Controller Design and Trajectory Tracking of a Two-Link Robotic Orthosis via Sinusoidal-Input Describing Function Model

Kar Mun Chin, Sze-Hong Teh, Jee-Hou Ho, and Hoon Kiat Ng
The University of Nottingham, Semenyih, Malaysia
Email: kedx5ckn@nottingham.edu.my, {SzeHong.Teh, JeeHou.Ho, HoonKiat.Ng}@nottingham.edu.my

***Abstract*—This paper presents an application of controller design using sinusoidal-input describing function (SIDF) for a two-link robotic orthosis, which is a non-linear multivariable system. A controller based on closed-form solution of lead-lag compensator is generated via unified approached technique. The performance of the controller is evaluated with step response, tracking and decoupling qualities as well as the trajectories tracking and this is compared with the conventional PID controller.**

***Index Terms*—controls, describing function, lead-lag compensator, robotic orthosis**

I. Introduction

In the past few decades, robotic devices have gained more attractions in gait rehabilitation as an alternative solution to conventional treatments such as strength and treadmill training. For example, lower limb robotics orthosis was introduced to substitute the conventional rehabilitation therapies to reduce the workload of physiotherapists [1]. Robotic rehabilitation devices are able to lighten the burden of the healthcare system and always ready to be used for long-term plans. Studies show that these devices can help patients to correct their muscle activation patterns, regain normal gait speed, achieve normal range of joint motion and fully achieve independent walking [2]. There are numerous robotic control algorithms developed for rehabilitation devices. However, there is still room of improvement for standard protocols and procedures to obtain reliable assessment data. Moreover, the benefits of the robotic control approaches to stroke rehabilitation are still unclear [3]. Hence, further development of a robust control system for the robotic orthosis are aimed to be done.

Common control schemes deployed in robotic-assisted training include low level motion control (position control and tracking) and high level trajectory planning which may involve human-robot interaction. In our preliminary study, a two-link robotics orthosis was developed [4]. A control system was designed using conventional PID control scheme. A SIMULINK model was developed in the MATLAB environment according to the basic information of the plant model, including the dynamic model and information available from the data sheet of the motor driver, actuators and sensors. The MATLAB simulation results were validated with the experimental results. However, the results were not satisfactory and this could due to missing of unknown terms such as the link disturbance and system vibration that could alter the system behaviour.

Besides that, both the SIMULINK model and experimental setup control with PID controller were assessed with step inputs and trajectory inputs. The result from both system were compared, and it does not provide an adequate outcome as the classical system model transfer function is unable to fully mimic the actual plant model. Hence, representing the non-linear plant only from the dynamic model of the plant are not an ideal solution or even impossible with the present of load torque disturbances, discontinuous nonlinearities such as saturation and backlash as well as multivariable in the system. Thus, a linearized approximation for the non-linear plant at its nominal operation condition, as known as describing function approach is required.

The describing function is a successful approach to approximate the system model in a linear mathematical form suitable for controller design via simulation. In the past two decades, the describing function approach has been applied in various applications and it is a useful implementation for systematic design of non-linear control systems such as liquid propellant engine [5], space robots [6] and two-link robot in horizontal plane [7], [8].

In the year of 1983, a new approach for design of conventional non-linear feedback control system based on one or more describing-function prototypes of the plant was presented. This approach had been utilized to design vigorous non-linear feedback system in position control servo design problem from robotics [9], [10] and liquid propellant engine in aerospace industries [11]. In the year of 1987, a computer-aided engineering (CAE) environment for input/output characterization of extremely non-linear plants is published. This method is derived from gaining the sinusoidal-input describing function (SIDF) models of the non-linear system [12]. In 2002, the characterization method had been extended to accommodate multivariable non-linear systems with a

Manuscript received August 1, 2018; revised July 20, 2019.

doi: 10.18178/ijmerr.8.6.845-851

software developed in MATLAB [5]. To complement the controller synthesis procedures using SIDF approach, a new software based on non-linear optimization technique is developed [13]. A recent utilization of this design platform is applied for idle speed control of undetermined automotive engine. The method is used to obtain the actual internal combustion engine model which consists of discontinuous non-linear expressions. The describing function method is implemented to deal with the discontinuous models and a conventional controller is design using the algebraic approach via the computer-aided method. The designed controller is successfully tested on the engine of a real automobile and it is able to account for the time delay [14].

