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# A Comparative Study on Control Strategies for FES Cycling Using a Detailed Musculoskeletal Model

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**Abstract:** Although advances in technology promoted new physiotherapy approaches for rehabilitation, there is still an urge for equipment and techniques to improve quality of life for patients with motor disabilities. Functional Electrical Stimulation Cycling (FES Cycling) is an example of this type of technology, in which we control stimulation parameters to enable a spinal cord injured person to ride a bicycle. The presented research proposes a new detailed musculoskeletal platform using OpenSim to test and develop control strategies. With this platform, we were able to compare performance of four control techniques in transient and steady states.



*Keywords:* Neurostimulation, Assistive devices.

## 1. INTRODUCTION

Advances in technology promoted new physiotherapy techniques for restoration of movements in individuals with lower limbs disabilities, such as Spinal Cord Injury (SCI). Functional Electrical Stimulation (FES) stands for a well-known rehabilitation technique for motor functions improvement. It is based on the generation of muscle contraction in order to produce torque (Lynch and Popovic (2012); Martin et al. (2012)). Figoni et al. (1991) and Bélanger et al. (2000) presented FES rehabilitation vantages for SCI individuals, such as enhancement of muscle strength, decrease of bone loss, cardiovascular and respiratory improvement, and quality of life (Szecsi et al. (2014)).

Controllers in FES Cycling regulate pulses trains parameters (frequency, pulse width and current amplitude) to generate enough contraction on muscles to ride a bicycle (Ambrosini et al. (2014); Fornusek et al. (2013)), i.e., the SCI patient legs produce the mechanical work. Although feasible, the greatest challenges of this system remains in finding efficient controllers to provide the necessary stimulation for the desired torques. As electrical stimulation accelerates muscle fatigue (Ibitoye et al. (2014)), time of experiments are limited, avoiding maximum stimulation throughout the entire procedure.

Therefore, complex controllers requiring a high number of trials are still not applicable in real systems, only in simulation (Kim et al. (2008); Li et al. (2010); Peng-Feng Li et al. (2009); Kawai et al. (2014)). In these projects, researchers model cycling movements in different software for proof of concepts. The representations are usually simple and limited due to non-linearity of muscles and bones. As far as we know, there is no free available platform with a detailed musculoskeletal model for cycling.

The main goal of this paper is to provide this platform in order to compare four different control strategies for FES cycling: open loop, phase adjustment, proportional integral control and fuzzy logic control. In each controller, we applied stimulation with three sets of muscle groups: quadriceps, quadriceps and hamstrings, and quadriceps, hamstrings and gluteus.

This paper presents a simulation environment for FES Cycling in Section 2, describing the basic framework and models. In the proposed platform, we performed the four control strategies described in Section 3. We presented and discussed the results in Sections 4 and 5, the simulations suggest that the model performs better with PI Control. Lastly, we exposed our final considerations in Section 6.

## 2. SIMULATION ENVIRONMENT FOR FES CYCLING

### *2.1 Basic Framework*

The basic framework of this FES Cycling Platform requires *OpenSim* and its integration with Matlab.

*OpenSim* The OpenSim platform is a free available, open-source software to simulate highly detailed musculoskeletal models (Delp et al. (2007)) [1]. The software provides kinematics and dynamics tools to understand and analyze motions. Using a graphical interface, users can generate simulations with default models or develop new models and controllers.

These tools measure states variables during simulations. Users can also regulate the muscle excitation in real time

[1] It is being developed in maintained in `https://simtk.org/projects/opensim`

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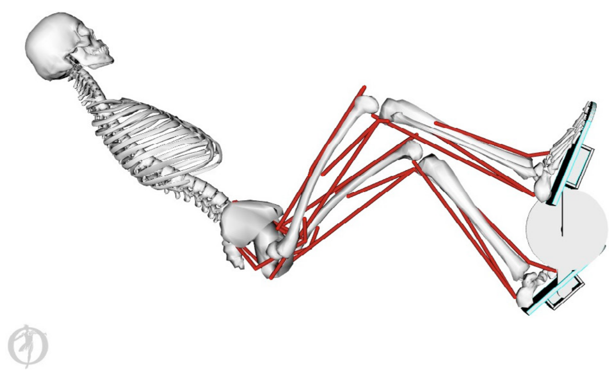

Fig. 1. Complete model for cycling positioned similar to the EMA Trike (Bó et al. (2015)). OpenSim represents muscles as red lines.

for dynamic simulation (for simplicity, we define excitation as the same as stimulation level). For FES control strategies evaluations, we use the forward dynamics tool; however, the OpenSim API only allows open loop analysis.

