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TEST BENCH TO EXPERIMENTAL MODELING OF AN MAGNETO-RHEOLOGICAL ACTUATOR FOR KNEE PROSTHESES AND EXOSKELETONS

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Abstract. *The movement performed by the knee is essential to reproduce proper gait in transfemoral prostheses and exoskeletons. The development of actuators to replace the knee or to reproduce their movement has been extensively studied in last few decades. Despite advances and research in assistive technology, developed active knees still have some limitations, such as high weight, low active and resistive torque and high energy consumption. This paper describes a test bench for experimental modeling of a magneto-rheological (MR) actuator for knee prostheses and exoskeletons. The actuator possesses multiple functions working as motor, clutch, or brake, reproducing the movement closest to a real knee. The test bench uses a National Instruments USB-6003 data acquisition board and the software LabVIEW to control the actuator subsystems and another bench devices and to acquire data from sensors of torque, current, temperature, and others. The sampling rate is about 1.0 kHz, and it is possible to identify the transfer function of several elements of the actuator, essential for comparison with its theoretical model. The results show that the developed actuator is promising for the proposed applications, which require multiple functions with compact size and quick response time.*

Keywords: *Magneto-Rheological Actuator, prostheses, exoskeletons, biomechanics, test bench.*

1. INTRODUCTION

According to the 2010 demographic census, in Brazil there are 45,606,048 disabled people, about 23.9% of the population. The motor disability is the second leading cause of disability in the Brazilian population with 13,273,969 people, or 6.96%. On the other hand, according to the Health Ministry, there were 281,841 lower limb amputations in Brazil between 1992 and 2015. Considering all hospital admission in that period, it has a total of approximately 98 lower limb amputations per 100,000 patients. It is estimated that the lower limb amputation corresponding to 85% of all amputations (Carvalho, 2003; O'Sullivan and Schmitz, 2004).

In an attempt to minimize the difficulties faced by disabled people, many researchers have made efforts over the years to develop equipment such as prosthetics and exoskeletons most appropriate for each situation. Despite the progress, there are still limitations on the usage of these devices. Regarding exoskeletons, the main difficulties are related to the weight and high-energy consumption (Bogue, 2015; Cestari et al., 2015). Such equipment must be connected directly to the power grid or carry heavy batteries to supply the power consumption of engines, actuators and other devices. According to Cestari et al. (2015), the development of low weight and power consumption actuators is a very important issue to increase the viability of exoskeletons. MR devices, which typically have low power consumption and low resistive torque-weight ratio, can be useful in these cases, increasing the energy efficiency of such devices (Chen and Liao, 2010).

Magnetorheological fluids (MR) are colloidal solutions formed by up to 50% by volume of magnetically polarized micro particles mixed with inert oil, usually mineral based or silicone-based. When the fluid is subjected to an external magnetic field, particles begin to form columnar structures parallel to the magnetic flux lines. This behavior changes the rheological properties of the fluid, such as viscosity, yield stress and others. The response time is in order of milliseconds (Yang, 2001). Due to these characteristics, MR devices are used in various applications in engineering and industry: vehicle suspensions (Sung and Choi, 2008), clutches (Kavlicoglu et al., 2006), brakes (Nguyen and Choi, 2010), structural vibration damping (Takashi and Sano, 2005), intelligent prosthesis (Carlson et al., 2001; Dong et al., 2005, 2006), and others.

In general, actuators can be divided into three main groups: passive, semi-active and active (Andrade et al., 2015; Martinez-Villalpando and Herr, 2009). The passive devices do not allow damping level control and do not require a power source for its operation, they are designed for every application and do not allow performance adjustments (Martinez-Villalpando and Herr, 2009). The semi-active devices only dissipate energy through controllable dampers (Lauwerys et al., 2002). In this case, MR dampers have good efficiency (Yang, 2001; Sung and Choi, 2008)). On the other hand, the active type devices are able to supply and dissipate energy through the actuators and dampers with controllable damping level.