Describing function is a linearization of a non-linear element subjected to a sinusoidal input. It is an approximate method to characterize the non-linear system. The sinusoidal-input describing function (SIDF) widely implemented among the numerous describing functions. The input and output behaviour of a non-linear system is dependent on the amplitude of excitation signal and it can be captured with the SIDF model. This model also capable to describe the dependency of the non-linear system on the predicted range of frequencies of interest. Furthermore, a vigorous stable closed-loop systems without losing the effectiveness of the system can be achieved. This method has been applied in the control of non-linear systems with discontinuities and time delays [8], [12], [14].

In this work, describing function approach is applied for characterizing the input-output behaviour of the two-link robotic orthosis at an operating regime of interest. A controller design procedure based on describing function approach [14]is then applied to design a multivariable controller for the SIDF model obtained using describing function approach. The procedure utilizes an algebraic technique given in [15] and it is complemented by a lead-lag compensator design technique developed in [15], [16]. the resulting control system could achieve good tracking and decoupling qualities while meeting the desired performance specifications. The paper is organized in the following manner. The controller synthesis procedure based on describing function approach is first outlined in Section 2. The demonstration of the procedure is then detailed in Section 3. Some results and discussion are presented in Section 4, and finally the paper is concluded in Section 5.

II. Controller Synthesis Procedures

The synthesis of sinusoidal input describing function and controller design procedure of this non-linear 2-inputs-2-outputs system is methodical and the unified approach is used to tune the controller. This method consists of two major procedures:

- Generate of SIDF model and stabilize the model.
- Controller design using any unified approach.

A. Generate of SIDF Model and Stabilize the Model

The Simulink model as shown in Fig. 1 is generated based on the dynamic model of the unstable system. The proportional K_p and integral K_i gain were used for unity velocity feedback for both links for system stabilization. Torque limiters range were set based on experimental current data obtained from motor testing.

In order to generate the SIDF models, sinusoid signal is excited on the system in the following form:

$$u_v(t) = u_{0,v} + a_v\, cos(\omega_v t),\ \ v = 1,2,3,\dots,m \qquad (1)$$

where, u_v is the input, v is the input channel index, $u_{o,v}$ is the DC component of the input signal, a_v is the amplitude of the excitation signal and w_v is the excitation frequency. Both links are excited at the same time with similar but unequal frequencies to isolate the individual effects of the inputs on the two outputs. The Fourier integrals are evaluated once the output histories are generated to obtain the output, y_q.

$$I_{q,p}^{h,k} = \int_{(k-1)T}^{kT} y_q(t)\, exp[-jh(\omega_p t + \theta_p)]dt \qquad (2)$$

where k is the period index, h is the index for the measured harmonics, T is the total period. For this two-inputs-two-outputs system, $T= 2\pi/(\omega_1-\omega_2)$. Then, the multivariable SIDF models at discrete frequencies are obtained and give in the following relation:

$$G_{q,p}^{h,k}(j\omega; u_o, a, \theta) = {}^{2}/_{a_p T}\, I_{q,p}^{h,k} \qquad (3)$$

We use a MATLAB software developed for this purpose [7] to characterize the non-linear behaviour of the system at the operating condition of interest. The SIDF model of the lower limb exoskeleton is obtained. Linear fitting is done to obtain the linear model of the lower limb exoskeleton, $G(s)$. The system is concluded stable when the closed-loop describing functions are finally obtained as converge of the Fourier integrals would not occur unless the output are constrained.

$$G(s) = \begin{bmatrix} g_{11} & g_{12} \\ g_{21} & g_{22} \end{bmatrix} \qquad (4)$$

B. Controller Design Using Any Unified Approach

The SIDF model obtained in step 1 is utilized in step 2 for the controller design. The algebraic technique is used

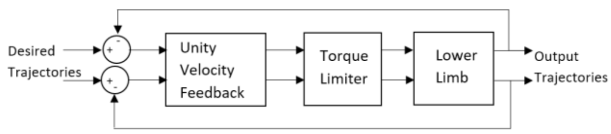

Figure 1. Block diagram of closed-loop two degree-of-freedom lower limb exoskeleton control system

to exhibit the decoupling procedure for this 2x2 process. The following relation holds for the classic unity feedback system.

