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Application of Hardware-in-the-loop Simulation for the Development and Testing of Advanced Control Systems for Joint Wear Simulators

Kaushikk Iyer
Key Engineering Solutions
School of Mechanical Engineering
University of Leeds
Leeds, United Kingdom
Email: k.iyer@key-es.co.uk

David Keeling
Managing Director
Key Engineering Solutions
Leeds, United Kingdom
Email: d.g.keeling@key-es.co.uk

Richard M Hall
School of Mechanical Engineering
University of Leeds
Leeds, United Kingdom
Email: r.m.hall@leeds.ac.uk

***Abstract*–Hardware-in-the-loop (HIL) simulation is an advanced technique for developing and testing complex real-time control systems. This paper presents the benefits of HIL simulation to develop, test and validate advanced control algorithms used in an artificial joint wear simulator for the tribological testing of prostheses.**

A benchtop HIL setup is created for experimentation, controller verification, and validation purposes, allowing different control strategies to be tested rapidly in a safe environment. The HIL simulation attempts to replicate similar joint motion and loading conditions of that of the spinal wear simulator. The simulator contains a four-bar link powered by electromechanical actuators. As a result, the implant articulates with an angular motion specified in the international standards, ISO-18192-1, that defines fixed sinusoid motion and load profiles for wear testing of both lumbar and cervical disc implants.

Using a PID controller, a velocity-based position control algorithm was developed to interface with the benchtop setup that performs HIL simulation. The simulation results strongly support the efficacy of the test setup using HIL simulation to verify and validate the accuracy and robustness of the prospective controller before its deployment into the spinal wear simulator. This method of testing controllers enables a wide range of possibilities to test advanced control algorithms that can potentially utilize real-world data of patients performing daily living activities that place adverse demands on the artificial joint.

***Keywords* – PID controller, hardware-in-the-loop (HIL), real-time simulation, wear simulator.**

I. INTRODUCTION

Changing demographics and the rise of living standards particularly in Asia is increasing the global demand for joint replacements. Kurtz et al [1] predicted that by 2030 the need for primary hip replacements would grow by 174% and knee replacements by 673% in the United States alone [2].

Joint simulators are extensively utilized to assess the tribological performance of articulating devices for total knee, hip and spinal disc replacements. These simulators are more sophisticated than a simple pin-on-disc machine. Joint simulators facilitate a more specific testing environment that reflects the main features of the tribology found in vivo. This includes the assessment of functional joints with loads and motions that reflect some central notion of activity as well as pertinent lubricants [3]. The testing regimes are well defined within internationally approved standards. As a result, they are used to predict how the prosthetic biomaterials will wear over a specified number of cycles, usually 5MC or 10MC. Also, it plays a critical role in determining the suitability of the joint prior to implantation including that of regulatory compliance [4].

However, recent poor outcomes particularly in metal-on-metal hip prostheses has led to close scrutiny of testing methods. This led to a call for input data that reflects more adverse conditions that place greater demands on the prosthesis in terms of performance. Additionally, the existing simple position control techniques does not allow the simulator to test waveforms that are real-world and represent daily-living activities [5][6].

The primary aim of this paper is to demonstrate the methods and significance of HIL simulation. In particular, investigate the simulator system on a small benchtop setup to test proposed control algorithms rapidly, rigorously, and safely before its deployment to a main simulator for implant testing. While these wear simulators are advanced in terms of replicating the loads and motions of a simplified gait cycle, they use relatively simple control techniques that are challenged when more complex real-world input data is used that go beyond the sinusoidal or simplified waveforms used in the current standards e.g., ISO 18192-1. Thus, there is a need for better and more advanced control methods that can be developed and tested rigorously but safely before deploying it into the real simulator.

A flexible, velocity-based PID control algorithm was developed. The controller interfaces with a benchtop setup and attempts to replicate the spinal motion and loading conditions that exists between two adjacent vertebrae. The algorithm was developed according to the user specifications and ISO requirements for motion and loads.