*OpenSim integration with Matlab for closed-loop control* There are also scripting environments to use OpenSim API without any requirement to set up a development environment. It is possible to access OpenSim tools to create, simulate and analyze models using Matlab.

Nevertheless, basic OpenSim scripting does not enable performing dynamic simulations to integrate closed-loop artificial controllers. In our solution, we convert OpenSim models and states to Matlab components, and perform forward dynamic simulation using Matlab tools (e.g. ode45).

### *2.2 Models*

In order to study control strategies for FES cycling using Opensim, we need a musculoskeletal model containing involved limbs and muscles, as well as its mechanical coupling with pedals and crankset. Such models are not readily available within Opensim database. Fig. 1 illustrates the resulting model developed for this study, in which the lower limbs are attached to the foot support with pedals and crankset.

*Lower limbs* The Lower Limb is a default model[2] simplified for fast simulations, focused in lower extremities. The original model includes 10 degrees of freedom and 18 muscles. We locked lumbar, pelvis and ankles movements to simulate a person riding a bicycle, in which hips and knees run freely. Table 1 presents the locked positions based on the EMA Trike, developed in University at the Brasília (Bó et al. (2015)).

Table 1. Locked degrees of freedom.

| DOF | Value |
|---|---|
| Pelvis Tilt | 45° |
| Pelvis Tx | $0mm$ |
| Pelvis Ty | $0mm$ |
| Ankle Angle Right | 0° |
| Ankle Angle Left | 0° |
| Lumbar Extension Tilt | 0° |

[2] Available in `http://goo.gl/XSaArf`.

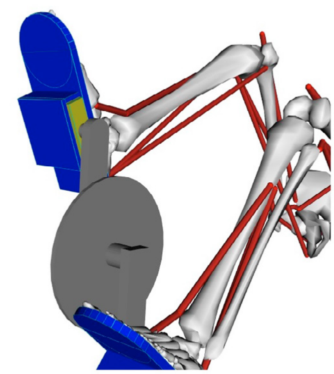

Fig. 2. Detail from the complete model focused at the foot support with pedal and crankset.

State variables of the model are position, speed and force from hips, knees, crankset and pedals. In addition, the available muscles in the model are *Hamstrings*, *Biceps Femoris Short Head*, *Gluteus*, *Iliopsoas*, *Rectus Femoris*, *Vastus Lateralis*, *Gastrocnemius*, *Soleus* and *Tibialis Anterior*.

*Foot support with pedal and crankset* Using the free software Blender, we added three objects to the Lower Limb model, a *drivetrain* and two *foot supports*, as shown in Fig. 2. The drivetrain is divided into *crankset* and *pedals*. The crankset can only rotate in the sagittal plane, and cannot move in translation. The length of the crankset is $78mm$. We attached each pedal ($90mm \cdot 86mm \cdot 26mm$) to the crankset at the end of the crank arms, allowing rotation along the axes perpendicular to the crank arms. The foot support immobilizes the ankles and connects the foot to the pedals through a box in which the pedal is accommodated. Consequently, the foot support transmits the force to the pedal using contact geometries (physical shapes that allow collisions in OpenSim).

## 3. CONTROL STRATEGIES

Cyclists with full volitional muscle control contract a set of muscles to provide necessary torques for pedal stroke. For similar cycling movements, we choose to apply coordinated excitation on the following muscle groups, based on previous work (Hunt (2005); Bó et al. (2015)):

- Quadriceps femoris: excitation of *rectus femoris* and *vastus lateralis* for knee extension;
- Hamstrings: excitation of *hamstrings* for knee flexion and hip extension;
- Gluteus: excitation of *gluteus* for hip extension.