$$y = e_i\big(g_{ii}c_{ii} + g_{ij}c_{ji}\big) + e_j\big(g_{ii}c_{ij} + g_{ij}c_{jj}\big),$$
$$i = 1,2;\ j = 1,2;\ i \neq j \qquad (5)$$

where y is the output, e is the error signal, g is the matrix I/O model of the system, is the matrix I/O model of the controller to be calculated. To attain decoupling, the given relation must retain:

$$c_{ij} = -\frac{g_{ij}c_{jj}}{g_{ii}},\ i = 1,2; j = 1,2;\ i \neq j \tag{6}$$

To accomplish tracking, (5) and (6) are compared to obtain the following.

$$\frac{y_i}{r_i} = \frac{c_{ii}k_i}{1+c_{ii}k_i}, i = 1,2 \tag{7}$$

$$k_i = g_{ii} - \frac{g_{ij}g_{ji}}{g_{jj}},\ i = 1,2; j = 1,2;\ i \neq j \tag{8}$$

Hence,

$$K = [k_1\ k_2] \tag{9}$$

The unified approach in cad_controller MATLAB function can be utilised to design the c_{11} and c_{22} [17] :

Step 1. The desired transfer function is expressed as following.

$$h_d = \frac{\omega_n^2}{s^2+2\zeta\omega_n+\omega_n^2} = \frac{Z_1}{Z_2} \tag{10}$$

The 2nd order system is utilized in as it is the fundamental system that exhibits oscillations and overshoot. Besides that, the parameters such as damping ratio, ζ and the undamped natural frequency, ωn are capable to determine aspects of various kind of responses such as the settling time with the following equation, $t_s = \frac{4}{\zeta\omega_n}$.

Step 2. As the system is formed in a unity feedback configuration, the actual closed-loop transfer function in the forms of the compensator parameters is assumed to be given as:

$$h_a = \frac{Y_1}{Y_2} \tag{11}$$

Step 3. With the h_d and h_a, the objective function could be obtained as shown in (12). The desired outcomes could be achieved by minimizing the objective function with compensator parameters as the independent variables. Solving of a set of simultaneous non-linear numerical equation as shown in (13) is required to determine the compensator parameters. However, under optimality condition, $Z_1Y_2 \approx Z_2Y_1$ is found, hence, the alternative objective function as shown in (14) is minimized instead of the objective function.

$$J = \int_{\omega_1}^{\omega_2} \left|\frac{Z_1}{Z_2} - \frac{Y_1}{Y_2}\right| d\omega \tag{12}$$

$$J = \int_{\omega_1}^{\omega_2} |Z_1Y_2 - Z_2Y_1|\ d\omega \tag{13}$$

$$J = \int_{\omega_1}^{\omega_2} |Z_1Y_2 - Z_2Y_1|^2\ d\omega \tag{14}$$

Step 4. The solution from minimizing the objective function will lead to obtain the value of the compensator parameters as follow.

$$C(s) = \begin{bmatrix} c_{11} & c_{12} \\ c_{21} & c_{22} \end{bmatrix} \tag{15}$$

Next, optimum gain for controller will be tuned if the dynamic behaviour of the non-linear system is not satisfactory. The tuning of the controller is based on optimization approach to determine the optimum constant gain before it functions in the best way with the actual non-linear system. The four gains, K_{ij} for each controller in the controller matrix are optimized and the objective function, E to be solved is show in (16).

$$E = \left[\theta_{1,1}(t) - \theta_{1,d}(t)\right]^2 + \left[\theta_{1,2}(t)\right]^2 + \left[\theta_{2,1}(t) - \theta_{2,d}(t)\right]^2 + \left[\theta_{2,2}(t)\right]^2 \tag{16}$$

where,

$\theta_{n,1}(t)$ is the actual response of n^{th} angle where $n=1,2$ when the command angle n is a unit step and the command of the other angle is zero (rad/s).

$\theta_{n,2}(t)$ is the actual response of the n^{th} angle where $n=1,2$ when the command motor speed is zero and the command of the other angle is a unit step (rad/s).

$\theta_{n,d}(t)$ is the desired decoupled response of the n^{th} angle where $n=1,2$.