II. HARDWARE-IN-THE-LOOP SIMULATION

Hardware-in-the-loop (HIL) simulation is a standard methodology for control verification and validation of a real physical system [7]. The methodology provides emulation capabilities that enable physical hardware integration with a real-time simulation. In addition, the input and the output signals show the same time-dependent values as the actual dynamic process [8]. HIL simulation is an essential process for the overall life cycle development of the system. It strives to reduce effort, time and cost spent on the validation activities [9]. The advantages of HIL simulation are as follows:

- Development and validation of control strategies can be achieved faster and with greater scope.
- Cost-effective, safe, and rapid repeatability of experiments.
- Provides a platform to test the robustness of prospective controllers.
- Enables the actuators to test under extreme operating conditions (e.g., speed, frequency and real-world challenging waveforms).

III. BENCHTOP SETUP

The electromechanical setup of the HIL shown in Fig. 1 comprises of two identical DC motors controlled individually by two independent ESCON servo controllers by Maxon Motor. The two motors are coupled with the profile motor being the representative of the linkage drive motor that provides physiologic motion on the specimen (Profile motor in Fig. 1). The load motor, on the other hand, provides a controllable resistance to the profile motor – as would be observed on the spinal simulator when loads are applied to the specimen. Additionally, a power supply and CompactRIO (cRIO). cRIO is a combination of a real-time controller, reconfigurable I/O modules, FPGA module and an ethernet expansion chassis. The real-time controller of cRIO contains a processor that reliably and deterministically executes the real-time code for the HIL setup. The three I/O modules attached in the cRIO chassis shown in Fig. 1 are Digital I/O, analogue input (AI) and analogue output (AO) modules. The reconfigurable I/O FPGA chassis is the centre of the embedded system architecture. The FPGA circuit inside the chassis is directly connected with each I/O module providing high performance and timing, triggering and synchronization with minimal control latency.

The ESCON servo controller comes with its own embedded software called ESCON Studio. The controller configuration is set within the software based on system requirements. This includes actuator types – EC/DC, motor characteristics such as speed constant, max permissible speed, nominal current, etc., and sensor selection with resolution. Also, the analogue and digital set values and voltage to speed conversion. Hence, the parameters can be saved and used for any models developed within LabVIEW once the configuration is set. Furthermore, while the program is running continuously within LabVIEW, the controller's performance can also be accessed from ESCON Studio simultaneously.

