportional gain of velocity control loop, K'_v = 141 has been applied to the motor driver.

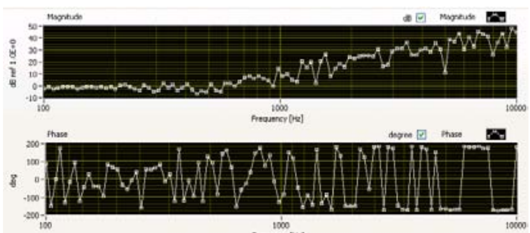


Fig. 5 Bode plot of open loop transfer function

The integral gain of velocity control loop, K_i, can be obtained from an integration time constant. When the integration time constant is applied to an integrator, it can be determined as the reciprocal of frequency whose is 10 times of gain crossover frequency. As shown in Fig. 6, the gain crossover frequency is 71.315Hz.

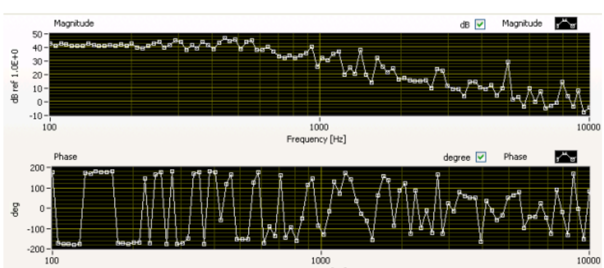


Fig. 6 New Bode plot of open loop (K'_v =141)

Thus the integration time constant can be obtained as 14ms, *i.e.*, the reciprocal of 10 times of gain crossover frequency. Now the integral gain K_i can be resulted from Eq. (3) as follows:

$$K_i = K_v / T_i \tag{3}$$

which leads to K_i= 1014.

The proportional gain of position control loop, K_p, can be obtained by

$$K_p = \frac{\pi f_c}{2\varsigma^2} \tag{4}$$

where ζ is the damping ratio; f_c is cut-off frequency. The value of ζ is given experimentally by 0.707 in this paper. It can be noticed that the transfer function of velocity control loop has been used for figuring out the closed loop bandwidth (*i.e.*, cut-off frequency) at the frequency whose magnitude in dB amounts to -3dB as shown in the Bode plot of Fig. 7. In this figure, f_c can be figured out as 220Hz. Therefore Eq. (4) gives K_p = 700 for the 6th joint servo.

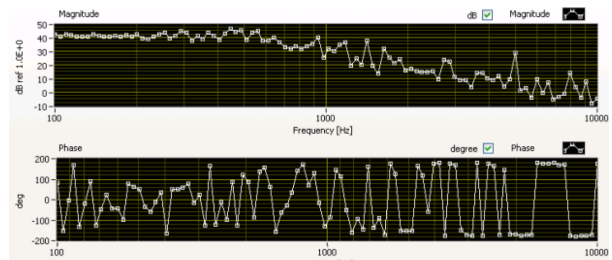
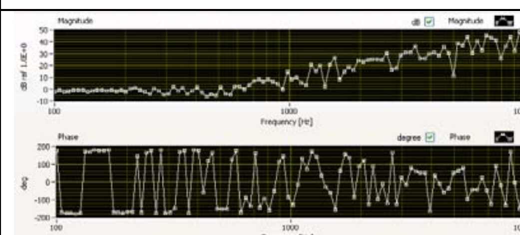
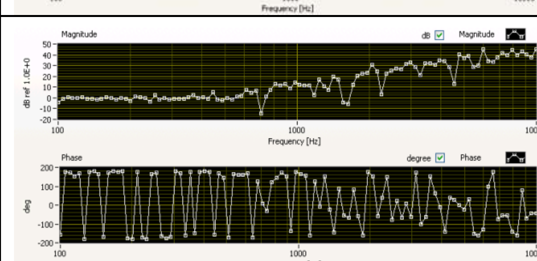


Fig. 7 Bode plot of close loop apply K'_v

Through the process mentioned above, we have performed the gain optimization for the remained 5 axes joint servo controllers of 6-axis articulated robot. Consequently, Fig. 8 and Table 1 show the experimental results of the optimized gains for all 6 joint servo controllers.