Hence, the returning result of the controller is formed in (17). Finally, verification of the controller can be done with digital simulation.

$$C(s) = \begin{bmatrix} K_{11}c_{11} & K_{12}c_{12} \\ K_{21}c_{21} & K_{22}c_{22} \end{bmatrix} \tag{17}$$

III. Controller Design of the Two-Link Robotic Orthosis

The two-link lower limb robotic orthosis moving in vertical plane is considered. Let L_n, M_n, θ_n be the length, the total mass, and angle of link n. In this case, M_1=0.518kg, M_2=0.411kg, L_1=0.225m, L_2=0.2m, θ_1 and θ_2 are operation in range of 55 and 65 degrees respectively. The equation of motion derived using Lagrange's method as below.

$$T_1 = \frac{d}{dt}\left(\frac{\partial L}{\partial\dot\theta_1}\right) - \frac{\partial L}{\partial\theta_1} \tag{18}$$

$$T_1 = m_{11}\ddot\theta_1 + \ddot\theta_2 - 2M_2L_1L_2\left(2\dot\theta_1\dot\theta_2 + \dot\theta_2{}^2\right)\sin\theta_2 + (M_1gL_1 + 2M_2gL_1 + 2M_3gL_1)\sin\theta_1 + M_2gL_2\sin(\theta_1+\theta_2) \tag{19}$$

$$T_2 = \frac{d}{dt}\left(\frac{\partial L}{\partial\dot\theta_2}\right) - \frac{\partial L}{\partial\theta_2} \tag{20}$$

$$T_2 = m_{21}\ddot\theta_1 + m_{22}\ddot\theta_2 + 2M_2L_1L_2\dot\theta_1{}^2\sin\theta_2 + M_2gL_2\sin(\theta_1+\theta_2) \tag{21}$$

where,

$$m_{11} = M_1L_1{}^2 + 4M_2L_1{}^2 + M_2L_2{}^2 + 4M_2L_1L_2\cos\theta_2 + 4M_3L_1{}^2 + I_1 + I_2 + I_3 \tag{22}$$

$$m_{12} = M_2L_2{}^2 + 2M_2L_1L_2\cos\theta_2 + I_2 \tag{23}$$

$$m_{21} = M_2L_2{}^2 + 2M_2L_1L_2\cos\theta_2 \tag{24}$$

$$m_{22} = M_2L_2{}^2 + I_2 \tag{25}$$

The suggested controller design method is performed as follows:

Step 1. As stated in section x, the proportional, K_p and integral, K_i gain used for the unity velocity feedback were subjectively set to be 20 and 2 respectively; the torque limiters, T_L range were set at -29 < T_L <29.

Step 2. SIMULINK model is simulated to ensure the system was stabilized. The MATLAB software [12] is prompted to acquire the describing function. The last two inputs in MATLAB command to generate the transfer function to match with the frequency response data which are the numerator and denominator of the linear transfer functions are adjusted and hence, a nominal model with the best linear fitting line (Fig. 2 and 3) of the pseudo-frequency response is generated with the selected sinusoidal input signals: u_{01}=30°, u_{02}=30°, $a_1=2\frac{\text{rad}}{\text{s}}$, $a_2=4\frac{\text{rad}}{\text{s}}$, ω_1=[0.3, 0.5, 0.8, 1, 2, 4, 7, 11, 19, 32, 55, 94, 150], ω_2=[0.4, 0.6, 0.9, 2, 3, 5, 8, 12, 20, 33, 56, 95, 151].

Step 3. The SIDF model of the lower limb robotic orthosis generated via the invfreqs function of MATLAB software.

$$G(s) = \begin{bmatrix} g_{11} & g_{12} \\ g_{21} & g_{22} \end{bmatrix} \tag{26}$$

where,

$$g_{11}(s) = \frac{7.108}{s^2+15.3084s+0.0167} \tag{27}$$

$$g_{12}(s) = -\frac{4.0799}{s^2+19.2899s+94.2537} \tag{28}$$

$$g_{21}(s) = -\frac{5.9880}{s^2+17.7168s+121.5670} \tag{29}$$

$$g_{22}(s) = \frac{8.9008}{s^2+10.0748s+0.0559} \tag{30}$$

Step 4. Then, the cad_controller MATLAB function is executed to obtain the lead-lag compensator, c_{11} and c_{22}. By utilizing (9) and $G(s)$, the off-diagonal terms of 2 x 2 matrix, c_{12} and c_{21} are identified.