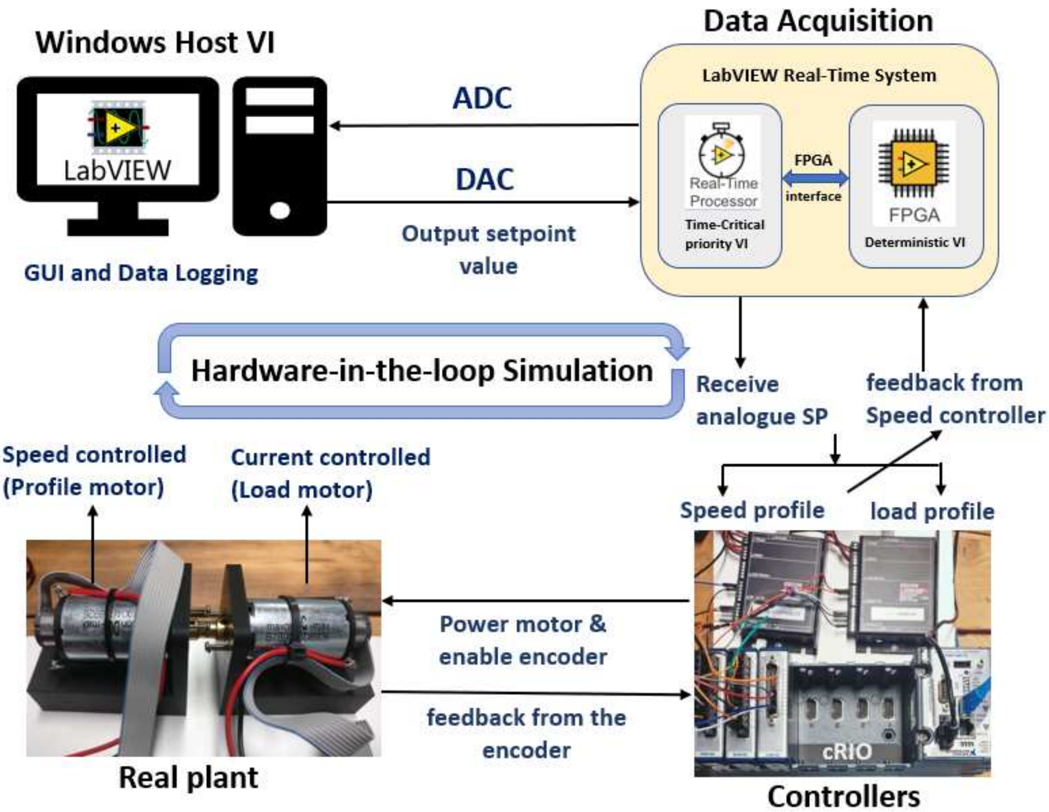

Fig. 1 A HIL simulation of the benchtop setup.

IV. SPINAL WEAR SIMULATOR

An example of the type of simulation provided by the spinal wear simulator is shown in Fig. 2. This is used for the wear testing of artificial spinal disc implants employed at the University of Leeds [10]. This bespoke machine encompasses attributes that allow testing beyond that required in ISO 18192-1. Further, it includes additional degrees of freedom as well as higher performance that enables testing of adverse scenarios that might induce higher detrimental wear.

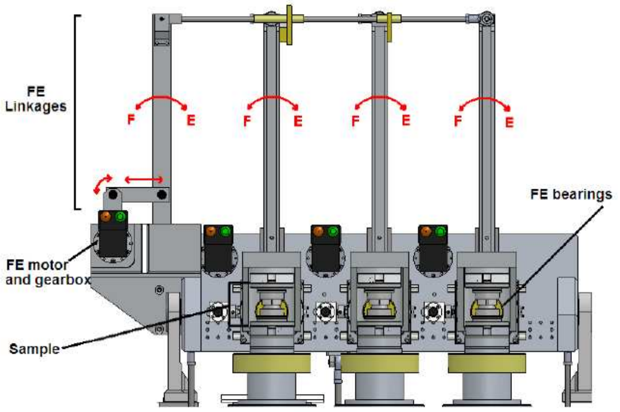

Fig. 2 Spinal wear simulator from the University of Leeds[10].

The simulator is specifically capable of producing 5 DOF movements: three rotational – flexion-extension (FE), lateral bending (LB), and axial rotation (AR), and two translational – anterior-posterior (AP) and axial compression (AC). However, for the purposes of the HIL, only three rotational displacements were tested against the axial compression load. Fig. 3 below illustrates the ISO 18192-1 standard profiles for loading and displacement for the wear testing of cervical disc implants.

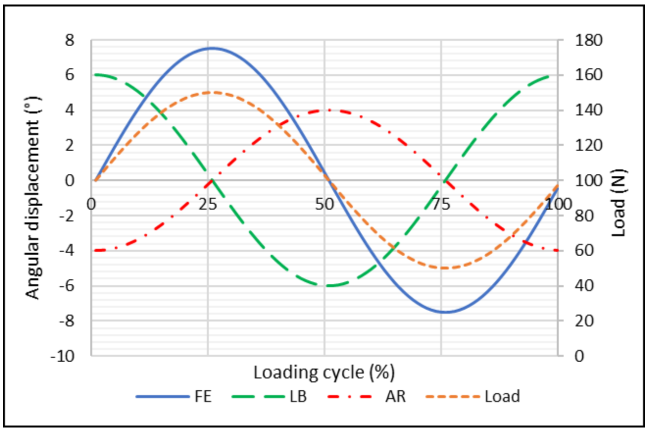

Fig. 3 ISO 18192-1 Phasing of the displacement and load curves for cervical prostheses[6].