Despite the disadvantages of semi-active and passive prostheses, there are a small number of active prostheses; just Power KneeTM (PK, Ossur, Iceland) is available on the market. In addition, the actuators for exoskeletons knees still need to be enhanced to reproduce an adequately gait with a low energy consumption. In an attempt to develop prostheses capable to reproduce the human leg movement in these indicated situations, different configurations and devices have been proposed. Pratt et al. (2004), Martinez-Villalpando and Herr (2009), Garcia et al., (2011) and Filho et al., (2014) propose use of linear serial elastic actuators between the femur and tibia. This configuration presents some characteristics such as tolerance to impact, low mechanical output impedance and passive mechanical energy storage. However, they are heavy devices with high power consumption, making it difficult to use in prosthetics and exoskeletons. Chen and Liao (2010) and Guo and Liao (2012) develop rotating magnetorheological actuators that can work as motor, when need to produce power, as a clutch when necessary to control the output torque, and as brake or damper when it is necessary to dissipate energy. However, they have some limitations. In Chen and Liao (2010) the motor set, gearbox and actuator is too big and too heavy to be used in a prosthesis or exoskeleton. In Guo and Liao (2012), despite the appropriate dimensions, the output torque is insufficient for these applications. The device reaches 0.27 Nm at 1300 rpm (36.8 W), but, according Kawamoto e Sankai (2002) and Kapti and Yucenur (2006), the minimum torque required for a normal walk is $T_{min} > 20.0$ Nm. In many cases the required output power is about 100 W.

This paper describes a test bench for experimental modeling of a magneto-rheological actuator for knee prostheses and exoskeletons, proposed by Andrade et al. (2016). The actuator possesses multiple functions working as motor, clutch, or brake, reproducing the movement closest to a real knee. The test bench uses a National Instruments USB-6003 data acquisition board and LabVIEW tool to control the actuator subsystems and another bench devices and to acquire data from sensors of torque, current, temperature, and others.

2. TEST BENCH DESIGN

The developed MR actuator possesses multiple functions and can provide both active and passive torque for knee prostheses and exoskeletons according to the required task. MR brake is used when braking is needed. When active torque is needed, the motor set, comprised of a DC Motor, a Harmonic Drive and a MR clutch, provides torque enough for a person to climb ramps and stairs. MR clutch and MR brake operate in a similar manner. When the magnetic field is activated, by controlling current in its coils, the relative movement is restricted by the increase in yield stress of the MR fluid, allowing transmission of torque (MR clutch) or dissipation of torque (MR brake).

The workbench was designed in such a way that the overall system provides the possibility to apply and acquire signals from each subsystem that makes up the actuator. This functionality can be achieved by using a data acquisition device NI USB 6003 and the software LabVIEW, both from the vendor National Instruments. Applying inputs and observe responses for each subsystem creates the necessary conditions to the identification process. Proceeding this way, it becomes possible to model the actuator properly. Once the actuator has been modeled, its behavior can be controlled to make it perform some desired tasks by the implementation of a closed-loop control system.

Figure 1 shows the wiring diagram for the experimental workbench to analyze the MR clutch/brake performance. The test bench has a stepper motor that transmits movement to the MR clutch/brake, and a torque transducer (MKTE-

100), for measurements of the transmitted torque. Black lines represent the physical connections, the green ones represents the power line and the blue represents the electrical signals. That is, analogic signals (AI) and pulse width modulation (PWM). The data acquisition device NI USB 6003 disposes of 8 analog input, 2 analog output and 13 digital input/output. Its sample rate is 100 kS/s with a resolution of 16 bits and this make possible to acquire data with a good sample time.

The stepper motor can be controlled from a graphical user interface created on the LabVIEW environment, where is possible to turn the motor on and off and set the desired motor speed. The motor speed is converted to a corresponding PWM signal that is generated from the Arduino 1 device – that is connected to the LabVIEW – and then, this signal is sent to the stepper motor driver (DR-SB050DC04-CS), which performs another conversion and generates a corresponding voltage level to the motor.

When the shaft rotates the generated torque is measured by the transducer torque (MKTE-100) and its signal is transmitted to the graphical user interface through the data acquisition device NI USB 6003. Motor speed is measured by an encoder that is directly connected to the motor shaft. The encoder sends pulses to Arduino 2, which reads the signal and send it to the graphical user interface.