$$C(s) = \begin{bmatrix} c_{11} & c_{12} \\ c_{21} & c_{22} \end{bmatrix} \tag{31}$$

where,

$$c_{11}(s) = \frac{0.5965s^2+8.7451s+53.6781}{0.0011s^2+0.1055s+1} \tag{32}$$

$$c_{12}(s) = \frac{1.3019s^4+38.9832s^3+406.9076s^2+1764.0818s+1.9219}{0.0052s^4+0.6306s^3+17.8280s^2+187.0939s+669.9309} \tag{33}$$

$$c_{21}(s) = \frac{3.5719s^4+88.3518s^3+849.1961s^2+3241.2151s+17.9678}{0.0098s^4+1.1118s^3+26.7190s^2+271.8088s+1082.0487} \tag{34}$$

$$c_{22}(s) = \frac{0.3191s^2+4.6700s+28.2399}{0.0007s^2+0.0746s+1} \tag{35}$$

Step 5. The gain of the controllers are optimized and the following gains are selected:
K_{11} = 5, K_{12} = 0.2, K_{21} = 0.2, K_{22} = 5.

IV. Result and Discussion

In order to examine the result, the designed model is tested with MATLAB SIMULINK model consists of the tuned controller and the non-linear feedback control system. The performance of the non-linear feedback control system is assessed with step inputs testing as well as the tracking and decoupling qualities of both links.

The normalized step responses of both axes are plotted in Fig. 4 respectively. Optimal static and dynamic behaviour is obtained from the tuned single-range controller. According to Fig. 4, optimal static and dynamic behaviour is obtained from the tuned single-range controller with 2% settling time of approximately 0.7 seconds to 1.2 seconds with input angle ranged from 1 to 30 degrees. The response for input of 30 degrees are slightly slower than the rest. For the second axis, good static and dynamic behaviour with 2% settling time of approximately 0.8s seconds was observed for all inputs. Both axes has a slightly overshoot responses for about 5%.

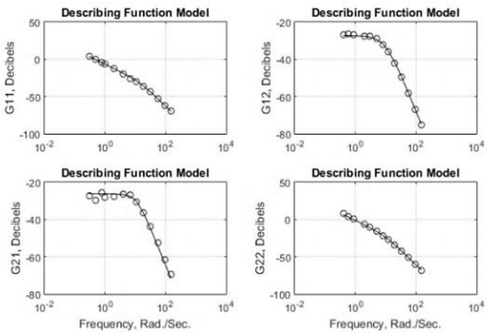

Figure 2. Gain matrix of the SIDF model at nominal condition

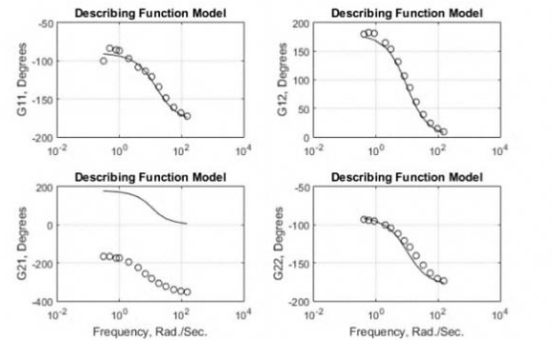

Figure 3. Phase matrix of the SIDF model at nominal condition

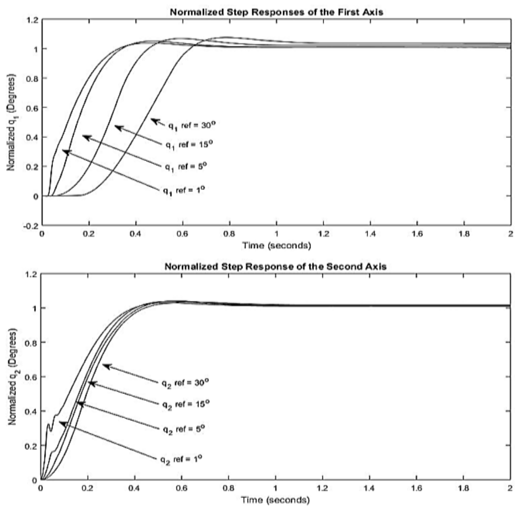

Figure 4. Normalized step responses of the first and second axis

This satisfied the objective of low sensitivity of non-linear closed-loop system with respect to the level of input command. The output step responses have a longer settling time than expected which is greater than 0.5

seconds. Since two links are turning at the same time, coupling effect between the links are present and hence the lengthy settling time are acceptable herein. Furthermore, the percentage overshoot is satisfactory as long as there is no significant oscillatory behaviour obtained from both axes.

