Application of Gain Scheduling Technique to a 6-Axis Articulated Robot using LabVIEW®

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Abstract— **Recently the high performance of industrial robots has been especially required according to the increase of demand and application range of industrial robots. Industrial robots performing repetitive motions do not have much trouble in the short term. Nonetheless, most robots are designed with a view to long-term operation, which is why it is very important to find optimal gain values for robots. In this paper, for accurate gain tuning of a (lab-manufactured) 6-axis articulated industrial robot (hereinafter called "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. Of course, gain tuning can enhance the response quality of output signal for a given input signal during the real-time control of robot. To cope with gain tuning for each work domain of the robot, an optimal gain value for each point will be found. Finally the tuned gains can be imported to each joint controller of RS2 in order to dynamically control the robot, which is just "gain scheduling." The domain-specific gain scheduling suggested by this paper can improve robots' tacking to input commands and thus the stability of kinematic parts.**

Keywords— **Gain tuning, Gain scheduling, RS2, LabVIEW® DAQmx, Articulated robot, Dynamic Signal Analyzer, Frequency response, Gravity-against motion, Zero position**

I. Introduction

Traditionally robots have been used in various industry fields such as handling or welding mechanical parts. But, Recently the high performance of industrial robots has been especially required according to the increase of demand and application range of industrial robots. Specially, unlike Cartesian Robot and SCARA (Selective Compliance Assembly Robot Arm) which have wide application in assembling electronic parts, the dynamic performance of a 6-axes articulated robot is greatly changed according to the position and orientation of the robot. This means that the gain tuning of the robot's servo controllers should be tuned considering the dynamic characteristics of robot mechanism. It is well known that gain tuning can reduce the vibration phenomena of a robot so as to improve the performance of positional control.

As one of previous studies, Jung *et al.* [1] has presented "Application of SoildWorks® and LabVIEW®-based Simulation Technique to Gain Tuning of a 6-axis Articulated Robot." in CSC 2012. In this paper, gain tuning using LabVIEW® has been performed for a 6-axis articulated *(lab-manufactured)* robot (*called as 'RS2', see Fig. 1*). Especially simulation was 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. In contrast to ref. [1], for accurate gain tuning of RS2 with less noise, we will utilize a program routine of DSA (Dynamic Signal Analyzer) [2] 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 gain tuning can be performed according to the position of robot's end-effector in workspace, and then optimally tuned values of gain can be stored in an array form in the LabVIEW® program. Finally the tuned gains can be imported to each joint controller of RS2 in order to dynamically control the robot, which is just "*gain scheduling*."

Fig. 1 6-axis articulated robot (RS2)

II. LabVIEW®-based Experimental Gain Tuning

A. *Gain Tuning of Zero Position*

As mentioned above, Fig. 1 illustrates the robot used in this paper, *i.e.*, RS2, which is a 6-axis articulated robot designed and developed in our laboratory. RS2 is a miniaturized version of a high-rigidity, high-torque and heavy-duty robot, which has a 600-kg load capacity and is 4 times the size of the established prototype of RS2. In this paper, to measure the frequency response of the 6-axis articulated robot, DSA (Dynamic Signal Analyzer) is implemented using LabVIEW® Sound and Vibration Toolkit. Also, the frequency response is measured to convert the robot's transfer function into a Bode Plot prior to the gain tuning. To receive the robot's frequency response, NI's LabVIEW® DAQmx is used.[3]. For the purpose of finding out *domain-specific* optimal gain values, we will carry out the gain tuning for each axis in the zero (or home) position of RS2 in each work domain of workspace.

For the higher control system of RS2, the Motion Controller of NI PXI-7350 equipment has been used with the universal control and measurement software of LabVIEW®. Figure 2 represents a program controlling the axis of RS2. 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.