The relay in Figure 1 works as a switch on the coil power circuit of the MR clutch/brake. When it is enabled, the coil circuit inside the clutch, showed in red on the figure, get closed and a current flows generating the necessary magnetic field. This current is measured by a current sensor and its data is sent to the acquisition data device NI USB-6003. Magnitude and direction of the current along the coil is driven by an H-bridge, which is controlled by a PWM signal from Arduino 3 and powered with a 12 volts power supply. By using this circuit, is possible to: enable the current, disable it, change its direction and finally implement a closed-loop control system with a PID controller.

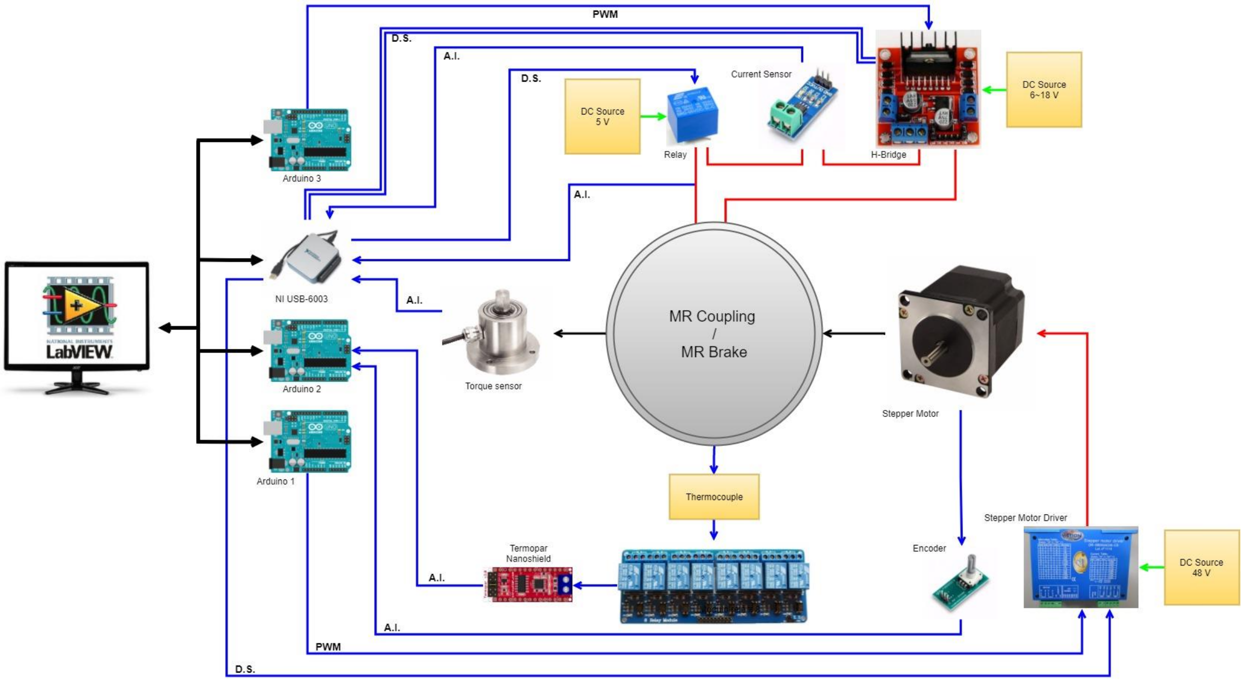

Figure 1. Schematic diagram of the experimental workbench for the MR Clutch and Brake.

Almost all input power on the MR fluid is converted into thermal power (Kowol and Pilch, 2015). Temperature variation due to the energy loss on the MR fluid and at the clutch coil by Joule effects measured by thermocouples directly inserted into the system. A relay module switches between which thermocouple should be read and a Nanoshield Thermocouple module working together with the Arduino 2 performs the reading and conversions of the thermocouple signals and sends them to the graphical user interface.

To produce active torque on the actuator, an EC 60 flat brushless motor of 100 Watt, in series with a CSG-14-100-2a harmonic driver and a driver of the ESCON Servo Controller 70/10 motor are used. Figure 2 show the workbench scheme created for testing the motor of the actuator.