V. KINEMATICS OF THE WEAR SIMULATOR

Fig. 4 depicts the kinematic model of the Leeds spinal wear simulator designed in LabVIEW 2017 software.

The primary purpose of developing the kinematic model of the Leeds wear simulator is to understand and calculate how much the profile motor, connected to link OA, rotates with respect to the implant articulating with link EF.

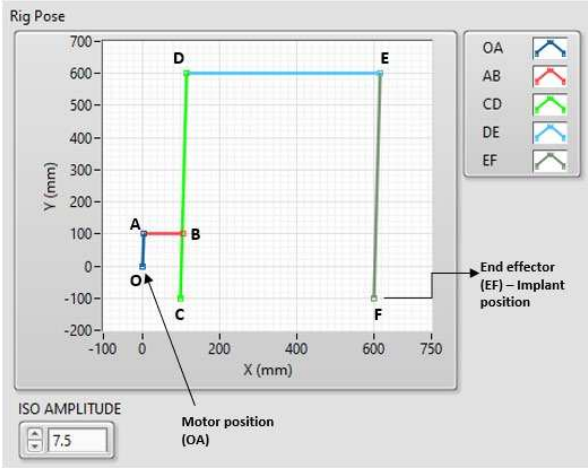

Fig. 4 Kinematic model of the Leeds spinal wear simulator developed in LabVIEW 2017 software.

Inverse kinematics approach is used whereby the link EF is the end-effector. The implant, or the sample location as shown in Fig. 2, is connected with point F. The whole rig moves in such a way that links EF and CD and parallel to each other and articulates vertically, for instance, 7.5° as mentioned in the ISO amplitude control block (Fig. 4) that is acting as an input to the system. And links DE and AB move approximately horizontally simultaneously causing the final link OA, which is connected with the motor, rotate. Table 1 illustrates the dimensions of all links and their angles with respect to joints O, C and F that are bolted to the simulator. Joint O is taken as a reference point to calculate all the other joints' X and Y positions respectively. Table 1 and Table 2 provides the link parameters of the kinematic model and the initialization of three fixed joints O, C and F.

TABLE 1. LINK PARAMETERS OF THE KINEMATIC MODEL SHOWN IN FIG. 4

Link	Length (mm)	Theta (θ°)
OA	100	90
AB	100	0
BC	200	90
CD	700	90
DE	500	0
EF	700	90

TABLE 2. INITIALIZING LINK POSITIONS OF 3 FIXED JOINTS

Position of 3 fixed joint	distance from joint O
OA.jO Pos X	0
OA.jO Pos Y	0
CD.jC Pos X	100
CD.jC Pos Y	-100
EF.jF Pos X	600
EF.jF Pos Y	-100

For link EF, where θ_F is 90° initially

$$\theta_E = \text{ISO amplitude} + \theta_F \tag{1}$$

$$jE\ Pos\ x = jF\ Pos\ x + EF \cos\theta_E \tag{2}$$

$$jE\ Pos\ y = jF\ Pos\ y + EF \sin\theta_E \tag{3}$$

For link DE,

$$jD\ Pos\ x = jE\ Pos\ x - DE \tag{4}$$

$$jD\ Pos\ y = jE\ Pos\ y \tag{5}$$

For link CD, all parameters will be the same as link EF since both links are parallel. Therefore,

$$\theta_F = \theta_D \tag{6}$$

$$jC\ Pos\ x = jD\ Pos\ x \tag{7}$$

$$jC\ Pos\ y = jD\ Pos\ y \tag{8}$$

Now, As link AB connects link OA to CD, the x and y position of joint B can be calculated. However, the x and y position of joint A (jA) needs to be calculated as well using the intersection of two circles with joint O (jO) and joint B (jB) as their centres.

For jB of link AB,

$$jB\ Pos\ x = jC\ Pos\ x + BC \cos\theta_D \tag{9}$$

$$jB\ Pos\ y = jC\ Pos\ y + BC \sin\theta_D \tag{10}$$

For jA of link AB,

First, the distance (D) between two centers of the circles, as shown in Fig. 5, is calculated.