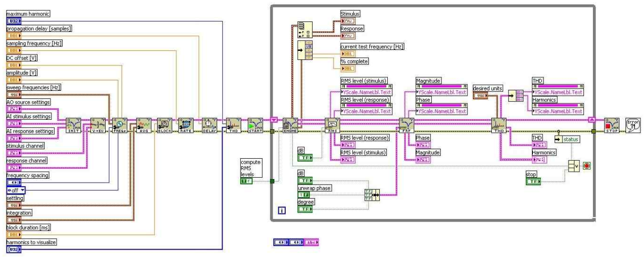


Fig. 2 DSA Programming by using LabVIEW®

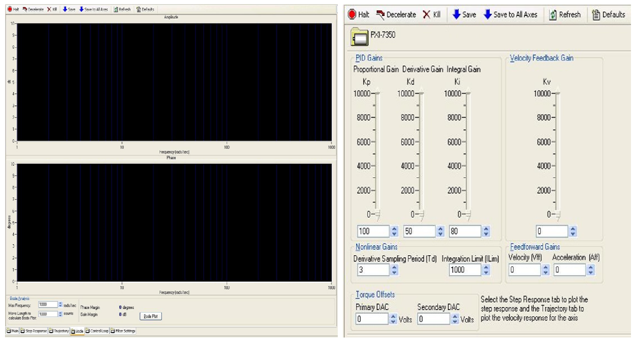
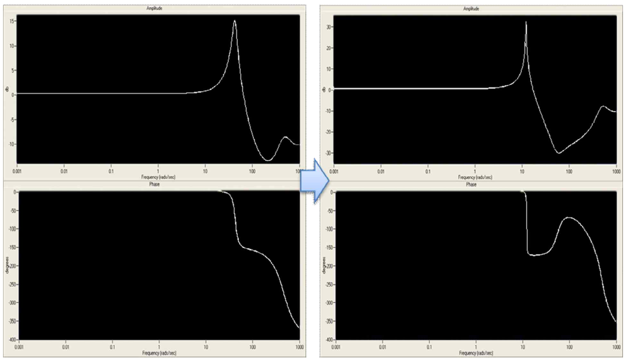


Fig. 3 Bode plot of DAQmx program

For the tuning of a gain value, the LabVIEW® DAQ (Data AcQuisition) equipment is connected with the 6-th (*i.e.*, the last) axis motor driver nearby the end-effector of RS2. 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. [4]. At this time, an integration effect has been eliminated by setting the integration time constant at 1000.[5]. 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 $G_c(s)$. Then, the closed loop transfer function found as such was used for the gain tuning. For theories relevant to gain tuning, this paper has been based on Jung *et al.*[1]. Equation (1) denotes the relationship between the closed loop transfer function and the open loop transfer function. Figure 4 shows the closed and open loop bode plots for the 6-th axis.

$$G_0(s) = \frac{G_c(s)}{1 - G_c(s)} \tag{1}$$

Fig. 4 Bode plot of open loop & closed loop transfer function of the 6-th axis before tuning



In general, according to Nyquist stability [6], gain margin should be -6dB ~ -20dB, while phase margin should be larger than 45 degree. The extracted Bode plot of open loop leads to the gain margin of -14.4dB and the phase margin of -52.3 degree. Based on Eq. (2), we can obtain the new proportional gain of velocity control loop, K_v=132.

$$\begin{aligned} 20\log x &= (-6dB) - (\text{Gain Margin}) \\ x &= 10^{\frac{-6-(\text{Gain Margin})}{20}} \\ K_v' &= xK_v \end{aligned} \tag{2}$$

The integral gain (K_i) in the speed control mode is determined by the integral time constant (T_i). For the integral time constant (T_i), the tuning starts on the 6-th axis at the end. Finally, the K_i can be found by Eq. (3). The integral time constant, T_i, is the point equivalent to 10 times the applied frequency (Hz) of the phase margin, so that no phase variation occurs when the proportional gain value (K_v) of the speed loop on each axis of the robot is applied. For the proportional gain (K_p) of the position control loop, the tuning starts on the 6-th axis at the end. The frequency, f_c, is measured at the point of -3dB of the resonance point on the closed loop bode plot. For ζ, the K_p value was found by substituting the value 0.707, which was calculated with an experimental method for general industrial robots, in Eq. (4). Figure 5 shows the closed and open loop bode plots for each axis found with the aforementioned method. These were used to find K_v, K_i, K_p and T_i values as in Table I.