During one pedal stroke, quadriceps provide most torque for the pedal stroke though knee extension. Hamstrings pull the feet to the top while the gluteus provide more power for knee extension. For efficient cycling, these muscle groups must be excited in specific ranges, depending on crankset angle and speed.

Part of the model analysis focuses on how the addition of muscles improves cycling efficiency. Hence, we compared the following set of muscles: (1) quadriceps only (Q), (2) quadriceps and hamstrings (QH) and (3) quadriceps, hamstrings and gluteus (QHG).

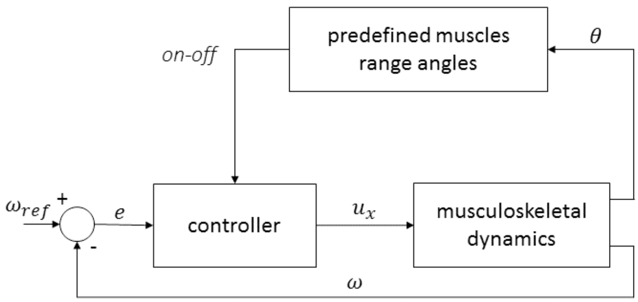


Fig. 3. Cycling control architecture of the controller considering the muscles range angles for excitation.

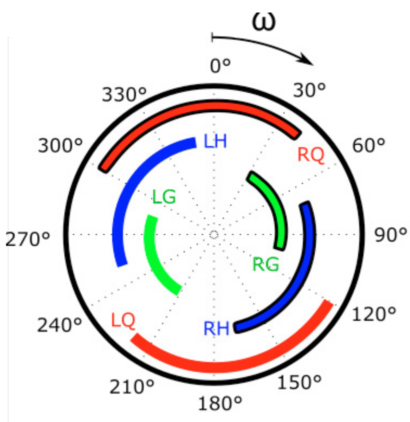


Fig. 4. Muscles range angles for excitation during a pedal stroke. Right and left quadriceps (RQ and LQ) marked as red, right and left hamstrings (RH and LH) as blue, and right and left gluteus (RG and LG), as green. The black contour marks the right leg.

Another part of the analysis compares four types of controllers: Open Loop, Cadence-based Phase Adjustment, Cadence-based Proportional Integral Control (Cadence-based PI Control) and Fuzzy Logic Control (FLC). We compare the error between the desired movement (angle and speed) and also the estimated measure of muscles energy to provide this response.

### 3.1 Open Loop Control

The control structure shown in Fig. 3 incorporates the predefined muscles range angles with the controller. Empirically, we defined ranges to excite each muscle to achieve cycling movement (illustrated in Fig. 4). Then, the controller applies the magnitude of the excitation to the musculoskeletal model. In open loop control, the controller applies maximum excitation for five seconds in order to provide the first pedal stroke. Therefore, the control output is

$$u_x = f_x(\theta)\, h(t)\,, \tag{1}$$

where $u_x$ is the control action for muscle group $x = \{quadriceps, hamstrings, gluteus\}$ and $f_x(\theta)$ stands for the FES on-off phase control that depends on crank angle $\theta$ (Fig. 4). $h(t)$ is the empirically defined excitation that depends on current time $t$.

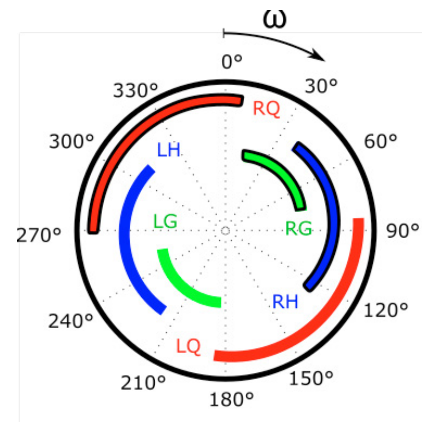


Fig. 5. Muscles range angles for excitation during a pedal stroke for $K = 30°$ and $\omega = \omega_{max}$.

