Fractional Horsepower Dynamometer – A General Purpose Hardware-In-The-Loop Real-Time Simulation Platform for Nonlinear Control Research and Education

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Objective:

To meet the requirement of testing the nonlinear and adaptive control schemes before testing them on real world machines.

Plant Description:

The dynamometer contains a geared DC motor which is connected, through a flexible coupling, to a hysteresis brake which provides load torque. The rotor shaft is also connected to an incremental encoder and a load cell.

The **Magtrol Hysteresis Brake**[1] used in the dynamometer produces torque strictly through an air gap, without the use of magnetic particles or friction components. The amount of braking torque transmitted by the brake is proportional to the amount of current flowing through the field coil. The brake and the motor are each driven by an Advanced Motion Controls Brush Type PWM Servo Amplifier Model 50A8.

Position and velocity measurements are performed on the dynamometer with the help of a **Lucas Ledex S-9974-1024** incremental encoder. This encoder outputs 1024 bits per revolution on two quadrature lines. The system also has a **Redington model no. 7631 tachometer** for velocity measurement.

The **MDB-10 load cell** from Transducer Techniques provides the force feedback on the dynamometer. The load cell senses torsional force from the hysteresis brake assembly. To reduce vibrations due to heavy mass of the brake, the moment arm of the brake is connected to a damper cylinder.

Abstract: This poster presents a hardware-in-the-loop real-time simulation platform for emulating mechanical nonlinearities such as friction, state-dependent disturbances etc. The novelty of this platform lies in generating arbitrary external load torque disturbances, using a controllable hysteresis brake, to a DC motor plant. Therefore many nonlinear systems and control schemes can be emulated physically.

Architecture:

The dynamometer can be operated using two two different sets of hardware for Matlab and LabVIEW software environments:

- **National Instruments (NI) LabVIEW** programs with graphical user interfaces (GUIs) were developed to test various parameters like torque, speed, current etc. for the DC motor. The GUIs provide real-time parameter monitoring for the DC motor. The dynamometer is interfaced to the PC through an NI AT-MIO-16DE-10 data acquisition card[2]. It has two 12-bit analog outputs, two 24-bit, 20 MHz counter/timers, and 32 digital I/O lines.

- **Matlab/Simulink** with Real-Time Workshop is used to test nonlinear control schemes using a Quanser MultiQ3 terminal board[3] that has 8 encoder inputs, 8 single-ended or differential analog inputs, 8 analog outputs, 16 digital inputs, and 16 digital outputs. The Matlab/Simulink environment uses the WinCon[4] application, from Quanser to communicate with the Quanser MultiQ3 data acquisition card. Win-Con is a Windows-based application that runs Simulink models in real-time on a PC. This brings rapid prototyping and hardware-in-the-loop simulation capabilities to Simulink models. The Matlab Real-Time Workshop generates C code from the Simulink model, which results in a Windows executable file that is run by Win-Con independently of Simulink. WinCon's architecture ensures that the real-time process is afforded the highest CPU priority and is not preempted by any competing tasks other than the core OS functions.

Proposed Applications:

- **Research – Rapid Testing and Prototyping of Nonlinear Controllers:**

Consider a generalized servo control problem:

$$\dot{x}(t) = v(t)$$
$$\dot{v}(t) = -f(t,x) + u(t)$$

where $x(t)$ is the position, $v(t)$ is the velocity, $f(t,x)$ is the unknown disturbance, which can be state dependent or time dependent, and $u(t)$ is the control input. The DC motor in the dynamometer can be modeled as a first order system. Moreover, the presence of hysteresis brake allows us to add time-dependent or state-dependent disturbance to the motor. These factors combined can emulate a system similar to the one given by above equations. A nonlinear controller can be designed for such a problem and can be tested in the presence of the real disturbance as introduced through the dynamometer. This eliminates the need for costly equipment to test nonlinear control algorithms and the system can be used as preliminary test bench for testing such theories. As shown in the next section, some of such nonlinear and adaptive control schemes like repetitive control (RC), adaptive coulomb friction compensation (ACFC), state-periodic adaptive learning control (SPALC) for state-dependent disturbance, adaptive feedforward cancellation (AFC) and sliding mode control (SMC) have been tested on the dynamometer as sample nonlinear control experiments.

- **Education:**

This setup can be used as a laboratory experiment for control and systems courses. At undergraduate level it can be used to teach techniques like sensor calibration, PID controller design and hardware-software interfacing. At graduate level it can be used to get a hands-on experience of complex adaptive controller design schemes.

Acknowledgement:

We are grateful for the financial support from the CSOIS for original development of this setup under the supervision of Dr Carl Wood.