The tracking qualities and decoupling qualities of the non-linear feedback control system are plotted in Fig 5 and Fig. 6. Result for link 1 is obtained with a step input to link 1 and zero input for link 2. Same method is used for second link to test on the robustness of the controller. Satisfied tracking and decoupling qualities are executed at the operating range of 1 to 30 degrees. The tracking response has a good behaviour as the settling time for both axes with 1 and 0.7 seconds as shown in the tracking quality of first and second axis Fig 5 and Fig 6. A slightly overshoot of 5% was detected for both axes. According to the decoupling plot in Fig 5 and Fig 6, the degree of coupling for both axes are 0.3 degree and 0.4 degree which is respectively small compared to the input of the system. Hence the satisfactory output proven the proficiency of the suggested design methodology herein in generating the linear controller to perform simultaneous signal tracking and decoupling for multivariable system.

Finally, the system model is executed with 5 continuous gait cycles of lower-limb trajectories (2 seconds for each cycle) for both links as shown in Fig. 7 and 8 respectively. The responses from the SIDF model with lead-lag compensator are compared with those previously gained with PID controller. Both responses of the trajectories are plotted in the same graph for comparison purpose. As illustrated in both Fig. 7 and 8, responses from PID controlled system have greater overshoot at every instant of changing of the rotational direction as compared to the newly generated model. The output from PID controller has an overshoot of 7 degrees as shown in Fig. 7 during the first turning point. A delay of 0.2s for each cycle is observed and significant jerk at 2.4 seconds is detected in the output trajectory plotted in Fig. 7. Output of PID controller for second link has an overshoot that is slightly greater than the response from SIDF model with lead lag controller as illustrated in Fig. 8.

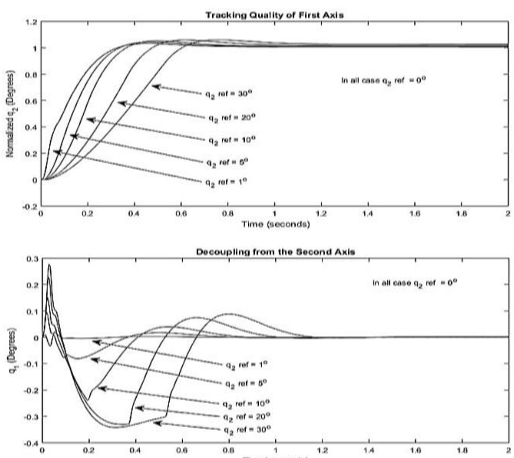

Figure 5. Tracking quality of first axis and decoupling quality from the second axis

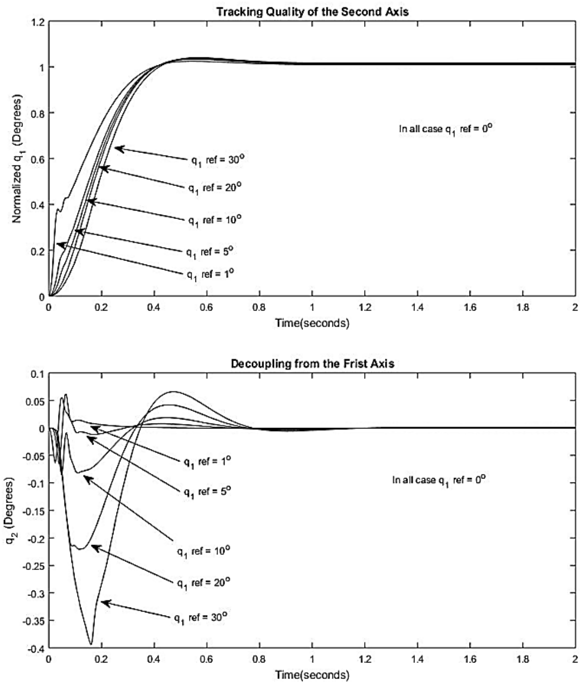

Figure 6. Tracking quality of second axis and decoupling quality from the first axis

As shown in Fig. 7, the output trajectory of SIDF model with controller consist of an overshoot of 3 degrees at the second turning of the graph. However, the SIDF model with lead-lag compensator generated smoother output trajectories with shorter response time for both links. By referring to both figure, trajectories responses from the lead lag controlled SIDF model has a better tracking ability compared to the responses from the PID controller. Overshoot of the output from SIDF model are not significant compared to the outcomes from the PID controller. Hence, the obtained result lead to a conclusion that the newly generated model is more stable with greater tracking capability and response time in the non-linear two-link lower limb feedback system.