Axis	Bode plot of close loop apply K'_v
1	
2	

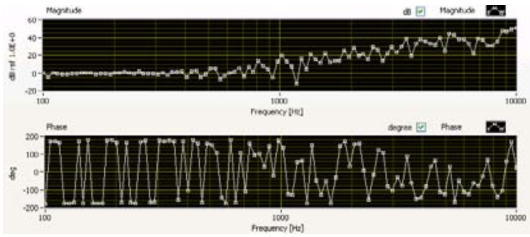
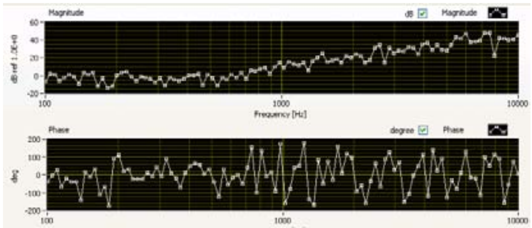
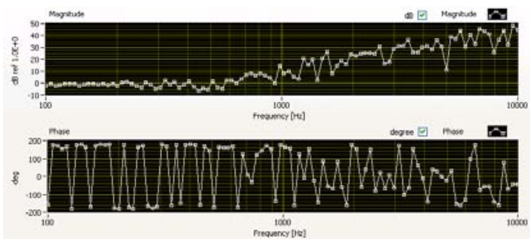
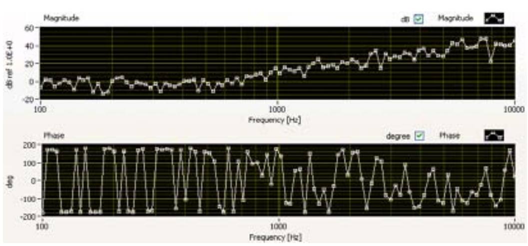
3	
4	
5	
6	

Fig. 8 Gain optimize results

Table. 1 Optimized Gains

	1Axis	2Axis	3Axis	4Axis	5Axis	6Axis
K_v	212	144	182	377	225	141
K_i	315	884	683	605	315	1014
K_p	465	562	561	53	47	700

3 Application of SoildWorks® and LabVIEW®-based Simulation Technique to Gain Tuning

To prove the test results of experimental gain tuning, a simulation technique using Solidworks® interlocked with LabVIEW® is proposed. For the simulation, 3 dimensional (or 3-D) modeling was first conducted by using the dimensions, material kinds and servo motor specifications of RS2 with SolidWorks®. Figure 9 represents the 3-D modeling of SolidWorks® for RS2. In the SolidWorks® 3-D modeling, each joint axis moved by RS2 was set from axis 1 through 6 as shown in Fig. 10.

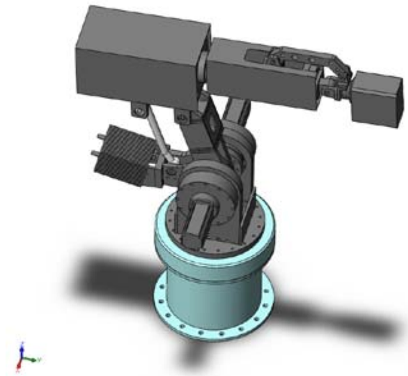
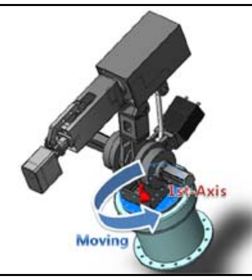
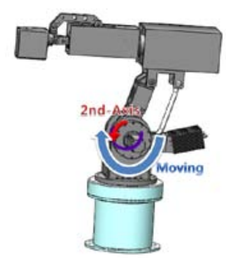
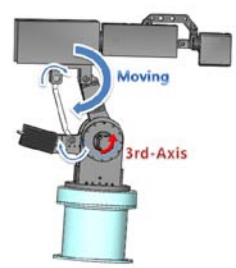


Fig. 9 SolidWorks® 3-D modeling of RS2 Using SolidWorks®

Axis	Set axis
1	
2	
3	
4	

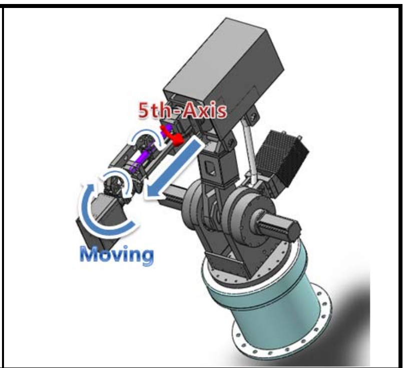
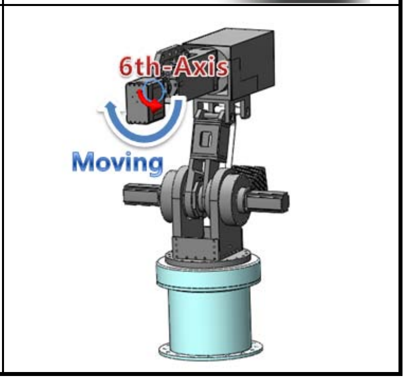
5	
6	