### 3.2 Cadence-based Phase Adjustment

Cycling cadence influences the stimulation range due to artificial delays promoted by the controller and natural delays by the neuromuscular system. These delays cause the stimulation to loose efficiency, since the muscle contractions take place in different angle positions. OpenSim simulates the activation and deactivation time of muscles. We need to counterclockwise a shift angle $\theta_{shift}$ defined as

$$\theta_{shift} = \frac{K}{\omega_{max}}\omega, \tag{2}$$

where $K$ is the correction factor defined empirically, $\omega$ is the current crankset speed and $\omega_{max}$ is the maximum speed for the trial. Fig. 5 presents an example from (2) for $K = 30°$ and $\omega = \omega_{max} = 300°/s$.

The control output $u_x$ is

$$u_x = f_x^{'}(\theta,\omega)\, h(t)\,, \tag{3}$$

where $f_x^{'}(\theta,\omega)$ represents the new shifted range from (2).

### 3.3 Cadence-based PI Control

The cadence-based PI Control manipulates the intensity of the excitation to achieve the required output-cycling cadence. Hence, the controller not only automatically maintains the speed reference $\omega_{ref}$, but also reacts to changes in muscle response, such as disturbances or muscle fatigue. Hunt (2005) computes control output as

$$u_x = f_x^{'}(\theta,\omega)\, h_{pi}(e,\Delta e)\,, \tag{4}$$

where $h_{pi}(e,\Delta e)$ is the PI control for excitation intensity, in which we use the error ($e = \omega_{ref} - \omega$) and the rate of change of error ($\Delta e$) to determine excitation for each muscle (interval of muscle excitation is $[0,1]$).

### 3.4 Fuzzy Logic Control

Another control strategy to achieve the required cadence is Fuzzy Logic Control (FLC). We adapted the presented FLC from Abdulla et al. (2014)

$$u_x = f_x^{'}(\theta,\omega)\, h_{flc}(e,\Delta e)\,. \tag{5}$$

The fuzzy controller ($h_{flc}(e,\Delta e)$) has two inputs ($e$,$\Delta e$) normalized by scaling factors ($G_1$ and $G_2$) and then fuzzified using a set of five equally distributed Gaussian membership functions. The fuzzy output, which results from the fired fuzzy rules of the FLC (Table 2), also follows the defuzzification method.

Table 2. Fuzzy rules (from Abdulla et al. (2014)).

| $e$ | $\Delta e$ | | | | |
|---|---|---|---|---|---|
| | NB | NS | Z | PS | PB |
| NB | NB | NB | NB | NS | Z |
| NS | NB | NB | NS | Z | PS |
| Z | NB | NS | Z | PS | PB |
| PS | NS | Z | PB | PB | PB |
| PB | Z | PB | PB | PB | PB |

## 4. RESULTS

We simulated each configuration (controller and muscle group) for 30 seconds. Controllers activation frequency are 50 Hz, and speed reference is $200°/s$ for the first $20s$ and $300°/s$ for the last $10s$. The model initial position is with the right foot standing on the top, at $\theta = 0°$, and all states with $w = 0°/s$. In each controller, we kept the same initial parameters in order to compare robustness.

### *4.1 Performance measures*

From these simulation responses, we calculated and compared the rise time, overshoot, maximum error, root-mean-square deviation error and muscles excitation levels (Table 4) for each configuration.

The rise time ($t_r$) is the time the cycling takes to change from 10% to 90% of $w = 0°/s$, and the overshoot ($PO$) is the maximum peak value of the response minus the target speed.