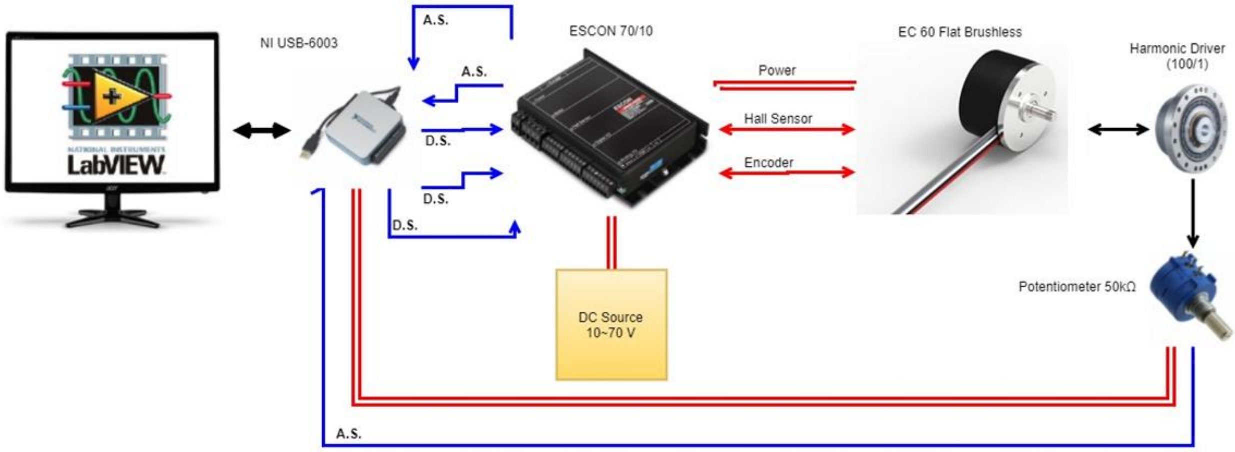

Figure 2. Schematic diagram of the experimental workbench for the EC 60 flat motor and harmonic drive.

The motor driver is powered by a 500 Watt and 48 Vdc power supply and it disposes of analog and digital input and output that communicates with the data acquisition NI USB 6003. This enables monitoring and control of the motor. Three digital inputs are responsible for commands of Enabling, Direction and Stop. To control motor speed, an analog output is sent from the acquisition system to the driver. A level of 0 volts corresponds to 0 rpm and a level of 10 volts corresponds to the maximum motor speed, which is 5000 rpm. The driver feeds back the speed and current of the motor by means of 2 analog output. A level of 0 volts corresponds to 0 rpm and 0 Ampère, and a level of 4 volts corresponds to 5000 rpm and 6 Ampère. To implement a closed-loop control of the harmonic reducer position, a high resolution potentiometer of 50 kΩ and 10 turns is used to read the reducer position. Figure 3 shows the assembled experimental workbench.