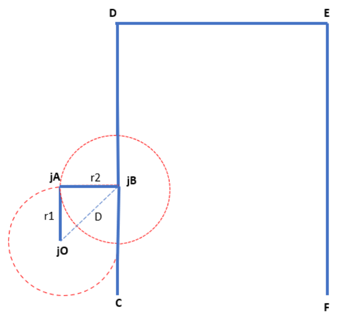

Fig. 5 calculating x and y position of jA using the intersection of circles with centre points as jO and jB

We have to use the x and y positions of joint O (jO) from link OA. Therefore, let

$$jO\ Pos\ x = X1 \tag{11}$$

$$jO\ Pos\ y = Y1 \tag{12}$$

Now, X2 and Y2 can be found from the x and y positions of jB of link AB which is Eq. (9) and (10).

$$jB\ Pos\ x = X2 \tag{13}$$

$$jB\ Pos\ y = Y2 \tag{14}$$

The distance (D) between two circles as shown in Fig. 5 can be calculated as:

$$D = \sqrt{(X2 - X1)^2 + (Y2 - Y1)^2} \tag{15}$$

Finally, the formula of intersection points of two circles is used to calculate the x and y positions of jA of link AB. That is:

$$x_A = \frac{X1 + X2}{2} + \frac{(X2 - X1)(r1^2 - r2^2)}{2D^2} \pm 2\frac{Y1 - Y2}{D^2}\delta \tag{16}$$

$$y_A = \frac{Y1 + Y2}{2} + \frac{(Y2 - Y1)(r1^2 - r2^2)}{2D^2} \mp 2\frac{X1 - X2}{D^2}\delta \tag{17}$$

Whereby,

$$\delta = \frac{1}{4}\sqrt{(D + r1 + r2)(D + r1 - r2)(-D + r1 + r2)} \tag{18}$$

Hence,

$$jA\ Pos\ x = x_A \tag{19}$$

$$jA\ Pos\ y = y_A \tag{20}$$

Thus, the resulting articulation of the link OA driven by the DC actuator produces approximately twice as much rotation as the implant produces, with the input provided by the user in terms of ISO amplitude shown in Fig. 4.

VI. CONTROL METHOD

Velocity-based servo systems are primarily controlled by a proportional-integral-derivative (PID) control algorithm with PID coefficients tuned for optimizing the operation. The objective of the PID controller in a velocity control system is to maintain a velocity set point at a given value and be able to accept new set-point values dynamically. Fig. 6 illustrates the control block diagram used for the HIL test setup and the communication between the software code and hardware.

The PID controller in the control loop uses the rate of change of the process variable instead of the rate of change of error for the derivative action. This is to avoid the sudden spike or "kick" to the overall control output when the error $e(t)$ changes abruptly during a set-point change.