Fig. 1 The Dynamometer

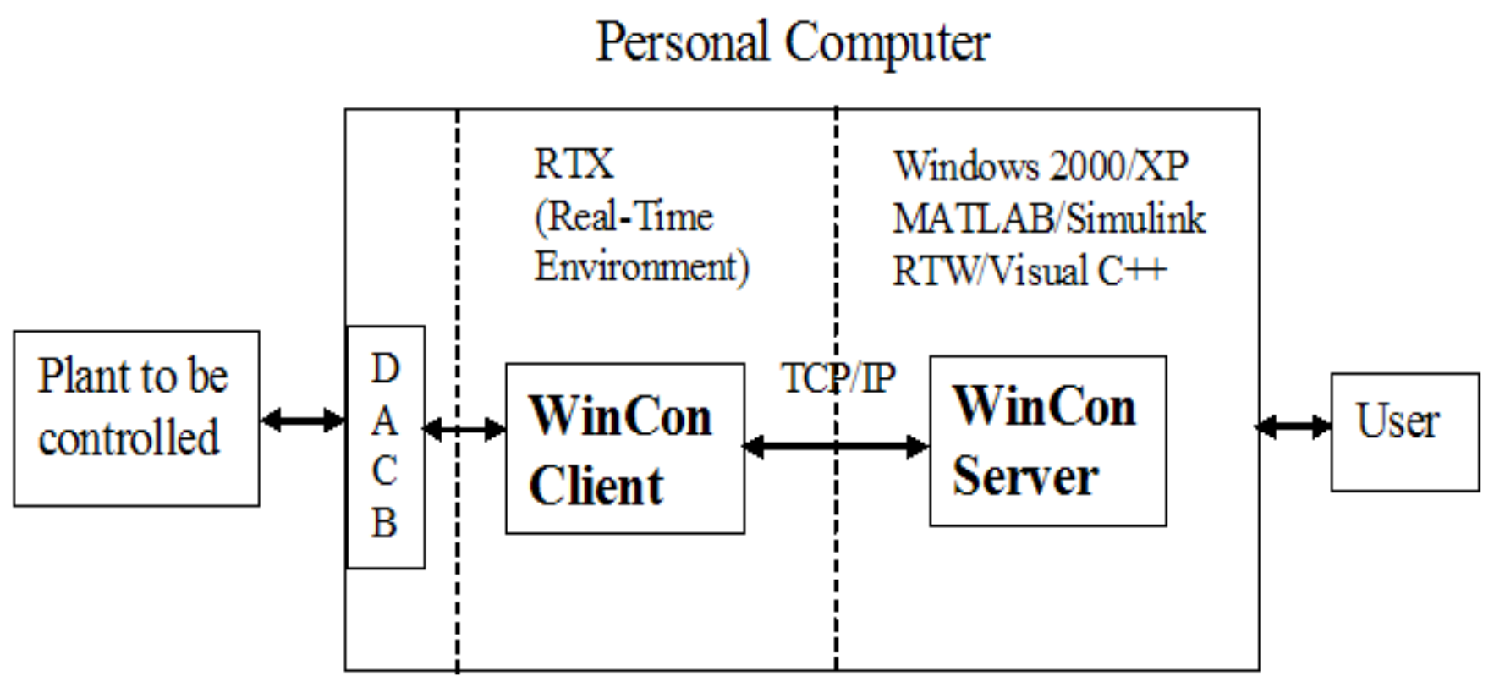

Fig. 2 Software Architecture

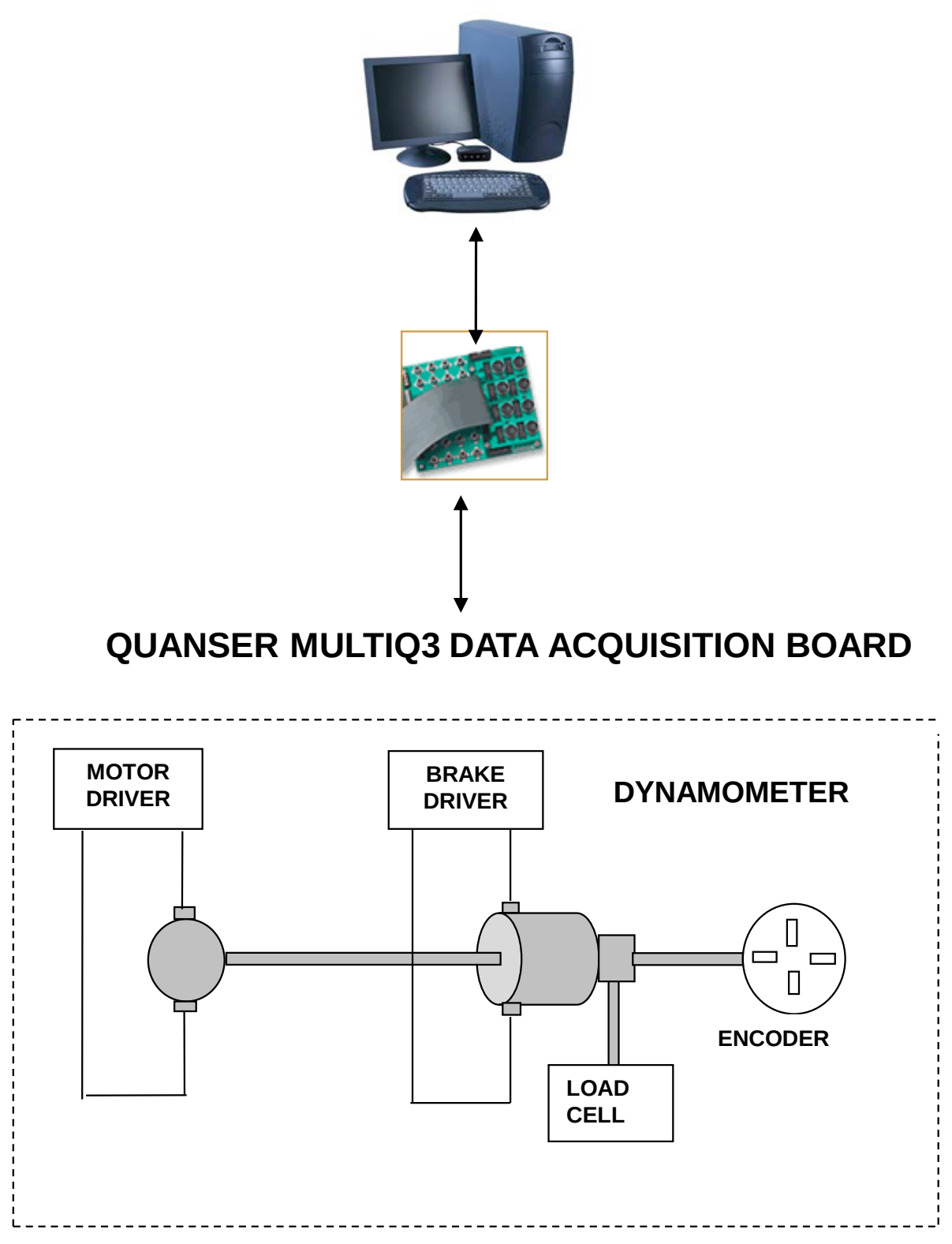

Fig. 3 Hardware Architecture

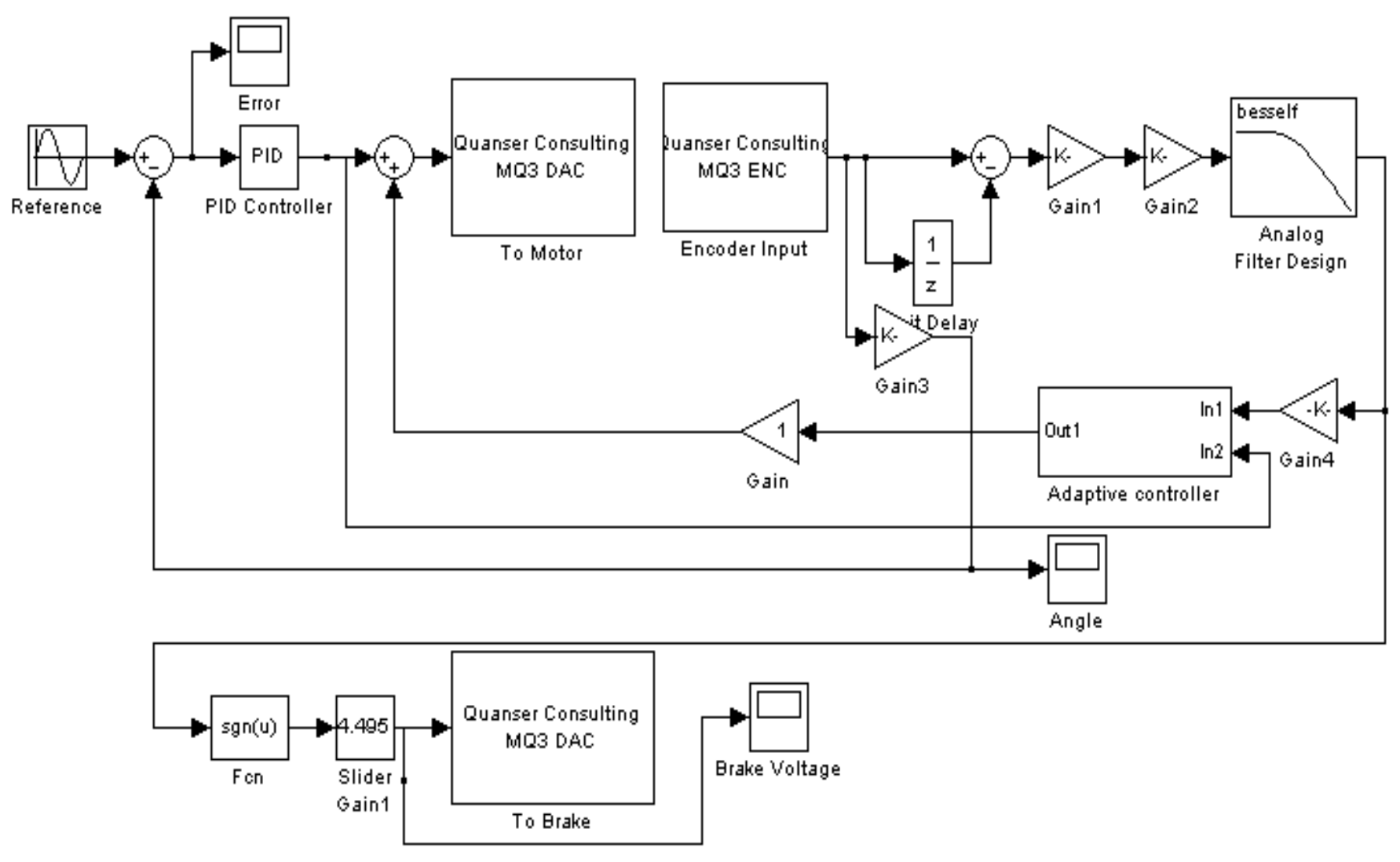

Fig. 4 The Simulink Model for Testing

[1] http://www.magtrol.com/datasheets/hb-mhb.pdf
[2] http://sine.ni.com/nips/cds/view/p/lang/en/nid/11924
[3] http://www.quanser.com/english/html/solutions/fs_soln_hardware.html
[4] http://www.quanser.com/english/html/solutions/fs_soln_software_wincon.html