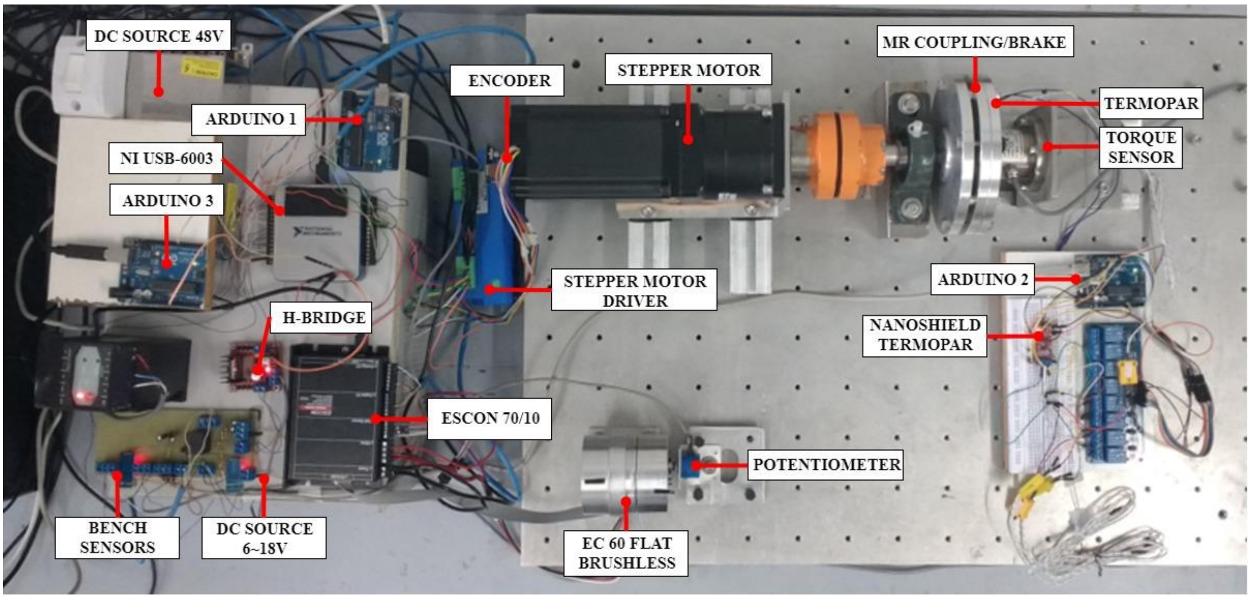

Figure 3. Experimental workbench for modeling of the EC 60 Flat motor and harmonic drive, MR clutch/brake.

3. HUMAN-MACHINE INTERFACE

The test bench interface was developed with the software LabWIEW. The Figure 4 presents the interface for testing the MR clutch and brake. Through the Virtual Instrumentation (VI) of the bench, it is possible to read and calibrate current and voltage in the coils and the torque sensor. In addition to these data, the speed read by the stepper motor encoder and the temperature measured in 08 points of the MR clutch/brake are saved in TDMS format file for further analysis. This format it is the fastest way to acquire and store data on LabVIEW, since it uses only binary operations.

Voltage, current and torque levels are plotted in real-time at the interface for user monitoring. By using the interface it is possible to activate the relay and reverse the current direction on the H-bridge by sending Boolean signals to the data acquisition system.

The system was developed to allow the torque control level in the MR clutch/brake in closed-loop, using the torque read by the sensor MKTE-100 and a PID controller. The controller gains can be changed in the developed interface. These features allow testing the MR clutch and brake more realistically, using as input the torque that the knee performs during gait (Kapti and Yucenur, 2006).

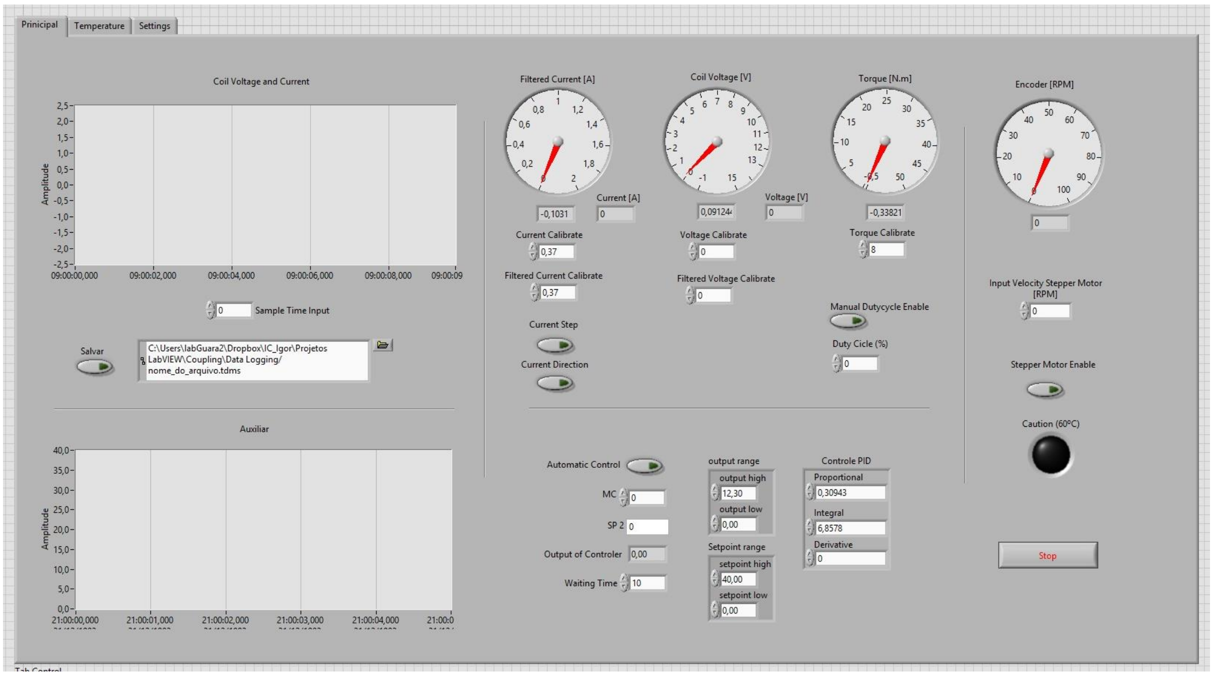

Figure 4. Interface for MR clutch and brake.