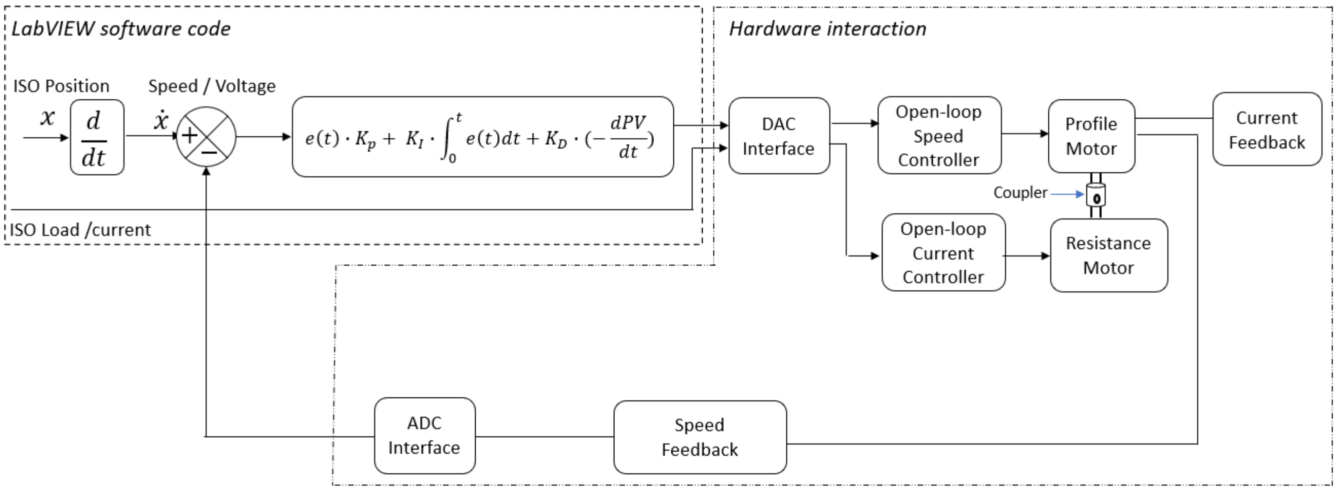

Fig. 6 Velocity based control algorithm for HIL simulation

The frequency of the input sinewave signal is 1 Hz as per ISO requirements, and the sampling frequency (f_s) was set to be 100 Hz. This rate provides a high resolution and ensures that all frequency components are included. Case structures within LabVIEW GUI were developed where the user can choose between any ISO profiles to be differentiated and used as a set-point to the controller.

VII. RESULTS

Fig. 7 below illustrates the results obtained for FE, LB and AR with HIL simulation. The set-point for the PID controller were speed profiles derived from the angular displacement profiles of FE, LB, and AR obtained from ISO-18192-1 standards (Fig. 3).