Experimental Verification of Some Nonlinear Control Schemes On The Dynamometer

State-Periodic Adaptive Learning Control (SPALC):

This examples emulates state-dependent disturbance and tests an adaptive controller to track position signal given by $x(t) = 2\pi\sin(2\pi t/20)$. Here the disturbance is given by $f(t,x)=a(x)sgn(v(t))$, where $a(x)$ is the unknown disturbance (brake voltage) parameter that depends on position of motor shaft.

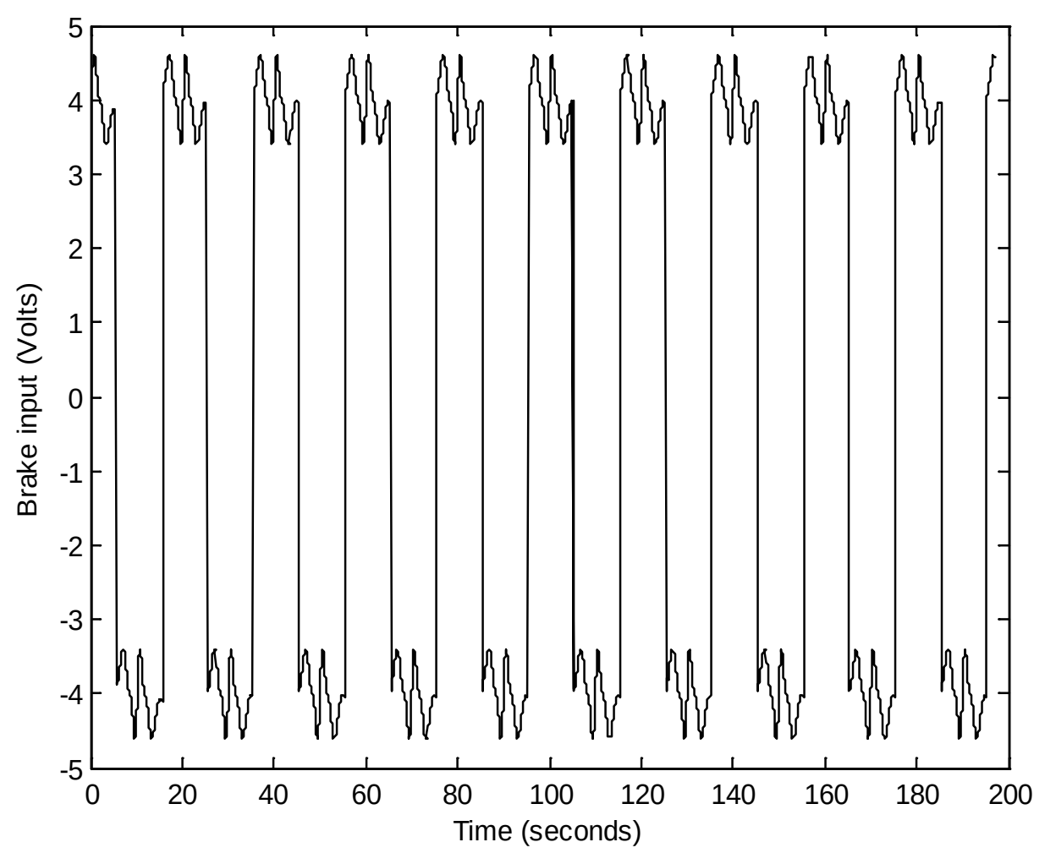

Fig. 5 State-dependent disturbance (brake voltage)

