INCLUDING NON-IDEAL BEHAVIOUR IN SIMULATIONS OF FUNCTIONAL ELECTRICAL STIMULATION APPLICATIONS

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Abstract

Simulations of FES systems are usually based on the typical or ideal stimulated muscle response, which may result in an overly optimistic prediction of the FES system's performance in real-world applications. We have developed a Simulink block that allows actual non-ideal behaviour of electrically stimulated muscles to be incorporated into existing FES simulations. This block is based on data collected from complete SCI subjects, and it modifies the nominal stimulated muscle response to reflect undesirable behaviour seen in real-world FES applications, including spasms, tremors, and fatigue. The severity of each type of undesirable behaviour can be specified by the user. In this paper, we discuss the design of the block, and also present an example of how the block can be used to more accurately assess the probable real-world performance of FES systems prior to testing with SCI subjects.

Keywords: *functional electrical stimulation, spinal cord injury, stimulated muscle response, model, simulation*

Introduction

Functional electrical stimulation (FES) can be used to restore or replace lost motor function in individuals who have spinal cord injuries (SCI). Each new FES application must be thoroughly tested with SCI individuals. However, it is time-consuming and expensive to recruit suitable subjects, re-condition the subjects' muscles using electrical stimulation, and then conduct exhaustive testing to verify the performance of a particular FES system.

For these reasons, it is common to refine the design of a FES system in simulation prior to the testing phase. Such simulations are usually based on models of the typical or ideal stimulated muscle response, which may result in an overly optimistic assessment of the FES system's likely performance in the real world. Stimulated muscle contractions in individuals with SCI are subject to fatigue, muscle spasms, and tremors due to incomplete tetanus, in addition to other undesirable effects. It is necessary to account for these non-idealities in an accurate simulation of the real-world performance of a FES system.

We created a Simulink block (The Mathworks, Natick, USA) that represents the range of spasm, tremor, and fatigue behaviour that stimulated muscles exhibit in the real world. This block uses data collected from complete SCI subjects, and modifies the nominal stimulated muscle response to reflect the undesirable behaviour seen in the real world. This "non-idealities block" can be incorporated into existing FES simulations in Simulink to analyze the performance of FES systems in the presence of undesirable behaviour.

This paper presents our pilot work on this project. We discuss the design of the block, and also present an example of how the non-idealities block can be used to assess the likely real-world performance of a FES system.

Material and Methods

Data Analysis

We developed the non-idealities block using previously collected data from subjects with complete SCI. The experiments were approved by the local research ethics board, and all subjects provided informed consent.

We extracted the muscle spasm and tremor data from experiments done with a single complete SCI subject. The subject's muscles were re-conditioned using electrical stimulation prior to data collection. The subject was seated with the shank free to swing during the data collection experiments. We transcutaneously stimulated the subject's quadriceps muscle group with a Compex Motion stimulator (Compex SA, Switzerland) using a bipolar, biphasic square wave pulse train with pulse width 250 μs and frequency 40 Hz. The stimulation amplitude was randomized for each trial between 0 mA and a pre-set maximum amplitude. We sampled the resulting knee angle at 100 Hz for 5 seconds after the onset of stimulation, by which time the knee angle had reached its steady state behaviour in each trial. We passed each trial through a de-noising filter. After identifying those trials that exhibited muscle spasms or tremors, we extracted only the spasm or tremor behaviour from the affected trials. The resulting spasm waveforms are zero except where the spasms are present, and the tremor waveforms are centred about zero. We also assigned each spasm and tremor waveform a classification of mild, moderate, or severe with respect to its particular type of undesirable behaviour.

We extracted the fatigue waveforms from data from a separate experiment done with seven complete SCI subjects. The experimental setup was similar to that of the experiment described above, except this experiment concerned isometric contractions of the quadriceps or tibialis anterior muscles. The stimulation amplitude was determined individually for each subject and each muscle to produce maximal force, and the isometric force was sampled at 100 Hz during 2 minutes of maximal electrically stimulated contractions [1]. We used a polynomial fit to approximate each force curve, and then scaled each curve from 1 to 0 to generate a fatigue waveform, with 1 corresponding to no fatigue and 0 corresponding to no measurable response to stimulation. We then classified each fatigue waveform as mild, moderate, or severe.

Construction of Non-idealities Block

The output of the non-idealities block can be described by

$$v(t) = (\tau(t) + s(t) + m(t)) \cdot fat(t)$$

where $\tau(t)$ is the nominal response of the stimulated muscle, $v(t)$ is the modified, realistic stimulated muscle response, and $s(t)$, $m(t)$ and $fat(t)$ are instances of the spasm, tremor, and fatigue waveforms, respectively. We implemented the block using a MatLab S-function, which defines a custom Simulink block. The user can vary the severity of the fatigue, spasm, and tremor waveforms that are included in a particular instance of the block. The actual waveform that is used for each facet of the block (spasm, tremor, and fatigue) is selected randomly from the group of waveforms having the desired classification (mild, moderate, or severe) each time the simulation is run.

Example of Block Implementation

We implemented the non-idealities block in a FES simulation to show how this block can be used to examine the potential real-world behaviour of a FES system. The example is a simulation of PID control of knee angle, based on the model of stimulated knee response described by Ferrarin and Pedotti [2]. Knee extension is provided by stimulated quadriceps contractions, and knee flexion is provided by gravity. Fig. 1 shows a block diagram of this simulation. We recorded unit step response metrics for the nominal case and using the non-idealities block with different parameter values.