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

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

$$f = \frac{\omega}{2\pi} = \frac{f_c}{2\zeta} \tag{5}$$

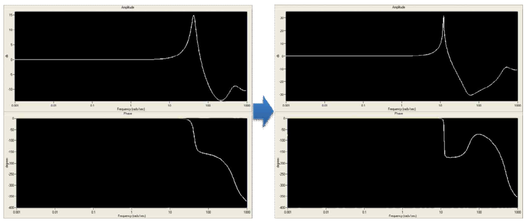
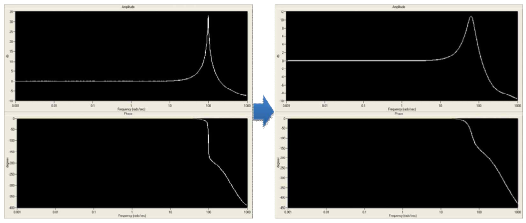
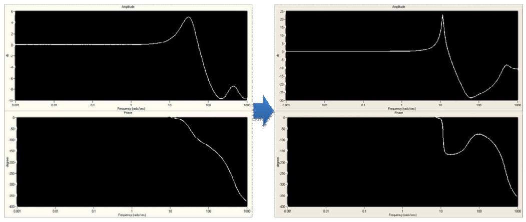
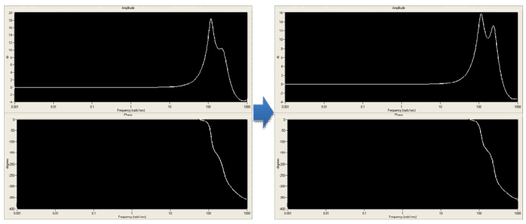
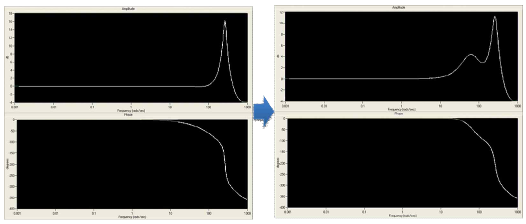
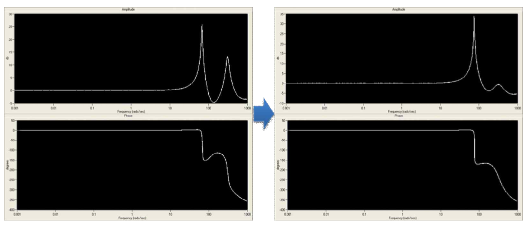
Axis	Bode plot
1st	
2nd	
3rd	
4th	
5th	
6th	

Fig. 5 Bode plot of open loop & closed loop transfer functions of the 6- axis before tuning

TABLE. II THE RESULT OF GAIN TUNING FOR EACH JOINT

Axis	State	1^{st}	2^{nd}	3^{rd}	4^{th}	5^{th}	6^{th}
K_v	before	50	50	50	50	50	50
	after	64	82	141	77	89	132
K_i	before	100	100	100	100	100	100
	after	256	713	1698	576	685	763
K_p	before	20	20	20	20	20	20
	after	125	273	379	236	242	182
T_i	after	0.252	0.115	0.083	0.133	0.130	0.172

B. *Response*

To verify the gain-tuning results, the frequency response technique was used as in Fig. 6. The frequency response technique is a practical and effective method for system analysis and design. The frequency response of system is defined as the normal response of system to trigonometric function input signals with varying frequencies such as $A\ \sin(\omega t)$. Figure 7 shows the stimulus command level, the response level at the optimized gains and the response level at the empirical gain settings simultaneously for each axis. As a result of Fig. 7, the response level at the optimized gains is much closer to the stimulus command level (red color line), compared with the response level at the empirical gain settings (blue color line). This means that the responses after tuning can be verified in line with the extent to which the output curve matches the sine wave input curve without disturbance.