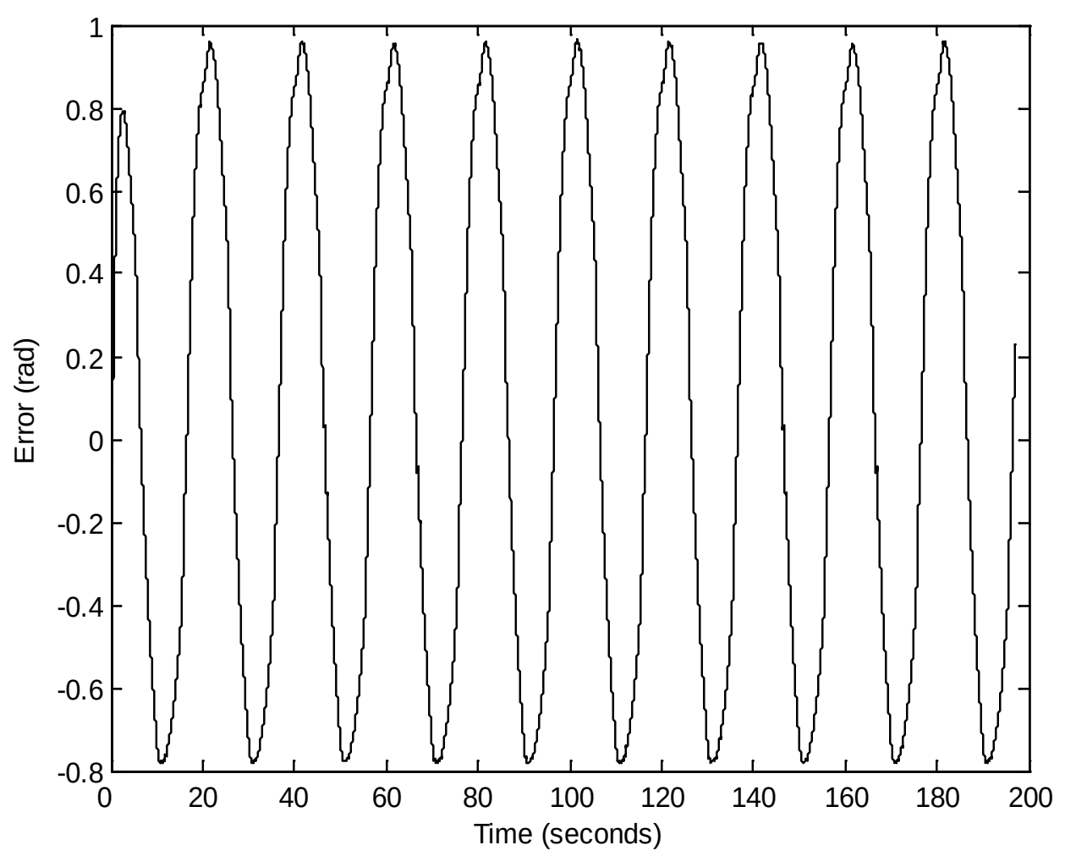

Fig. 6 Tracking error with PD controller

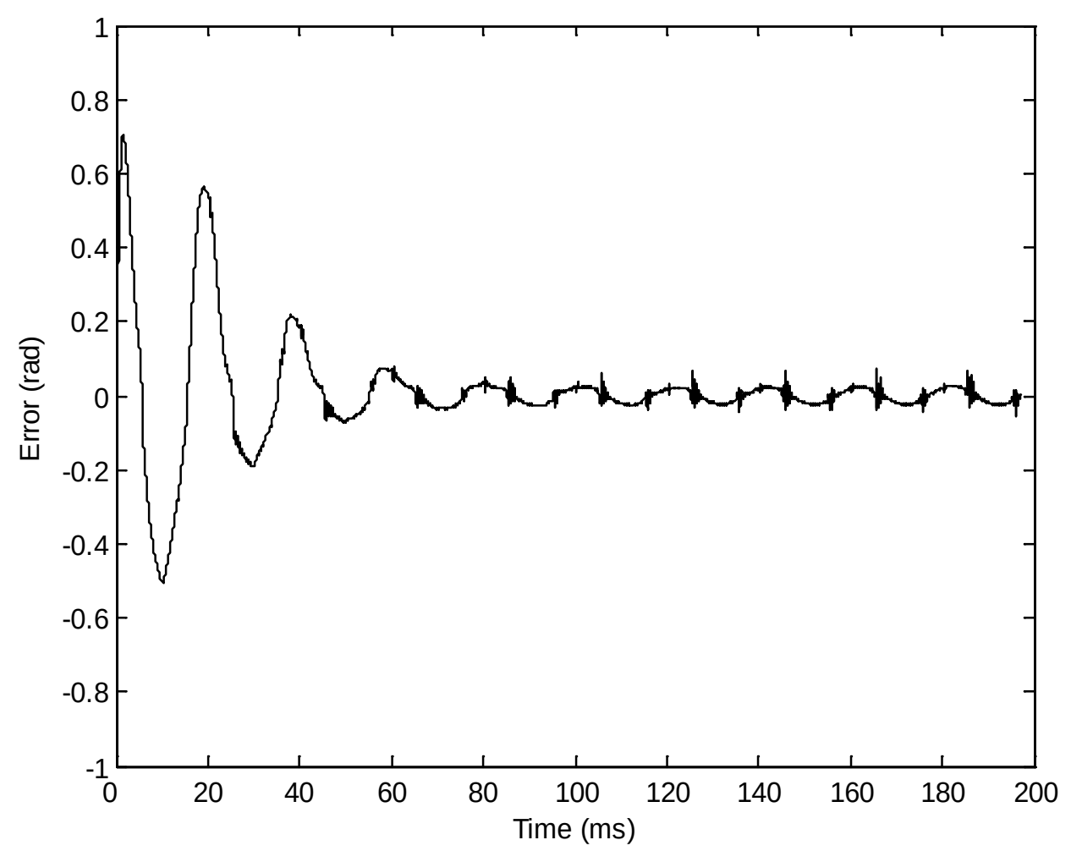

Fig. 7 Tracking error with periodic adaptive learning control

Repetitive Control (RC):

This example demonstrates sinusoidal signal tracking and disturbance rejection using continuous time repetitive control.

As shown in Fig. 8, repetitive control involves placing an internal loop with a delay equal to period of signal to tracked in the feedback path. This creates infinite gain at the frequency of reference signal.