We considered the steady states the intervals $t_1$ between 14 to 19 seconds and $t_2$ between 24 to 29 seconds. For analysis, we calculated the maximum errors ($e_{max1}$ and $e_{max2}$) and the RMSE ($e_{RMSE1}$ and $e_{RMSE2}$) in $t_1$ and $t_2$. The last parameter is a estimated measure of energy $\Phi$ defined as the integration of excitations

$$\Phi_x = \frac{\sum_{i=1}^{n} \phi_{x_i}}{\Phi_{max}}, \tag{6}$$

where $\phi_{x_i}$ is the excitation intensity of muscle group $x = \{quadriceps, hamstrings, gluteus\}$ in iteration $i$, $n$ is the number of samples of the simulation and $\Phi_{max}$ is the maximum excitation ($\phi_{x_i} = 1$ for the entire simulation). There is no differentiation between right and left muscles, therefore $\Phi_Q$, $\Phi_H$ and $\Phi_G$ stand for the sum between left and right quadriceps, hamstrings and gluteus, respectively.

The following sections present the parameters that we defined and the controllers response.

### *4.2 Simulation data*

To achieve the reference in open loop, we empirically found values for $h\,(t)$. All configurations were able to cycle if the start excitation ($t < 5s$) were maximum for the first $5s$. Table 3 presents the values used in Q, QH and QHG.

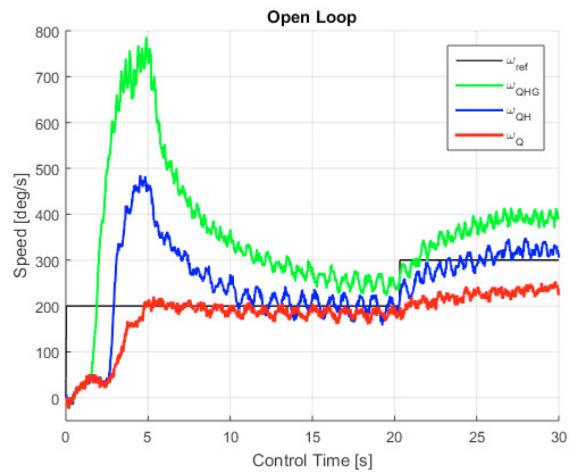


Fig. 6. Speed results for each 30s simulation trial of open loop for muscles group Q (red), QH (blue) and QHG (green).

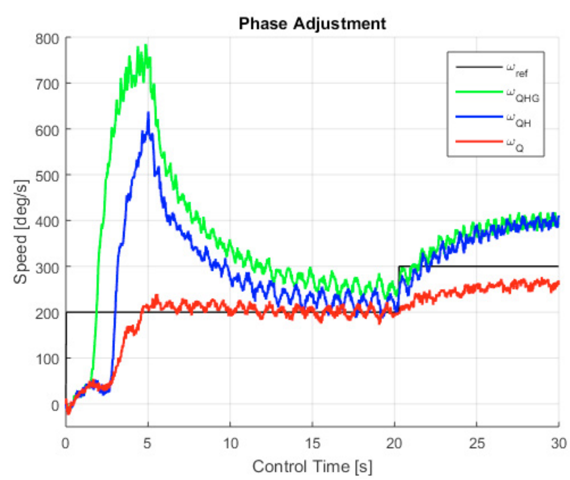


Fig. 7. Speed results for 30s simulation of phase adjustment for muscles group Q (red), QH (blue) and QHG (green).

The speed results presented in Fig. 6 shows that, with more muscles excited, the model produces higher velocities in less time, despite the larger overshoots. In addition, less excitation is necessary to provide and maintain the reference speed, as shown in Table 4.

For comparison, we maintained the same values from table 3 and empirically established $K = 30°$ and $\omega_{max} = 500°/s$ from (2). Cadence-based phase adjustment provides higher speed values at full excitation (compare blue line from Fig. 6 and 7, and $PO$ values from Table 4).

For the three muscle group configurations, we used the same proportional and integral coefficients $K_p = 1.2$ and $K_i = 1.0$ for the PI control, found empirically. The

Table 3. Values for $h\,(t)$.

| | $t < 5s$ | $5 < t < 20$ | $t > 20$ |
|---|---|---|---|
| Q | 1.00 | 0.65 | 0.80 |
| QH | 1.00 | 0.45 | 0.60 |
| QHG | 1.00 | 0.40 | 0.50 |