Figure 5 shows the interface developed for drive and monitoring the EC 60 Flat brushless motor. It is possible to monitoring in real time the speed, measured by the Hall effect sensor, and the motor current.

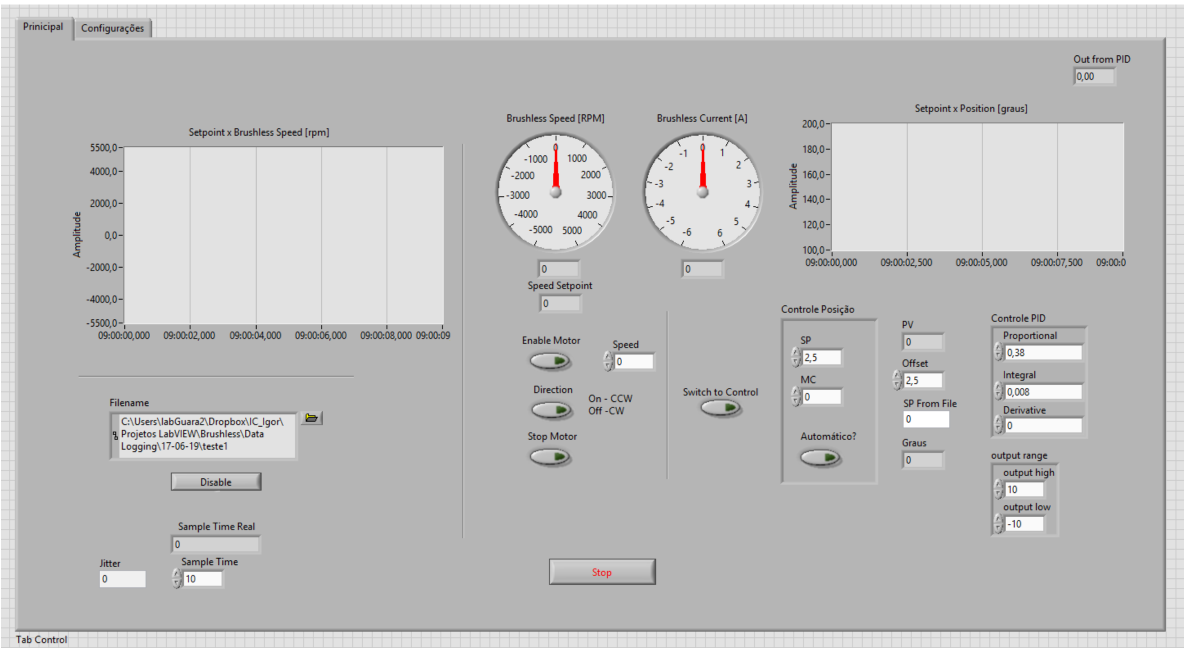

Figure 5. Interface for the EC 60 flat motor and harmonic drive.

The developed LabVIEW interface allows controlling the motor functionality in an open and closed loop system. In open loop it is possible to rotate the motor at different speeds in both directions. In closed loop, it is possible to control the position of the harmonic driver output, using as a feedback signal the position read to the potentiometer. The potentiometer is powered and its signal is measured by the acquisition system considering its voltage level.

4. RESULTS AND DISCUSSION

The testes in the workbench were conducted to evaluate the sample rates, output rates, noise level, accuracy, and repeatability of the data collected.

The first test is shown in Figure 6. The stepper motor was set to rotate at 20 rpm (mean angular velocity of the knee in a normal gait (Kapti and Yucenur, 2006)) and a step of 5.25 Volts, sufficient to achieve 1.0 Ampere current in the MR brake coil, was imposed on the circuit. Current and voltage data were acquired from the coil circuit and torque by the MKTE - 100 sensor.