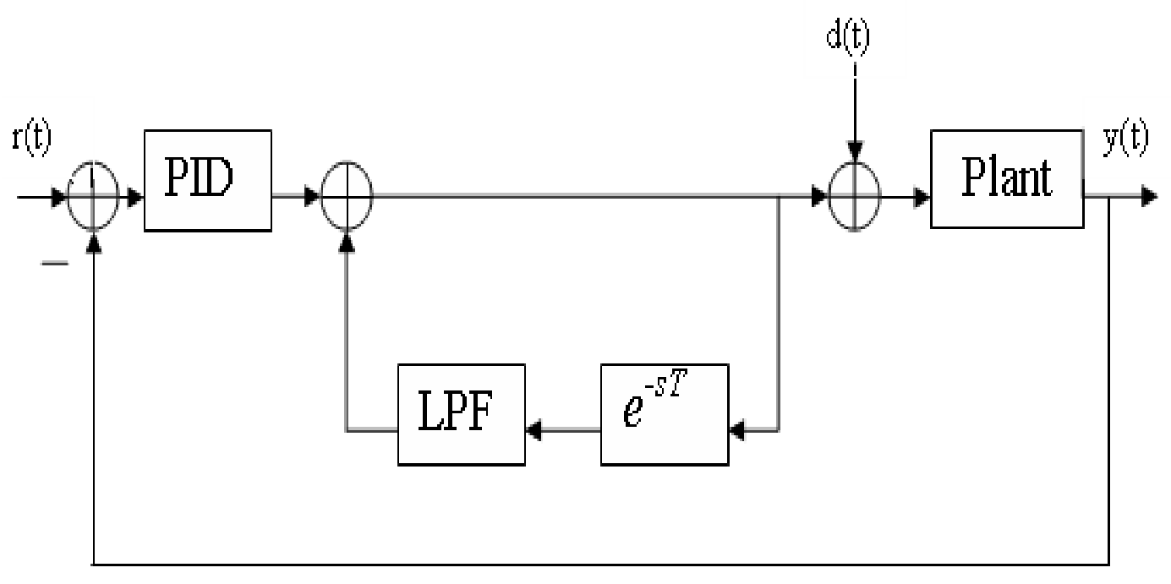

Fig. 8 Continuous time repetitive control

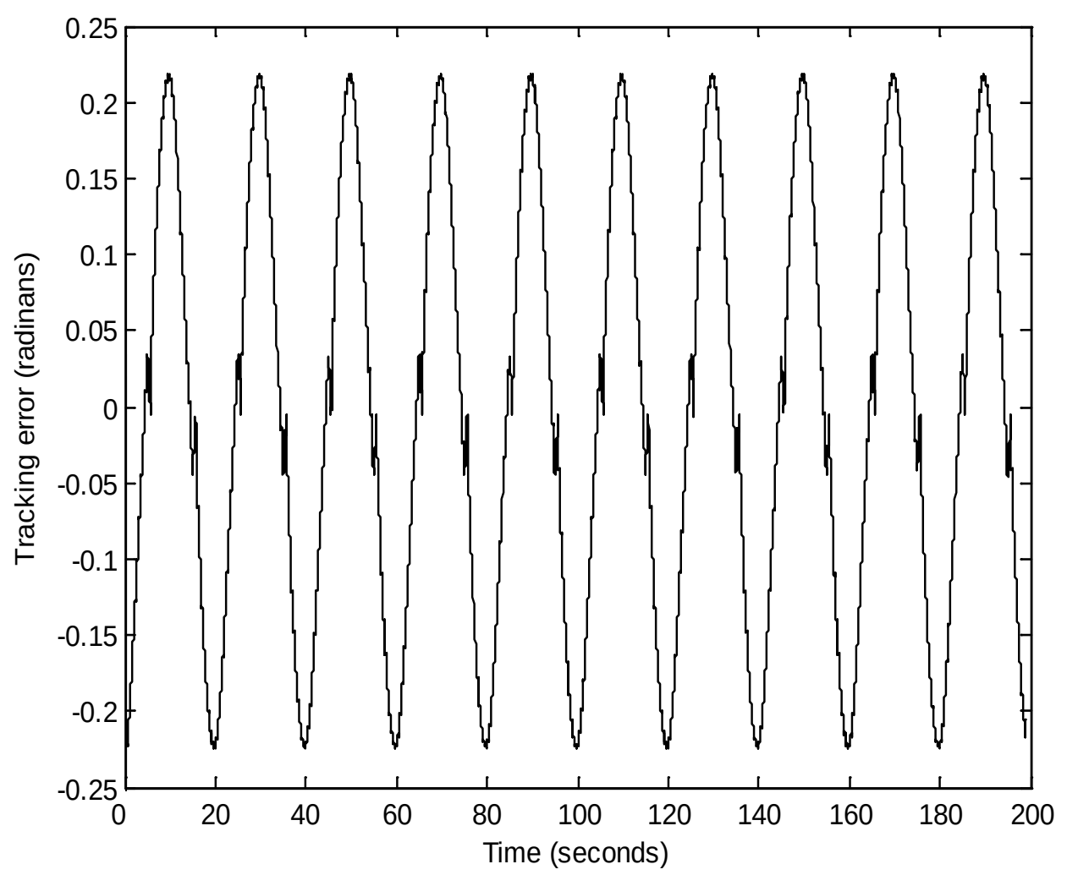

Fig. 9 Tracking error with PD controller

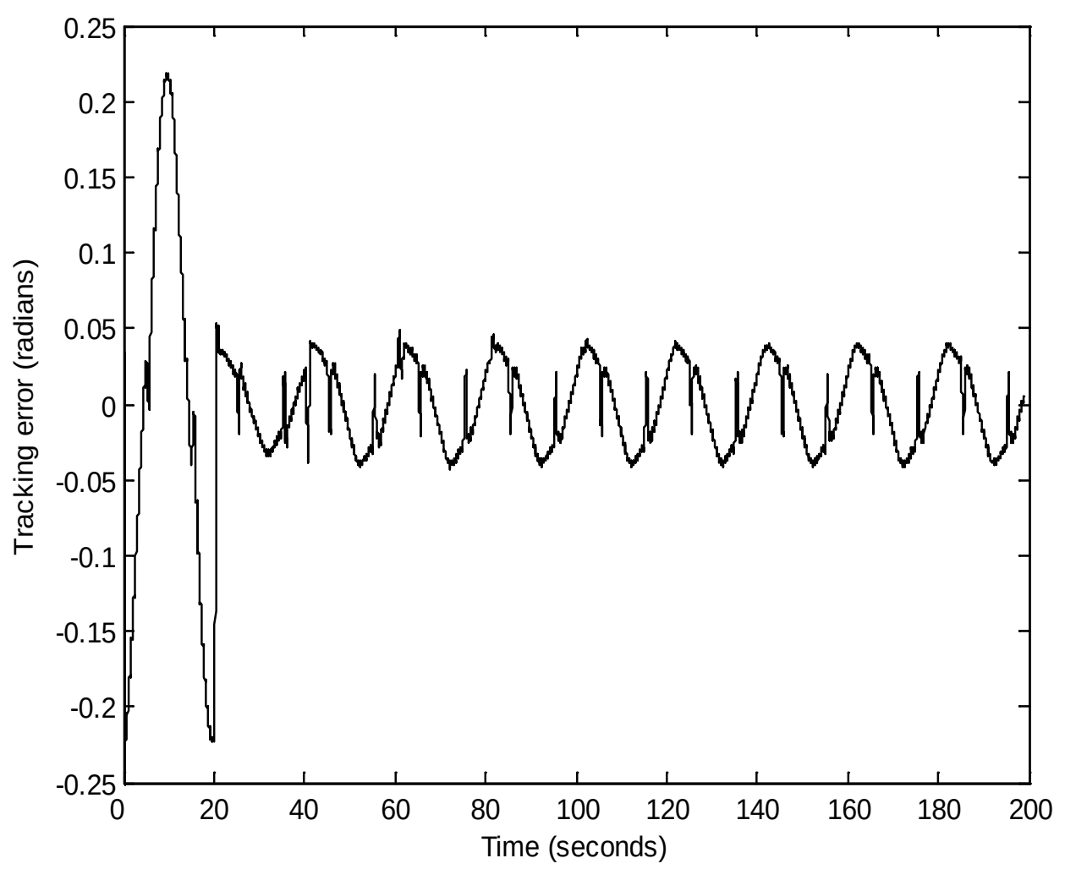

Fig. 10 Tracking error with repetitive control

Adaptive Coulomb Friction Compensation (ACFC):

This method estimates the friction by the use of a 'reduced-order' observer, the dynamics of which are designed to ensure asymptotic convergence of the estimation error to zero. Here the friction is given by $f(t)=a\,sgn(v(t))$, where a is the unknown friction parameter. The control law is designed so as to compensate this friction.

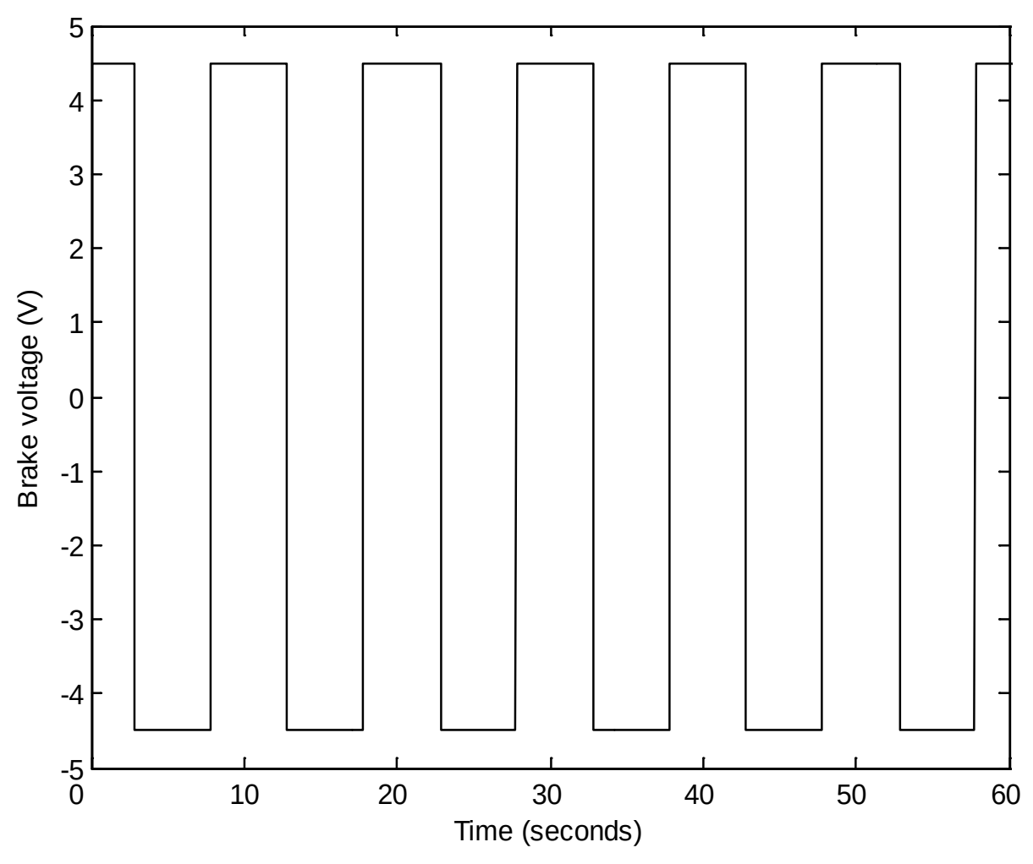

Fig. 11 Emulated Coulomb friction (brake voltage)