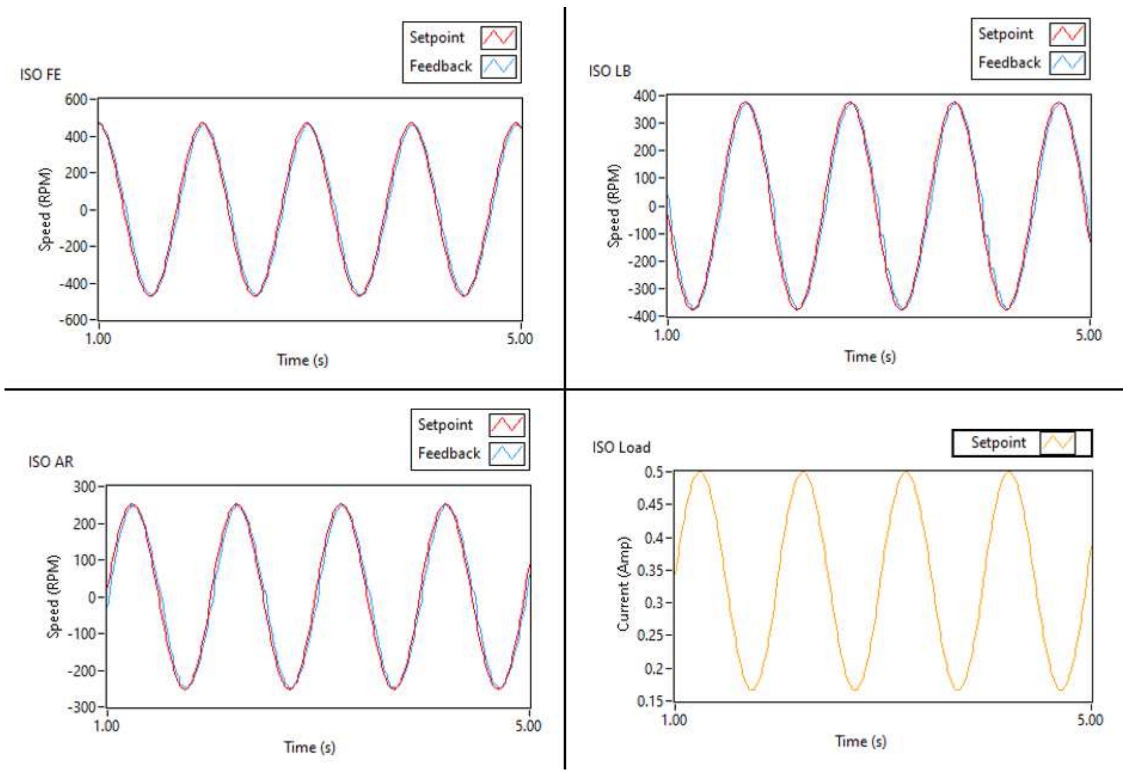

Fig. 7 Speed feedback of FE motion profile obtained from ISO-18192-1 for wear testing of the cervical spinal disc implants.

The optimized PID values for the results obtained in Fig. 7 were: K_p= 0.011 and K_i= 0.2 and K_d= 0. The derivative coefficient was kept zero all the time as it was too sensitive to the output of the process.

Fig. 8 below illustrates results of a speed profile derived from the displacement profile of a hip joint while performing daily living activities such as "Sit-Stand". This profile was obtained from real patients tested at a gait lab [11]. The HIL setup can also be utilized to test hip profiles because the underlying principle of controlling motion/speed profile against the load remains same for the hip as well as for the spine.

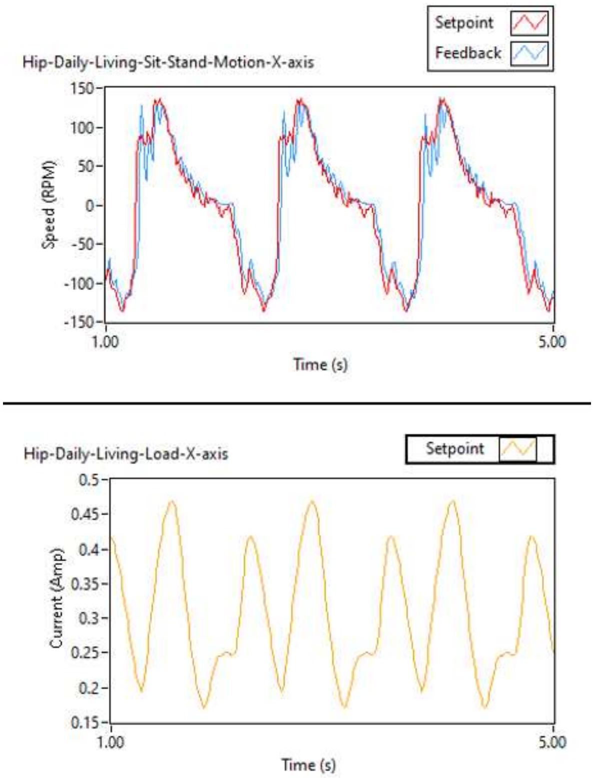

Fig. 8 Speed feedback of the daily-living activity of Sitting down and standing up for Hip replacements.

VIII. DISCUSSION AND CONCLUSION

The HIL simulation provided a testing platform to aid rapid, safe and low-cost development of a robust PID controller. The platform has also demonstrated that it is highly configurable and able to facilitate universal joint simulations. Within tribological applications, this approach of rapid controller testing using different profiles obtained from ISO standard and daily-living activities using HIL simulation can be seen as novel.

As mentioned, the HIL simulation provided a platform for a rapid development of a PID controller. Within the software component of the simulation, the controller programming interface has been designed with a defined schema to enable the controller to exchange data easily and securely with the rest of the system. Thus, as this project develops, the scope for rapid future development of more advanced controllers with swift interchange between them becomes a powerful testing architecture.

IX. FUTURE WORK

After the completion of this work, several areas have been identified as the areas of future work. Those include:

- Testing daily-living profiles of the cervical spine movements as this is one of the key tasks of this PhD project.
- Incorporate inertia of the simulator links into the HIL simulation to improve the efficacy of the controller's performance against disturbances.
- Develop and validate more advanced controllers.
- Test ISO and daily-living waveforms of hip and knee to enhance the performance, robustness and versatility of the prospective controllers and the HIL simulation.

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