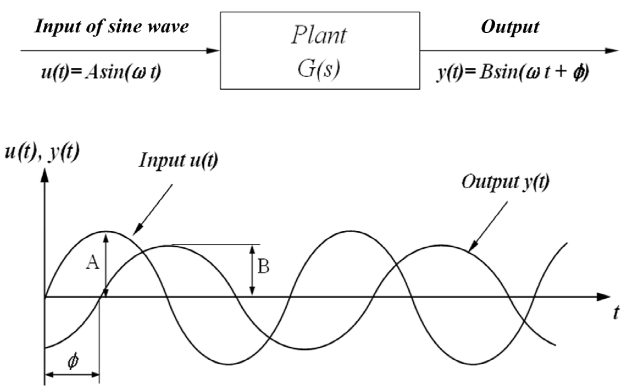


Fig. 6 Frequency response method

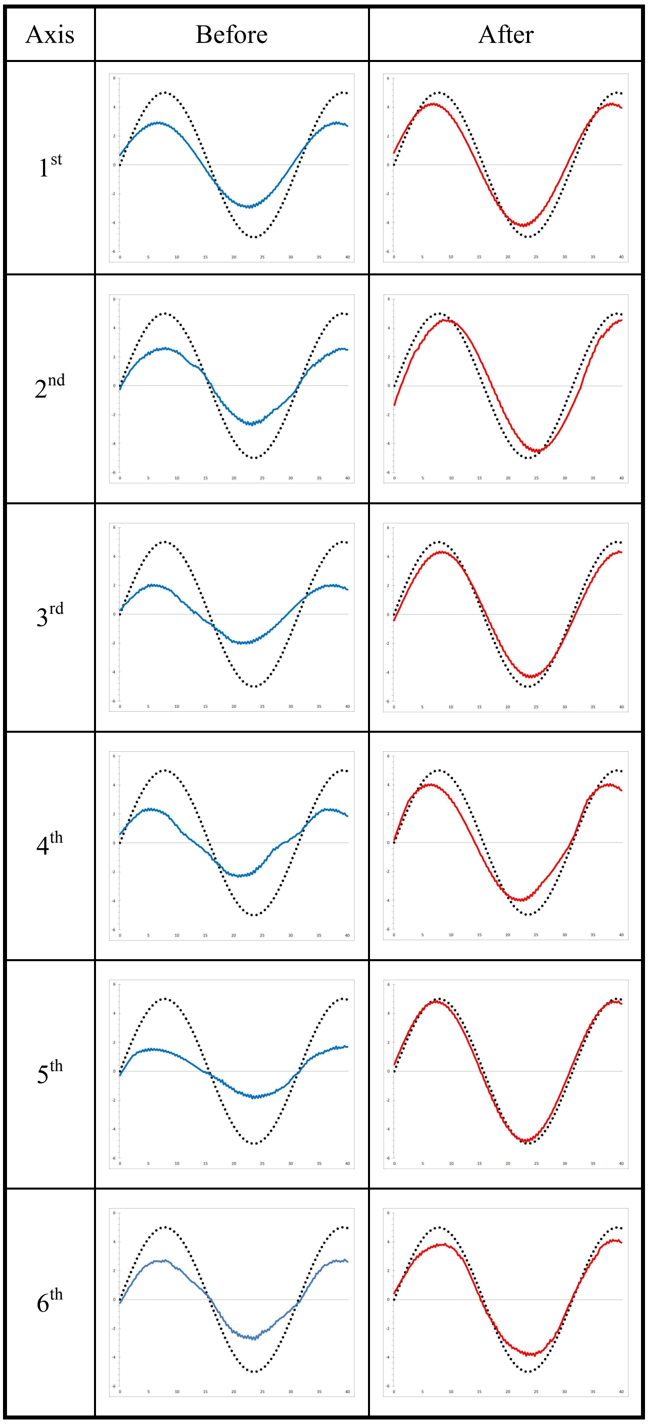


Fig. 7 Result of frequency response

III. GAIN SCHEDULING

So far, we have performed the gain tuning for the zero position prior to robot operation and verified the improvement of responsiveness. Now, this section deals with examining whether the gain values from the initial tuning carry out the optimal motion in other movements and to elicit the optimal gain values for each domain. Then this leads to gain scheduling.

As shown in Fig. 8, the gain values initially found at A and B points where RS2 has moved in the direction of gravity in the zero position (called as "coordinated gravity-against motion") are applied to verify the responsiveness. *A* and *B* points are the positions corresponding to the second-axis joint rotating at an angle of 30° and 60° , respectively, in the zero position. Since mainly the second and third axes move for the operation of RS2 in the direction of gravity, we focus on the verification of responsiveness on those axes. [7]

Fig. 8 Coordinated gravity-against motion of RS2

As shown in Fig. 9, in the experiment, the response signals (blue solid lines) of gain tuning performed in the zero position did not affect the improvement of responsiveness following the command movements signal (black dotted line) at A and B points. This means that new gain values are needed after RS2's movements at other points (or positions in the direction of gravity) except the zero position. Thus we have performed new gain tuning for two work domains according to the robot's movements. The gain tuning has been done in the same way as in the aforementioned zero position. Only the actually moving second and third axes have gone through the gain tuning and the resultant gain values are compared as in Table IIIIV. The resultant tracking response (blue solid line) to the input command signal (black dotted line) in Fig. 10 is shown to be explicitly good, compared with Fig. 9. Based on the experimental findings above, this study has conducted a LabVIEW® programming to apply the new gain values to two motions as in Fig. 11. An optimal motion has been obtained by replacing the gain values in the designated position where the experiment was performed.