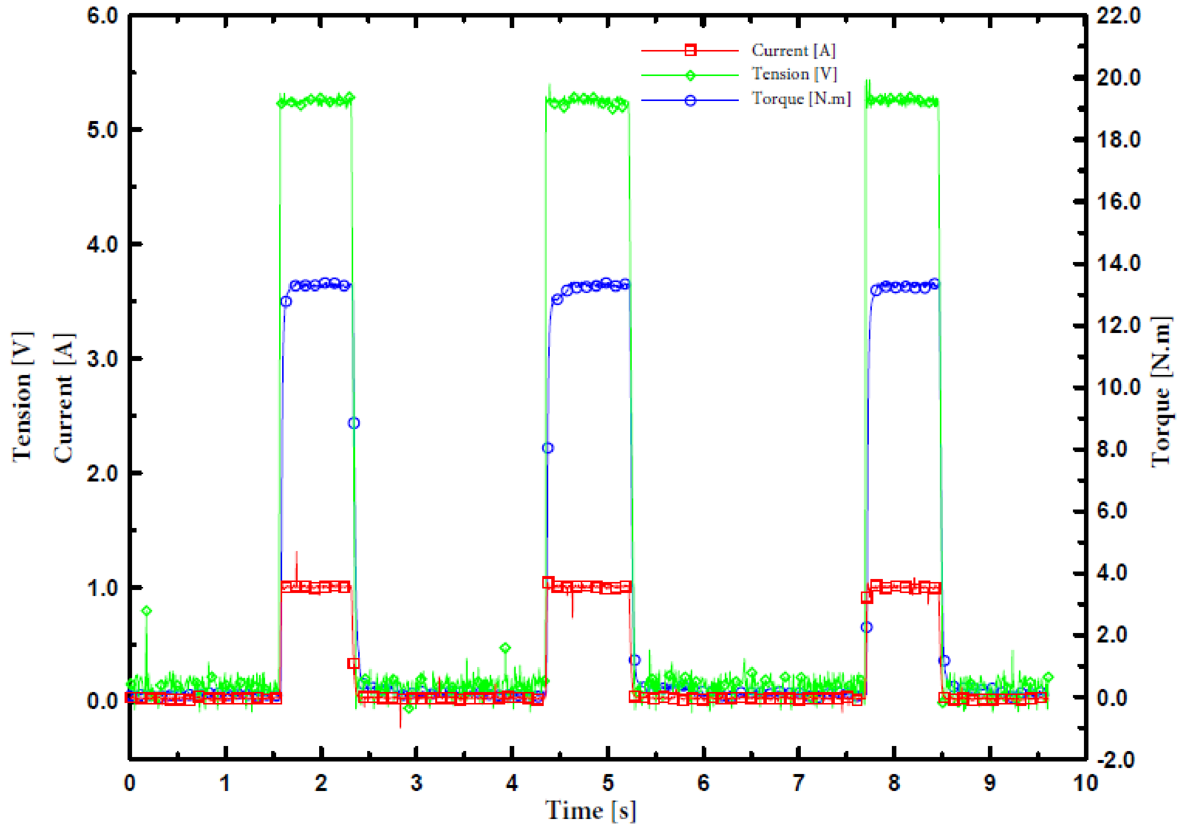

Figure 6. Step input of tension and current and torque response in the MR brake.

All data was collected at a minimum sampling time up to 0.001s, which is sufficient to understand the response characteristics of the MR brake. It is known that MR fluid has a response time in the order of milliseconds (Yang, 2001). By the Figure 6 it is noticed that the reaction of torque in the MR brake, blue circles, to the step input of tension, green diamonds, is very fast. Similar results are observed in the MR clutch.

The second test is presented in Figure 7, where it was evaluated the position of the harmonic drive output with the high precision potentiometer to a step input signal of speed in the EC 60 flat motor. A 10.0 Volts input signal, corresponding to a 5000 rpm, was applied to the analog input of the motor driver via the LabVIEW interface. The Motor accelerates rapidly until the corresponding speed, 5000 rpm, then the direction of rotation was reversed via the interface and then the motor was disabled.