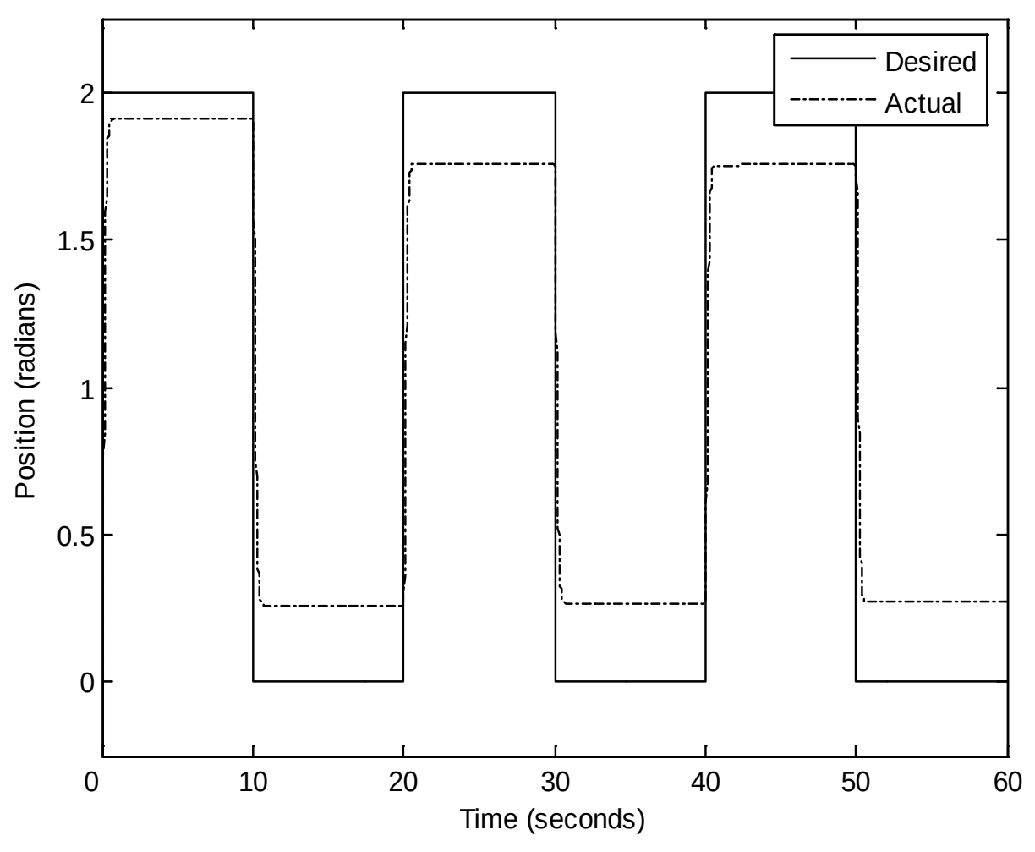

Fig. 12 Tracking performance with PD controller

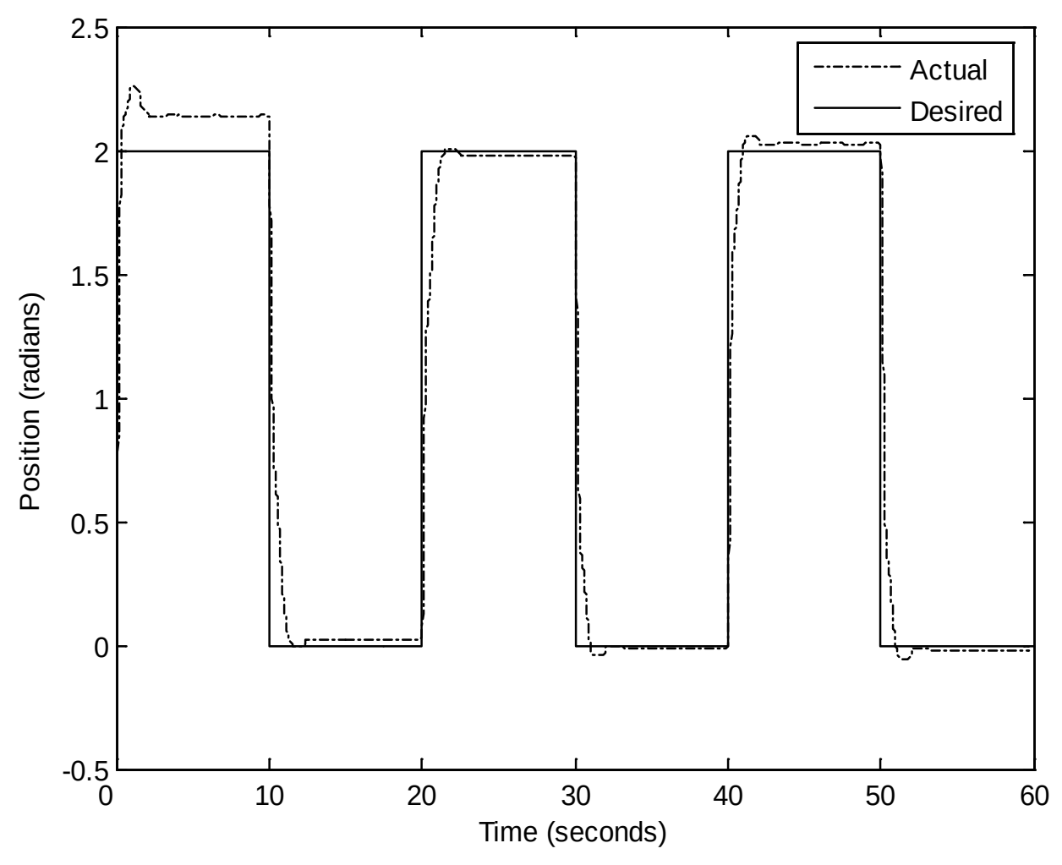

Fig. 13 Tracking performance with observer based controller

Adaptive Feedforward Cancellation (AFC):

Another approach for tracking and disturbance rejection is adaptive feedforward cancellation. In this method the disturbance is canceled at the input of the plant by adding a negative of its value at all times. Here magnitude and phase of the disturbance have to be estimated. The plots show tracking error for a velocity setpoint of 6 rad/sec with $f(t) = 2.5 + 2\sin(2t)$.