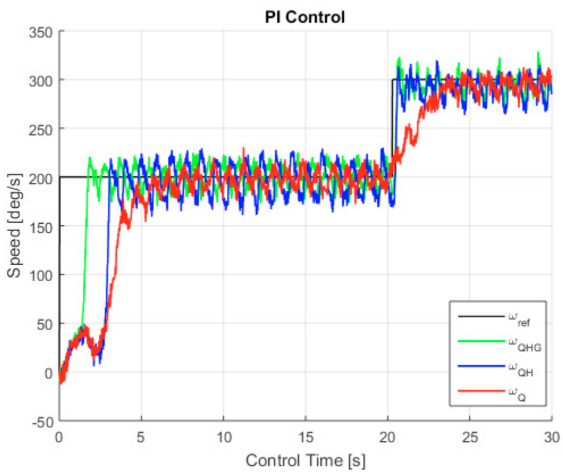


Fig. 8. Speed results for 30s simulation of PI control for muscles group Q (red), QH (blue) and QHG (green).

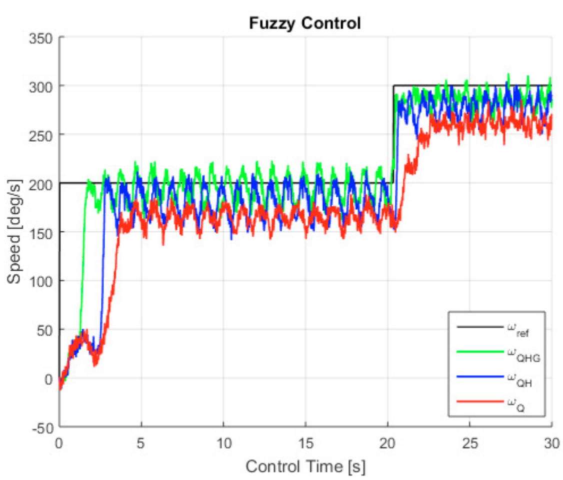


Fig. 9. Speed results for 30s simulation of FLC for group muscles Q (red), QH (blue) and QHG (green).

controller adjusts the speed and lowers excitation needed for the desired movement (Fig. 8).

Empirically, we defined the scaling factor $G_1 = 1.4$ for $e$ and $G_2 = 0.022$ for $\Delta e$ and simulated the FLC for the three muscle configurations (Fig. 9).

## 5. DISCUSSION

As a simulation platform, OpenSim offered the possibility to conduct several experiments without the fatigue drawback in real subjects. The model developed proved to be valid, providing expected results for FES Cycling. However, despite these promising results, the platform still requires a comparison with real experiments.

It is also necessary to update the model with new features for better approximations. OpenSim already allows the creation of new actuators dependent on state values (e.g., speed). These variables allow the simulation of crankset loads and disturbances. We can also implement a fatigue model, in order to evaluate the control response, and commercial stimulator models, to approximate its parameters (pulse width, frequency or current intensity).

All controller strategies presented were able to perform cycling with the muscles groups defined in Section 3. As expected, the use of more muscles provided more torque to cycling. In consequence, we achieved higher maximum speed and lower rise time (Fig. 6, 7, 8, 9 and Table 4).

In Open Loop and Cadence-based Phase Adjustment, it is still possible to achieve lower maximum errors and RMS with different values than the ones presented in table 3. However, open loop in FES cycling is inefficient due to a numerous of disturbances presented in real cycling: loads in the bicycle, bumps on the ride and muscle reactions. The research efforts focus on development and tests of more robust closed loop controllers. Sensors (e.g., IMU and force contact sensors on pedals) are easy to append to the setup. In addition, stimulation leads to faster fatigue (Ibitoye et al. (2014)), therefore the controllers ought to apply stimulation more efficiently with closed loop approaches (lower levels of excitation $\Phi_x$).

As PI controllers are easier to design ($K_p$ and $K_i$ adjustments), the presented simulations showed that PI control provided the best response in steady state (lower $e_{max}$ and $e_{RMS}$) compared to FLC. For linear or linearized plants, PI control has a simple structure. However, musculoskeletal systems are nonlinear, which explain the effort to use fuzzy logic controllers in FES Cycling. The FLC results showed better results in transient state (lower $t_r$ and $PO$), indicating that the controller responds better to nonlinearities and uncertainties of the musculoskeletal model. We consider that it is possible to improve the FLC with a more meticulous adjustment of table of rules, scale gains and membership functions.