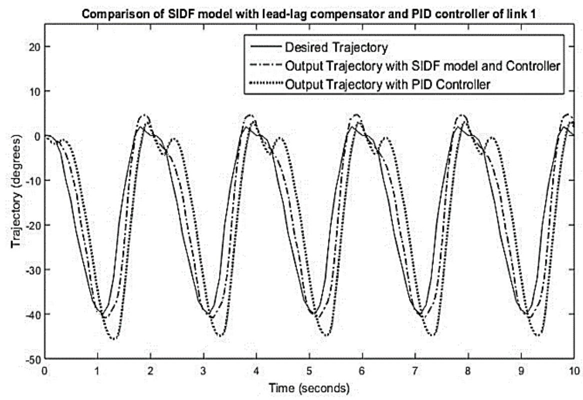

Figure 7. Comparison of SIDF model with lead-lag compensator and PID controller and of link 1

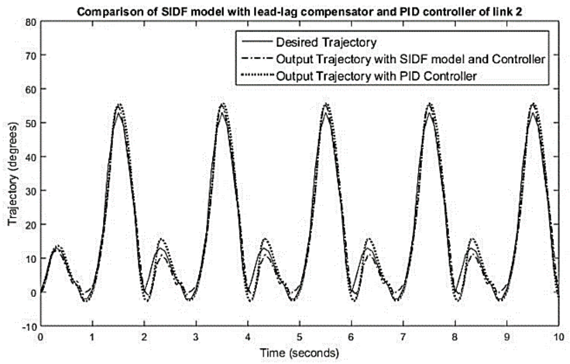

Figure 8. Comparison of SIDF model with lead-lag compensator and PID controller and of link 2

V. Summary and Conclusion

A control system of two-link lower limb robotics orthosis has been developed using the sinusoidal-input describing function approach. A SIDF model established to represent the system. A closed-form solution of lead-lag compensator is designed and validated. The trajectory tracking capability of both SIDF lead-lag compensator and PID controller are compared. The lead-lag compensator performed better in position tracking and decoupling for the unstable multivariable non-linear system. The next phase of work would focus on the experimental implementation of the controller based on the SIDF approach.

References

[1] P. Lum, D. Reinkensmeyer, R. Mahoney, W. Z. Rymer, and C. Burgar, "Robotic devices for movement therapy after stroke: current status and challenges to clinical acceptance," *Top. Stroke Rehabil.*, vol. 8, no. 4, pp. 40–53, 2002.

[2] I. Díaz, J. J. Gil, and E. Sánchez, "Lower-limb robotic rehabilitation: literature review and challenges," *J. Robot.*, vol. 2011, pp. 1–11, 2011.

[3] H. Herr, "Exoskeletons and orthoses: classification, design challenges and future directions," *J. Neuroeng. Rehabil.*, vol. 6, p. 21, Jan. 2009.

[4] S. L. Chong, C. Theam, C. Wong, C. H. Lo, A. Osamah, M. Alabd, S. Y. Loo, J. H. Ho, and L. P. Teo, "A dual mode emg-controlled robotic orthosis," *ARPN J. Eng. Appl. Sci.*, vol. 11, no. 1, 2016.

[5] A. Nassirharand and H. Karimi, "Input/output characterization of highly nonlinear multivariable systems," *Adv. Eng. Softw.*, vol. 33, no. 11–12, pp. 825–830, 2002.

[6] A. Nassirharand, 'Control system design of multivariable non - linear space robots," *Aircr. Eng. Aerosp. Technol.*, vol. 80, no. 1, pp. 27–34, Jan. 2008.

[7] A. Nassirharand, "Tracking and decoupling of multivariable nonlinear systems," in *2009 IEEE International Conference on Control Applications*, 2009, pp. 136–141.