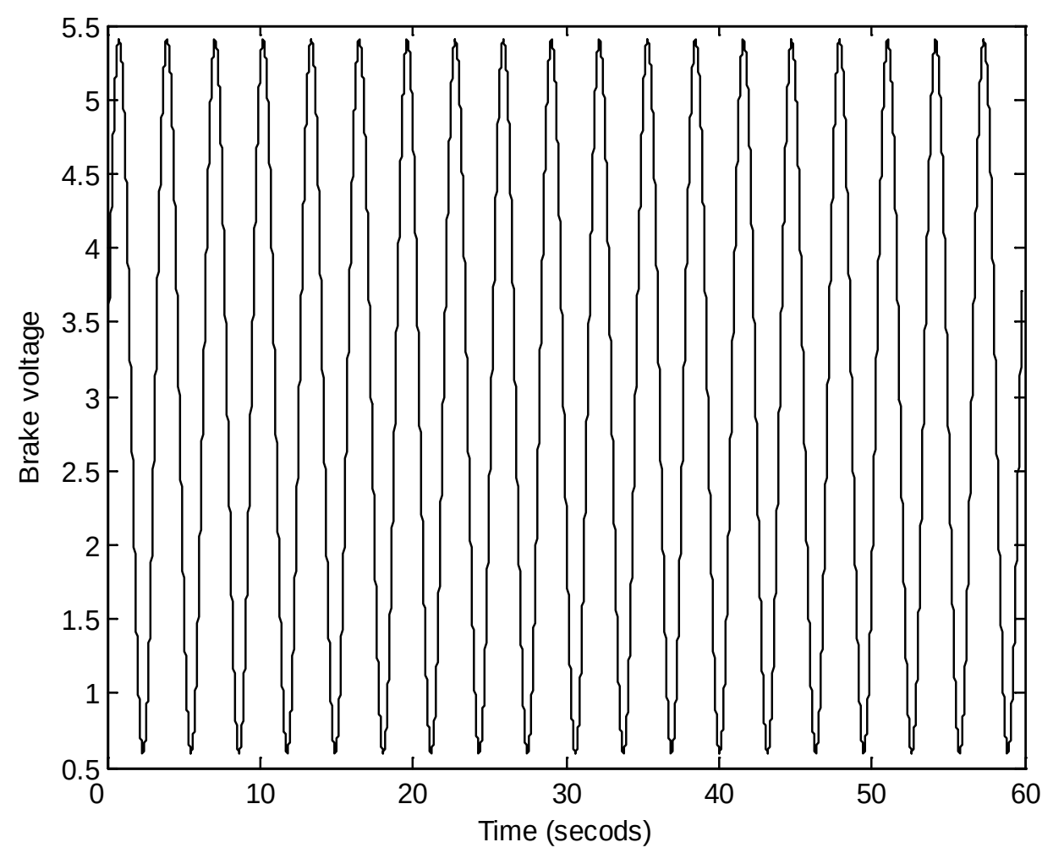

Fig. 14 Emulated sinusoidal disturbance (brake voltage)

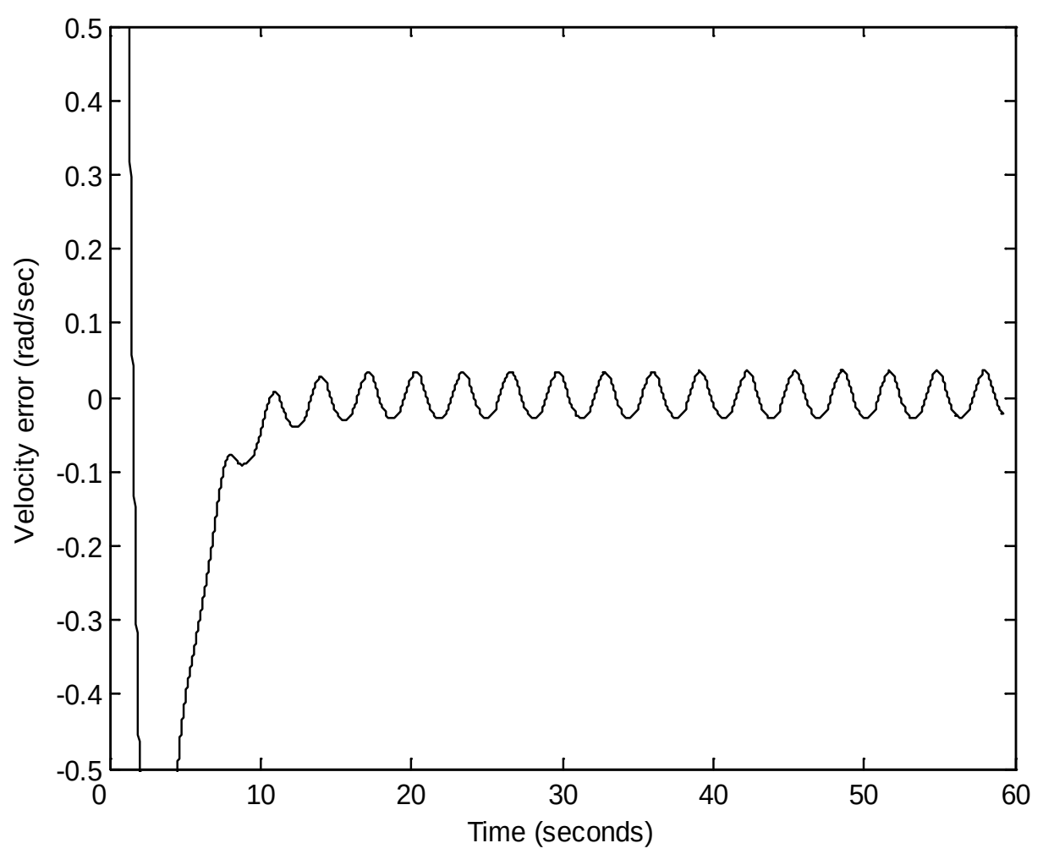

Fig. 15 Tracking error with PD controller

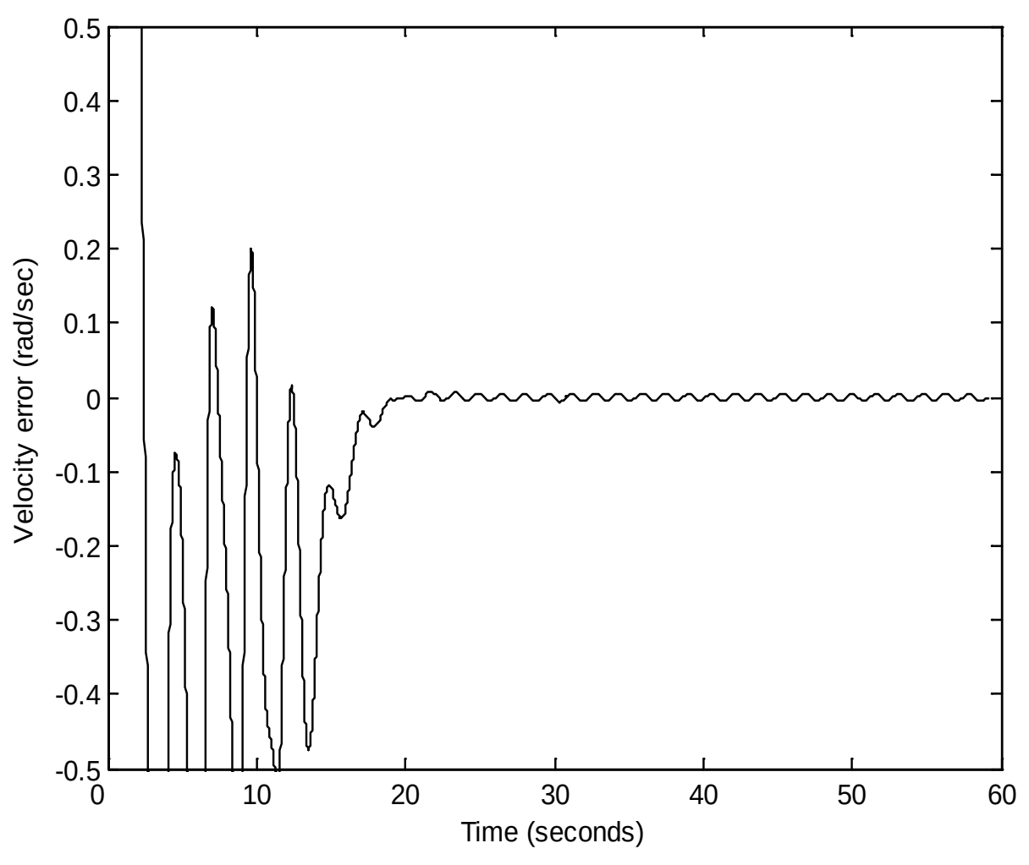

Fig. 16 Tracking error with feedforward cancellation

Sliding Mode Control (SMC):

In sliding mode control, trajectories are forced to reach a sliding manifold in finite time and to stay on the manifold for all future time. Consider a system given by

$$\dot{x}_1(t) = x_2(t)$$
$$\dot{x}_2(t) = h(x) + g(x)u$$

where h and g are unknown nonlinear functions. In order to stabilize the origin we design a control law that constrains the motion of the system to the manifold $s = a_1x_1 + x_2 = 0$. On this manifold, the motion is governed by $\dot{x}_1 = -a_1x_1$. Choosing $a_1 > 0$ guarantees asymptotic stability.