Fig. 10 Set axes of 6-axis articulated robot

To realize the simulation, the LabVIEW® program used in the previous section of experimental gain tuning was incorporated with SolidWorks®. The 3-D modeling of RS2 in SolidWorks® was loaded into LabVIEW®, instead of the physical robot of RS2. Moreover virtual 6 drivers were generated on the LabVIEW®, making the joint axes of 3-D model coincident with the ones of actual RS2. Then the LabVIEW® program used in the experimental gain tuning was loaded and connected to the virtual drivers. Finally SoildWorks® and LabVIEW®-based simulation is performed as shown in the interlocking program configuration of Fig. 11. More specific, the simulation has been executed from axis 6 through 1 in the same manner as in the experimental gain tuning. Figure 12 gives the simulation result of proportional gain of velocity control loop, K'_v.

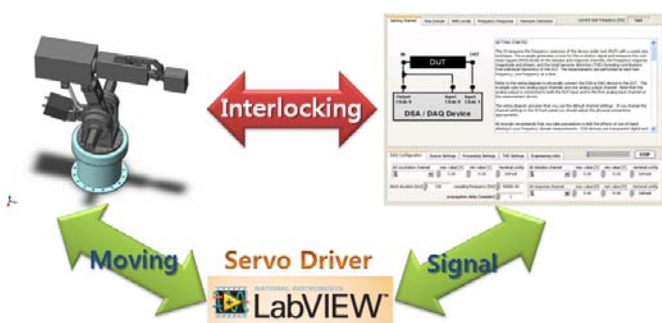


Fig. 11 Interlocking program configuration

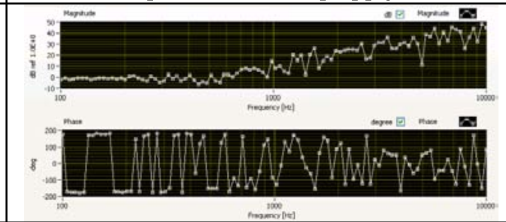
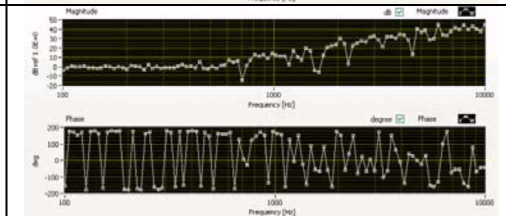
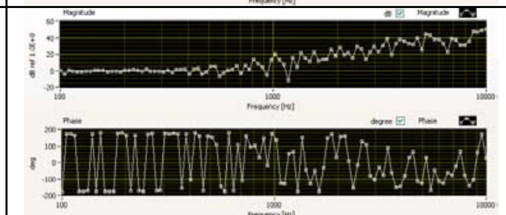
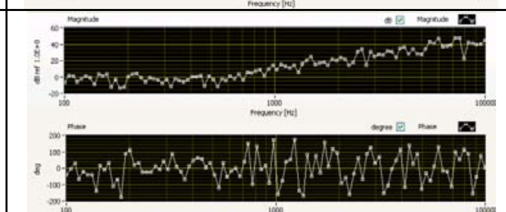
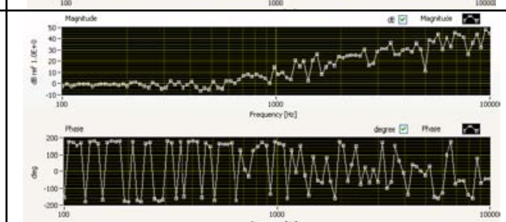
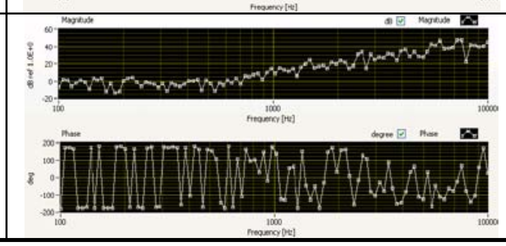
Axis	Bode plot of close loop apply K'_v
1	
2	
3	
4	
5	
6	

Fig. 12 Gain tuning results of simulation

Based on the above data, the optimal gain values of K_v, K_i and K_p are calculated for each axis, using Eqs. (1) to (4) in the same way as in the experimental gain test. Table 2 below shows the simulation results of optimal gains for each axis.