[8] A. Nassirharand and S. A. Hosseini, '"Tracking and decoupling of multivariable non-linear systems," *Int. J. Model. Identif. Control*, vol. 6, no. 4, p. 341, 2009.

[9] A. Nassirharand, J. H. Taylor, and K. N. Reid, "Controller design For nonlinear systems based on simultaneous stabilization theory and describing function models," *J. Dyn. Syst. Meas. Control*, vol. 110, no. 2, p. 134, 1988.

[10] J. H. Taylor and K. L. Strobel, "Nonlinear compensator synthesis via sinusoidal-input describing functions," 1985, pp. 1242–1247.

[11] A. Nassirharand and H. Karimi, "Controller synthesis methodology for multivariable nonlinear systems with application to aerospace," *J. Dyn. Syst. Meas. Control*, vol. 126, no. 3, p. 595, 2004.

[12] A. Nassirharand, "Input/output characterization of highly-nonlinear systems," *Adv. Eng. Softw.*, vol. 9, no. 3, pp. 129–133, Jul. 1987.

[13] T. Sze Hong and Nassirharand Amir, "Software for design of linear controllers for nonlinear systems," in *2010 International Conference on Advance in Mechanical Engineering*, 2010.

[14] S. H. The and A. Nassirharand, "Idle speed control using a describing-function approach," *Proc. Inst. Mech. Eng. Part D J.* Automob. *Eng.*, vol. 224, no. 4, pp. 533–545, Apr. 2010.

[15] C. T. Chen, *Linear System Theory and Design*, Internatio. New York: Oxford University Press, 1984.

[16] H. Nassirharan, Amir , Karimi, "Closed-form solution for design of lead-lag compensators," *Int. J. Electr. Eng. Educ.*, vol. 41, no. 2, pp. 172–180, 2004.

[17] A. Nassirharand, "Computer-aided design of classical linear compensators with application to aerospace," *J. Syst. Eng. Electron.* , vol. 20, no. 6, pp. 1373–1377, 2009.

Kar Mun Chin was born in Malaysia, in 1991. She received the B.E. degree in robotics and mechatronics engineering form Swinburne University of Technology, Sarawak Campus in 2014. She is currently a research assistance and postgraduate student working on control system of gait correction lower limb robotic orthosis under the Department of mechanical materials and manufacturing engineering of the University of Nottingham, Malaysia Campus.

Jee-Hou Ho received his B.Eng (Hons) and M.Eng degree in Mechanical and Production Engineering from Nanyang Technological University, Singapore and PhD degree from the University of Nottingham Malaysia Campus. He is currently an Associate Professor at the University of Nottingham Malaysia Campus. His research interests are in the area of vibration energy harvesting, bio-mechatronics and robotics. He is also interested in the application of nonlinear analysis techniques to solve real world problems, particularly in the area of signal processing, sensors, actuators and other nonlinear dynamical systems.

Dr Ho is a Chartered Engineer registered with the UK Engineering Council. He is also a member of Institution of Mechanical Engineers (MIMechE) and member of Institute of Electrical and Electronics Engineers (MIEEE).

Sze-Hong Teh was born in Malaysia, in 1988. He received his MEng in Mechanical Engineering in 2011 and PhD in Mechanical Engineering in 2016 all from the University of Nottingham Malaysia Campus. He is now an Assistant Professor at the Department of Mechanical, Materials and Manufacturing Engineering. His main research interests involve nonlinear dynamics and control of nonlinear systems.

Hoon Kiat Ng received his B.Eng (Hons) Mechanical Engineering from University of Sheffield, UK and PhD from University of Nottingham, UK. He is currently a Professor of Mechanical Engineering at the University of Nottingham Malaysia Campus. He served as the head of the Energy, Fuel and Power Technology research division, academic champion of the aerospace priority area and the founding deputy director of the Asia Aerospace City Research and Technology

Centre. He is currently the head of the department and the campus academic champion for the energy research priority area.

He works in a wide range of interdisciplinary experimental and computational projects, including chemical kinetics modelling of diesel/biodiesel combustion, biofuels production and combustion, engine testing, parallel processing and neural network analysis of engine performance/emissions, as well soil remediation using extraction, advanced oxidation processes (AOP) and bio-mechatronics.

Prof Ng is a Chartered Engineer registered with the UK Engineering Council. He is also a member of Institution of Mechanical Engineers (MIMechE).