In FES, a significant feature is the excitation level, as lower excitations lead to lower fatigue. It is understandable that closed loops provide more efficiently levels of stimulation to achieve the reference speed. Specifically in the implemented control strategies, the PI controller applied higher excitations; however, FLC was not able to achieve the reference speed.

## 6. CONCLUSION

Although FES provides clinical benefits for the user, controllers performance is still limited. In this scenario, we presented a detailed musculoskeletal model for FES Cycling for comparative simulation studies on control strategies. Preliminary evaluation provided a satisfactory platform, in which we can test new controllers more accurately and straightforwardly. The platform already offers tools for performance analysis and its integration with Matlab makes it more familiar to engineers. Using the presented platform, we were able to expose how PI control responds better in steady state and fuzzy logic control for transient state in FES Cycling.

## ACKNOWLEDGEMENTS

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Table 4. Error and Excitation for analysis.

| Open Loop | $t_r$ | $PO$ | $e_{max1}$ | $e_{max2}$ | $e_{RMSE1}$ | $e_{RMSE2}$ | $\Phi_Q$ | $\Phi_H$ | $\Phi_G$ |
|---|---|---|---|---|---|---|---|---|---|
| Q | 4.0200 | 21.0 | 39.9135 | 94.6912 | 0.3250 | 1.2269 | 0.2100 | - | - |
| QH | 2.2600 | 284.9 | -37.5040 | -48.6967 | 0.3002 | 0.3751 | 0.1658 | 0.1371 | - |
| QHG | 1.1800 | 586.3 | -99.9098 | -114.3801 | 1.0559 | 1.5172 | 0.1568 | 0.1289 | 0.0960 |
| **Phase Adjustment** | $t_r$ | $PO$ | $e_{max1}$ | $e_{max2}$ | $e_{RMSE1}$ | $e_{RMSE2}$ | $\Phi_Q$ | $\Phi_H$ | $\Phi_G$ |
| Q | 3.7800 | 40.0 | 27.5366 | 64.0234 | 0.1772 | 0.7621 | 0.2096 | - | - |
| QH | 2.3400 | 438.0 | -56.0704 | -111.2330 | 0.4921 | 1.4446 | 0.1605 | 0.1390 | - |
| QHG | 1.2200 | 585.3 | -98.4809 | -118.7917 | 1.0840 | 1.5721 | 0.1567 | 0.1286 | 0.0994 |
| **PI Control** | $t_r$ | $PO$ | $e_{max1}$ | $e_{max2}$ | $e_{RMSE1}$ | $e_{RMSE2}$ | $\Phi_Q$ | $\Phi_H$ | $\Phi_G$ |
| Q | 4.1400 | - | 27.9454 | 29.0088 | 0.1676 | 0.1701 | 0.2093 | - | - |
| QH | 2.4800 | 19.2 | 36.3964 | 36.4430 | 0.2845 | 0.2702 | 0.0824 | 0.0503 | - |
| QHG | 1.1600 | 20.7 | 26.8553 | 32.5926 | 0.2077 | 0.1948 | 0.0893 | 0.0154 | 0.0555 |
| **FLC** | $t_r$ | $PO$ | $e_{max1}$ | $e_{max2}$ | $e_{RMSE1}$ | $e_{RMSE2}$ | $\Phi_Q$ | $\Phi_H$ | $\Phi_G$ |
| Q | 3.9400 | - | 57.6800 | 61.2240 | 0.6183 | 0.6938 | 0.1803 | - | - |
| QH | 2.2000 | 6.9 | 49.7057 | 49.9101 | 0.4153 | 0.4245 | 0.0960 | 0.0636 | - |
| QHG | 1.0400 | 4.2 | 38.1635 | 42.6996 | 0.2725 | 0.3154 | 0.0774 | 0.0298 | 0.0573 |

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