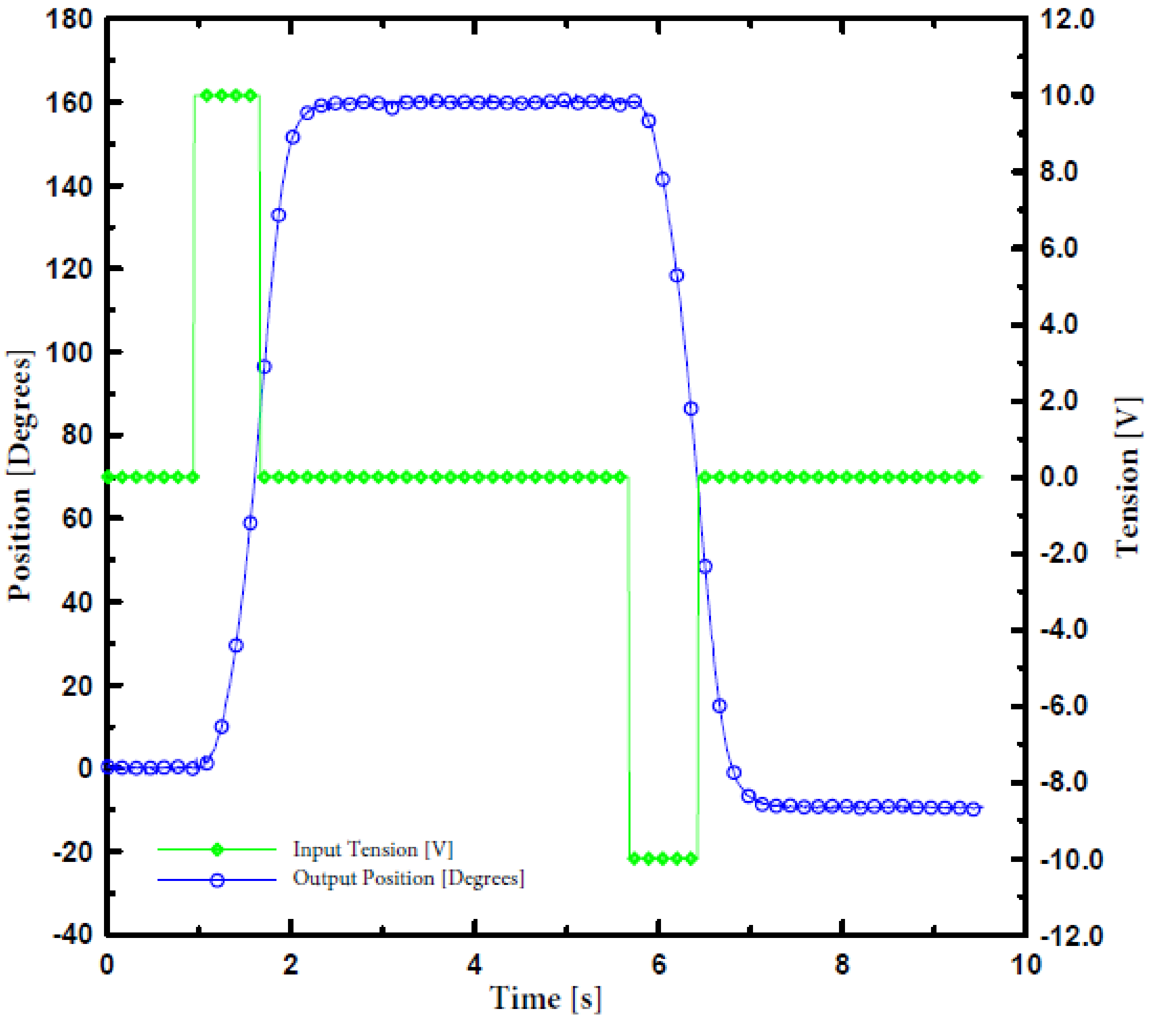

Figure 7. Step input of velocity in the EC 60 flat motor and position of harmonic drive output.

It is noted that the output position response of the harmonic drive with EC 60 flat motor is very fast. The output of the angular position has reached 160º in less than one second. This result indicates that the actuator motor set has sufficient capacity to control angular positioning of the knee during gait.

The future experiments on the bench will be conducted in order to build the dynamic model of the actuator. The experimental models of the MR clutch, MR brake and motor will be compared with the theoretical models implemented in the preliminary experiments carried out before the device being fabricated, in order to validate the design. The experimental modeling of the MR actuator will be important to understand the actual behavior of the device components and to implement a more effective controller.

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