Table. 2 Optimized Gains of Simulation

	1Axis	2Axis	3Axis	4Axis	5Axis	6Axis
K_v	210	151	180	364	239	139
K_i	309	879	679	615	327	1007
K_p	471	580	568	57	49	700

Table 3 illustrates the comparison of these simulation-based gain tuning with the previous experimental gain tuning. It can be noticed from Table 3 that the values of experimental gain tuning are almost the same as those of experimental gain tuning within 5% error bound. This verifies the effectiveness of SoildWorks® and LabVIEW®-based simulation technique for the gain tuning of a 6-axis articulated Robot. Moreover this simulation-based gain tuning is also compared with the experimental gain tuning in terms of velocity response at an applied velocity of $0.5V_{rms}$. Figure 13 shows both response levels for each axis. In Fig. 13, the experimental gain tuning is a little slower than the simulation-based gain tuning. Here the red line corresponds to a response velocity of the experimental gain tuning while the blue line corresponds to the simulation-based gain tuning.

Table. 3 Comparison of Experimental and Simulation-based Gain Tuning

Axis	Experimental			Simulation		
	K_v	K_i	K_p	K_v	K_i	K_p
1	212	315	465	210	309	471
2	144	884	562	151	879	580
3	182	683	561	180	679	568
4	377	605	53	364	615	57
5	225	315	47	239	327	49
6	141	1014	700	139	1007	700

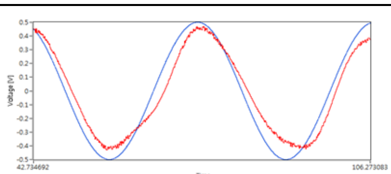
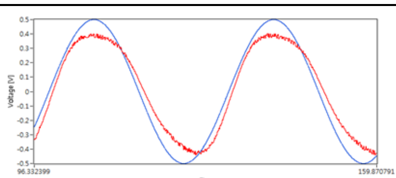
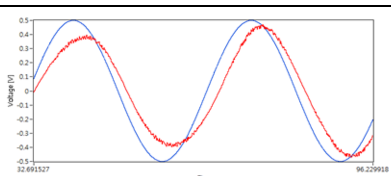
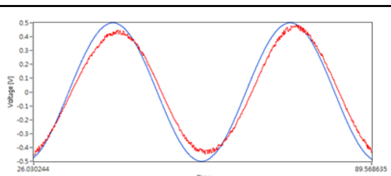
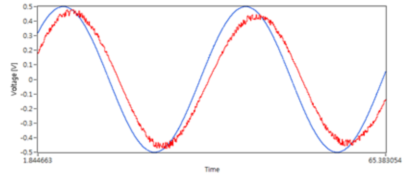
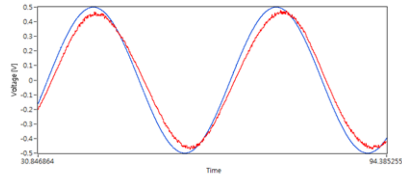
Axis	Response test
1	
2	
3	
4	
5	
6	

Fig. 13 Response test of experimental and simulation

4 Conclusion

In this paper, for accurate gain tuning of the lab-manufactured 6-axis articulated robot (called as "RS2") with less noise, an experimental gain tuning technique has been presented based on ref. [2]. The major contribution of this paper is the proposal of SoildWorks® and LabVIEW®-based simulation technique for the gain tuning of a 6-axis articulated robot. To realize the simulation, the LabVIEW® program used in the experimental gain tuning has been incorporated with SolidWorks®. The 3-D modeling of RS2 in SolidWorks® is loaded into LabVIEW®, instead of the physical robot of RS2. Moreover virtual 6 drivers are generated on the LabVIEW®, making the joint axes of 3-D model coincident with the ones of actual RS2. Then the LabVIEW® program used in the experimental gain tuning is loaded and connected to the virtual drivers. Finally SoildWorks® and LabVIEW®-based simulation was performed from axis 6 through 1 in the same manner as in the experimental gain tuning. The comparison of the simulation-based gain tuning with the experimental gain tuning was shown to be almost the same as those of experimental gain tuning within 5% error bound. Based on this comparisons, it can be concluded that the simulation-based technique of gain tuning can be applied to a 6-axis articulated robot through interlocking SolidWorks® and LabVIEW®, in lieu of the experimental gain tuning.

5 Acknowledgement

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6 References

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