Here we can emulate this problem on dynamometer by taking h as braking disturbance. The accompanying plots show the step response of the DC motor with sliding mode control.

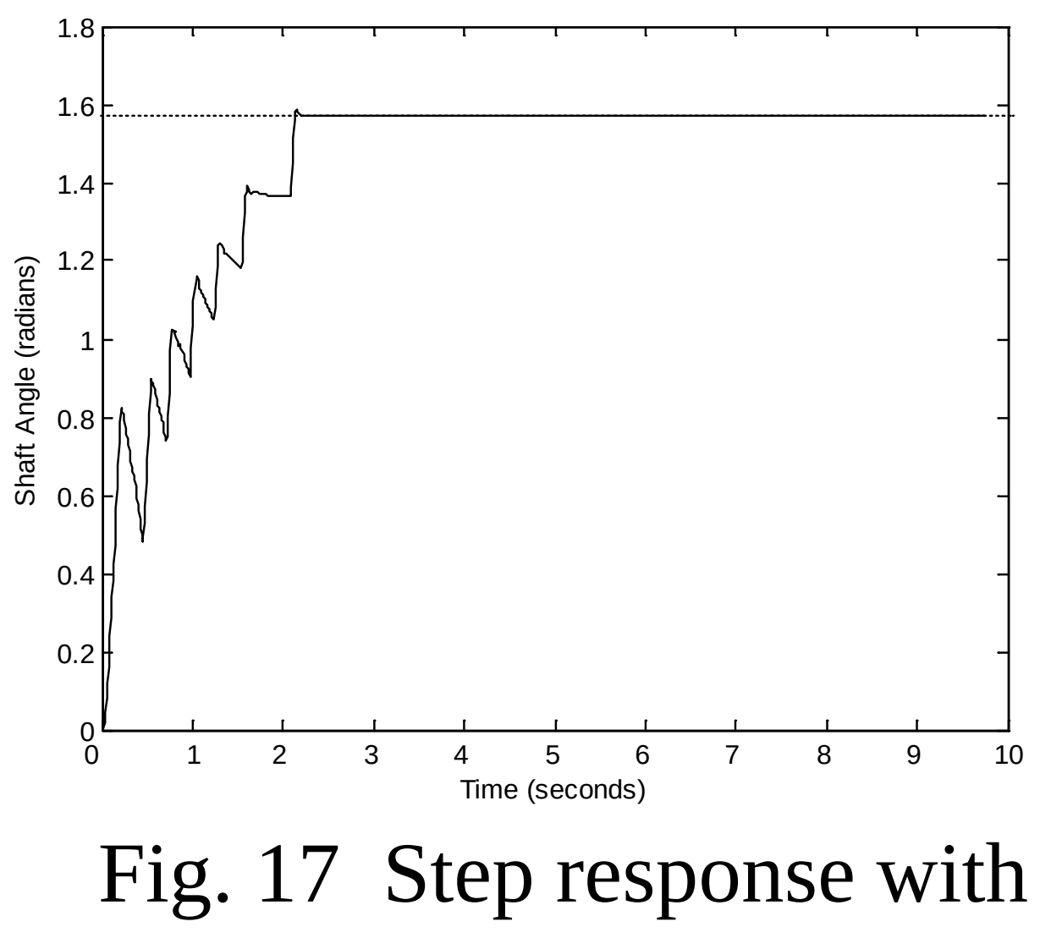

Fig. 17 Step response with sliding mode controller

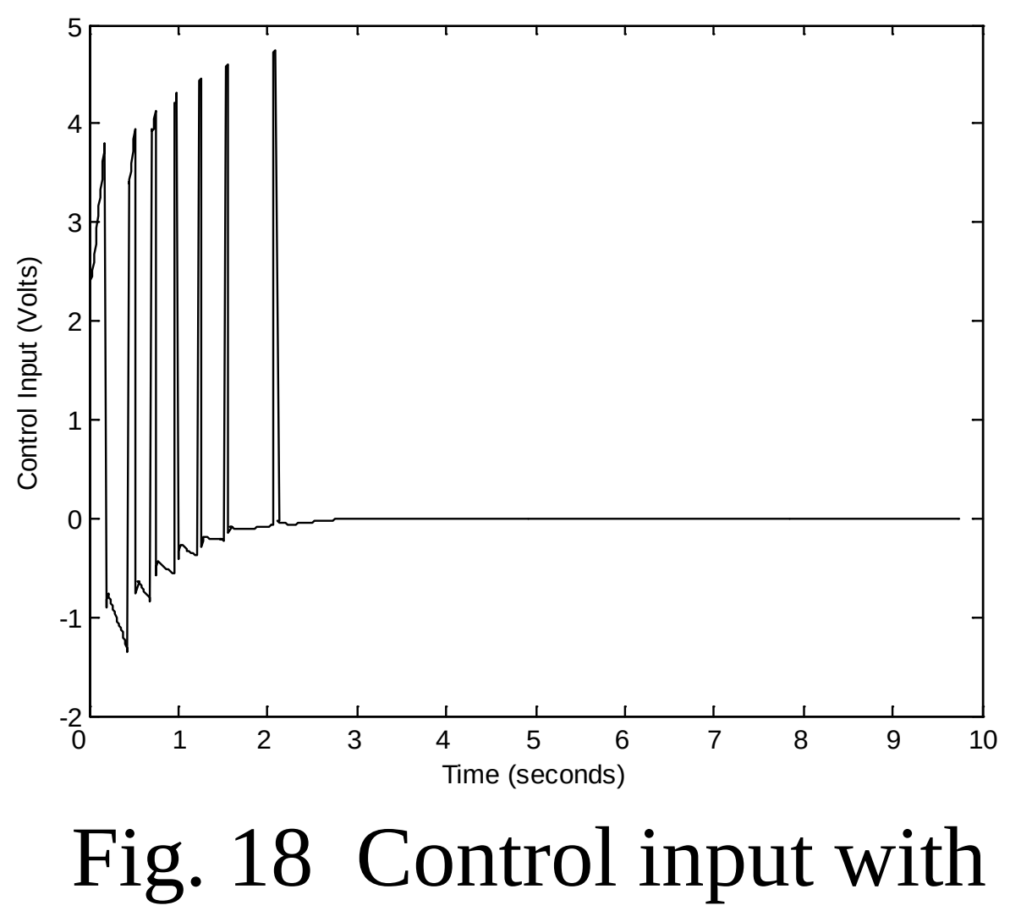

Fig. 18 Control input with sliding mode controller

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