Results

Fig. 2 shows how the non-idealities block modifies the nominal stimulated muscle response. The dotted line corresponds to the simulated nominal knee torque produced at the maximum stimulation amplitude in the open-loop. The solid line corresponds to the modified torque produced by the non-idealities block with mild spasms, mild tremors, and mild fatigue. Fig. 3 shows the response of the knee angle control example to a 60 degree unit step trajectory (Kp = 175, Ki = 250, Kd = 325). The dotted line corresponds to the step response without the non-idealities block. The solid line corresponds to the same response with the non-idealities block (mild spasms, tremors, and fatigue).

Table 1 shows selected unit step response metrics [3] for the knee control example. The settling time is not given because only the nominal case settled to with 2% of the desired steady-state value. The results for the moderate and severe cases of spasms, tremors, and fatigue were similar to but more pronounced than those shown in Table 1.

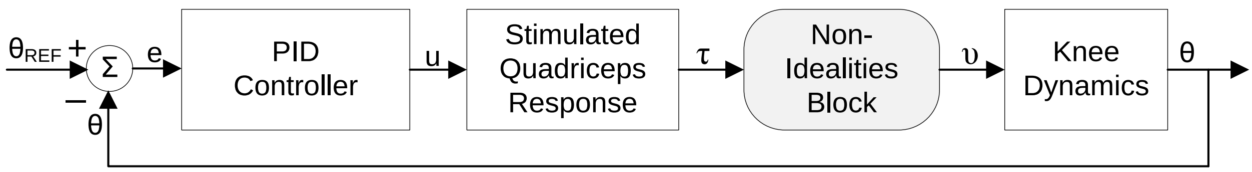

Fig. 1: Block diagram of simulation of PID control of electrically stimulated knee angle θ.

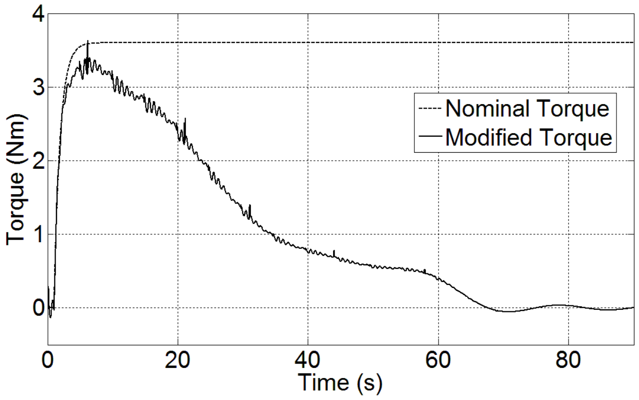

Fig. 2: Nominal knee torque at maximum stimulation, and modified torque generated by non-idealities block for mild spasms, tremors, and fatigue.

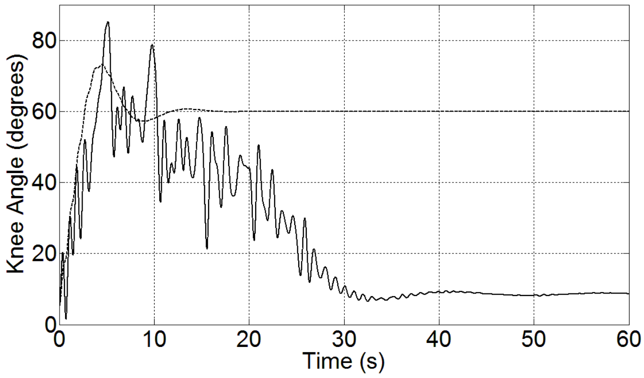

Fig. 3: Response of knee control example to 60 degree unit step trajectory. Dotted line is without non-idealities block. Solid line is with non-idealities block (mild spasms, tremors, and fatigue).

Table 1: Unit step response metrics for knee angle control example.

Case	10%-90% Rise Time (s)	Over-shoot (%)	RMS Error (deg)
Nominal	2.21	22.10	5.01
Mild Fatigue Only	2.24	21.00	41.77
Mild Spasm Only	2.14	22.14	5.06
Mild Tremor Only	3.53	45.65	11.73
Mild Fatigue, Spasm, and Tremor	3.51	42.15	46.54

Discussion

The modified torque produced by the non-idealities block is clearly different from the nominal torque. The spasms did not significantly degrade the performance of the control system, but fatigue and tremors both had a large effect on control performance. All combinations of undesirable behaviour resulted in poorer performance than the corresponding undesirable behaviours in isolation.

The non-idealities block represents a worst-case scenario with no muscle recovery. In reality, control performance will likely be modestly better than is indicated by the simulated results, since some recovery will occur during periods of no stimulation. Also, we use fatigue data collected from isometric contractions of untrained quadriceps muscles. Isotonic contractions in trained muscles may result in different fatigue profiles than those used in the non-idealities block.

Conclusions

We have developed a Simulink block that introduces realistic undesirable behaviour into simulations of the performance FES systems. This non-idealities block is based upon actual stimulated muscle responses of subjects with complete SCI, and allows researchers to assess the likely real-world performance of FES systems before testing with SCI subjects, thereby saving time and expense.

In the future, we plan to expand this work by including additional stimulated response data from SCI subjects. We also plan to make the MatLab code for this project freely available on our website for use by others in the FES field.

References

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