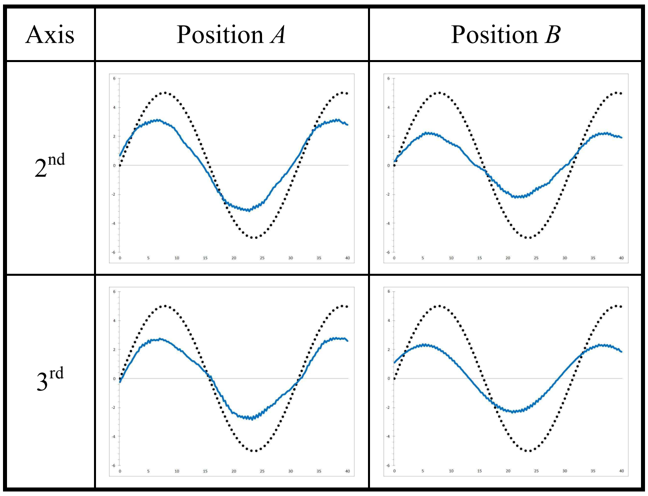


Fig. 9 Result of tracking (frequency) response level at zero position

TABLE VVI RESULT OF GAIN TUNING AT EACH POSITION

Axis	Zero position		A position		B position	
	2nd	3rd	2nd	3rd	2nd	3rd
K_v	82	141	89	223	69	182
K_i	713	1698	824	2468	589	1799
K_p	273	379	291	347	268	311
T_i	0.115	0.083	0.108	0.090	0.117	0.101

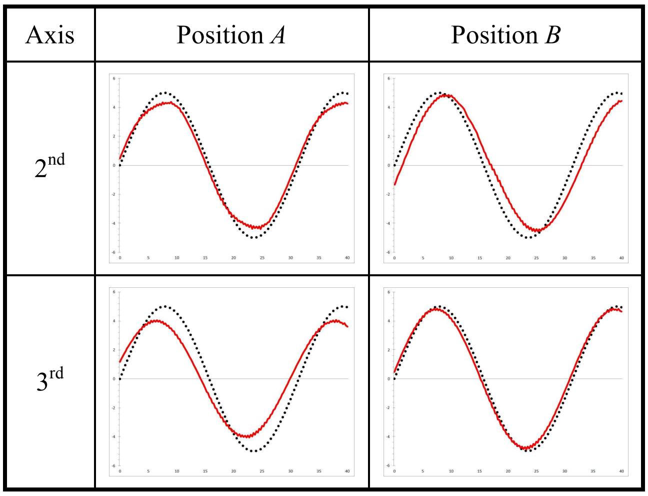


Fig. 10 Result of frequency response level for the 2nd and 3rd axes

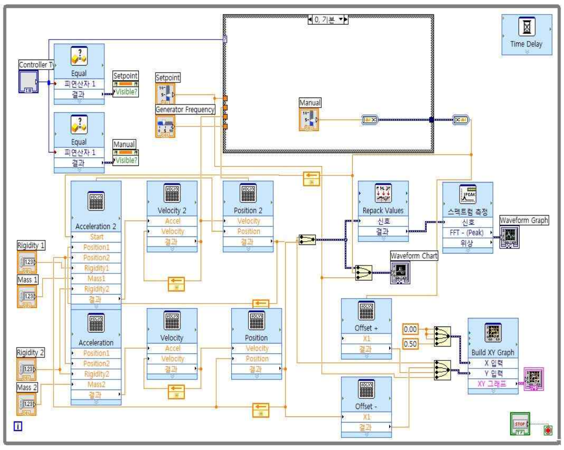


Fig. 11 LabVIEW® programming to apply the new gain values to two motions

IV. Conclusion

Industrial robots performing repetitive motions do not have much trouble in the short term. Nonetheless, most robots are designed with a view to long-term operation, which is why it is very important to find optimal gain values for robots. This paper aims at improving the responsiveness with gain tuning for each servo motor of the robot by implementing a Dynamic Signal Analyzer using LabVIEW® and measuring the frequency response. First of all, LabVIEW® was used for gain tuning in the zero position of the 6-axis vertical articulated (*lab-manufactured*) robot (*called as 'RS2'*). Then, the proportional gain (K_v) in the speed control loop and the proportional gain (K_p) of the position control loop were induced. Finally, the input trigonometric functions of varying frequencies were compared with the output values to verify the gain tuning. To sum up, the responsiveness following the gain tuning in the zero position was found to have improved. Also, with new gain tuning for each work domain of the robot, an optimal gain value for each point was found. The domain-specific gain scheduling suggested by this paper can improve robots' tacking to input commands and thus the stability of kinematic parts. The findings of this study suggest the viability of optimal control of robots via gain scheduling by applying the programming that finds gain values suitable for each moving point and then substitutes them sequentially in robots undertaking repetitive works.

V. Acknowledgement

This research was supported by Basic Science Research Program through the National Research Foundation of Korea (NRF) funded by the Ministry of Education, Science and Technology (2011-0013902).

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