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Overview

This project aims to design controller for Modular Servo System(**MSS**). The **MSS** consists of several parts mounted together at the metal rail and arranged in the chain:

- the DC motor with the tachogenerator,
- inertia load,
- encoder,
- eddy current brake,
- gearbox with the output disk.

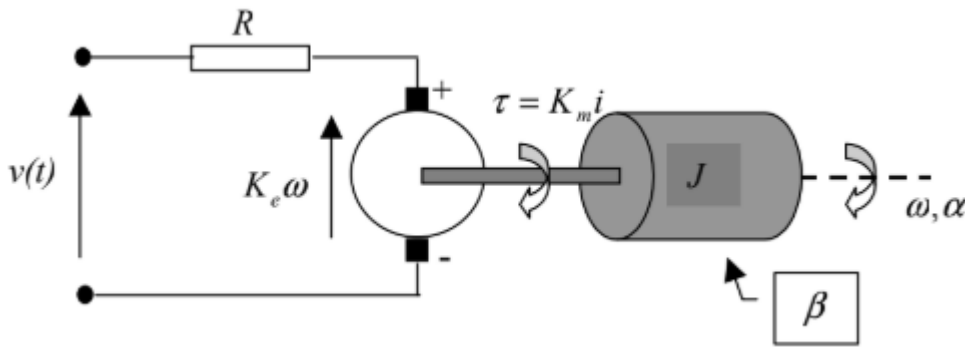
The rotation angle of the DC motor shaft is measured using an incremental encoder. A tachogenerator is connected directly to the DC motor and generates a voltage signal proportional to the angular velocity.

The servomechanism is connected to a computer where a control algorithm is realized based on measurements of angle and angular velocity. The accuracy of measurement of velocity is 5% while the accuracy of angle measurement is 0.1%. The armature voltage of the DC motor is controlled by PWM signal. For this reason the dimensionless control signal is the scaled input voltage, $u(t) = v(t)/v_{max}$. The admissible controls satisfy $|u(t)| \leq 1$ and $v_{max} = 12V$.

The measurement system is based on RTDAC/USB2 acquisition board equipped with A/D converters.

The I/O board communicates with the power interface unit. The whole logic necessary to activate and read the encoder signals and to generate the appropriate sequence of PWM pulses to control the DC motor is configured in the Xilinx chip of the RT-DAC/USB2 board. All functions of the board are accessed from the Modular Servo Toolbox which operates directly in the MATLAB/Simulink environment.

Proposed mathematical model



Equation 1:

$$\begin{aligned} v(t) &= Ri(t) + K_e \omega(t) \\ J\dot{\omega}(t) &= K_m i(t) - \beta \omega(t) - f_0 \cdot \text{sgn}(\omega) \end{aligned}$$

where:

$v(t)$ - input voltage

$i(t)$ - armature current

$\omega(t)$ - angular velocity of the rotor

R - resistance of armature winding

J - moment of inertia of the moving parts

β - damping coefficient due to viscous friction

$K_e \omega(t)$ - back EMF

$K_m i(t)$ - electromechanical torque

Sensors scaling

Motor Encoder

Rotor of DC motor was rotated 10 times. Obtaining raw measurements gave us following results:

Start position	Final position
-92.7568	-155.4122

$$(enc_{finish} - enc_{start})/10/2 = -3.1328$$

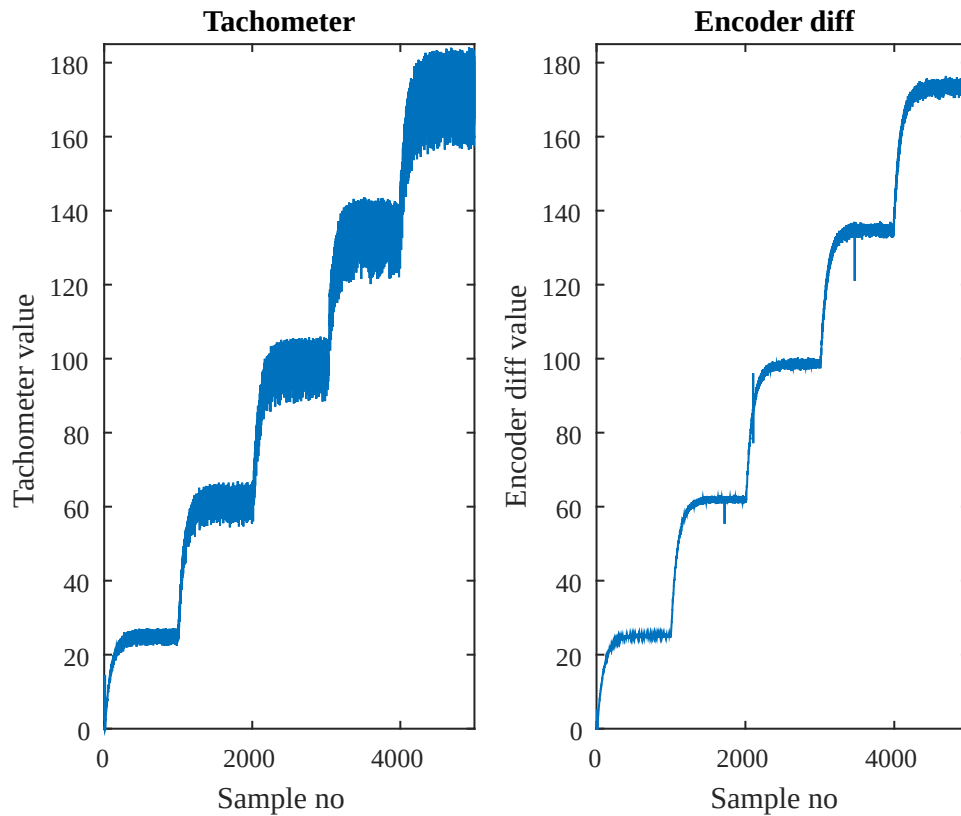
The result is close to π . That means that encoder reading is already scaled to radians.

Input Potentiometer

Absolute potentiometer, produces output with range [-99.11, 97.61]. Additional processing is necessary for continuous angle measurement.

Tachometer

We have acquired data for steady state conditions for 5 given outputs. Then we compare tachometer and encoder outputs. Given below chart we have noticed that the tachometer output is already scaled to rad/s.



Identification

Motor Inertia

Given the datasheet parameter motor inertia is established as:

$$J_M = 1.8 \cdot 10^{-5} \text{ kg} \cdot \text{m}^2$$

Motor torque constant

$$k = 5.3 \frac{\text{mNm}}{\text{A}} = 5.3 \cdot 10^{-3} \frac{\text{V} \cdot \text{s}}{\text{rad}}$$

Comparing the real model and our simulations we found out that the motor torque constant provided by the manufacturer can be invalid. In order to address this issue we performed an experiment to identify the real motor torque constant.

Using torque sensor and current measurement we calculated correct value of the motor torque constant.

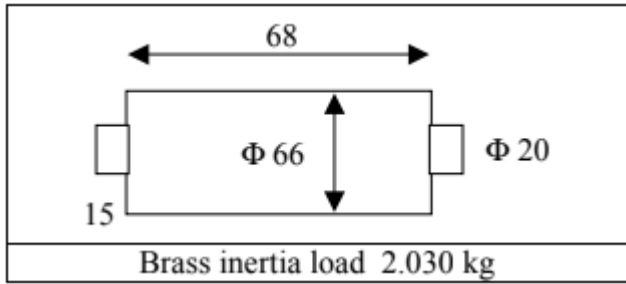
Set point	Current [A]	Torque [Ncm]
0.25	1.2	6
0.5	2.5	12.1
0.75	3.9	18
-0.25	-1.15	-5.5
-0.5	-2.4	-12.8
-0.75	-3.6	-18

Motor coil inductance

$$L_M = 1.0 \text{ mH}$$

Rotating mass inertia

Rotating mass has following dimensions and mass:



Inertia of the solid cylinder is given by the following equation:

$$J_{SM} = \frac{1}{2}mr^2 = 1.1 \cdot 10^{-3} \text{ kg} \cdot \text{m}^2$$

Resistance of the net

First of all we have measured the voltage of idle DC motor. In order to accomplish this task we have disconnected the DC motor power supply and measured the voltage value which is given below:

$$U = 6.65 \text{ V}$$

Then after reconnecting the motor we have locked the motor and measured the current with help of current probe. The result is given below:

$$I = 2.45 \text{ A}$$

Finally we have used well-known Ohm formula to calculate resistance of the net:

$$R = U/I$$
$$R = 6.65/2.45 = 2.71 \text{ } \Omega$$

Friction

In order to identify damping coefficient we have followed equations:

$$v = Ri + k\omega$$

$$ki = \beta\omega + f_0$$

They have been derived from the mathematical model, taking into account that we examine the system in steady-state.

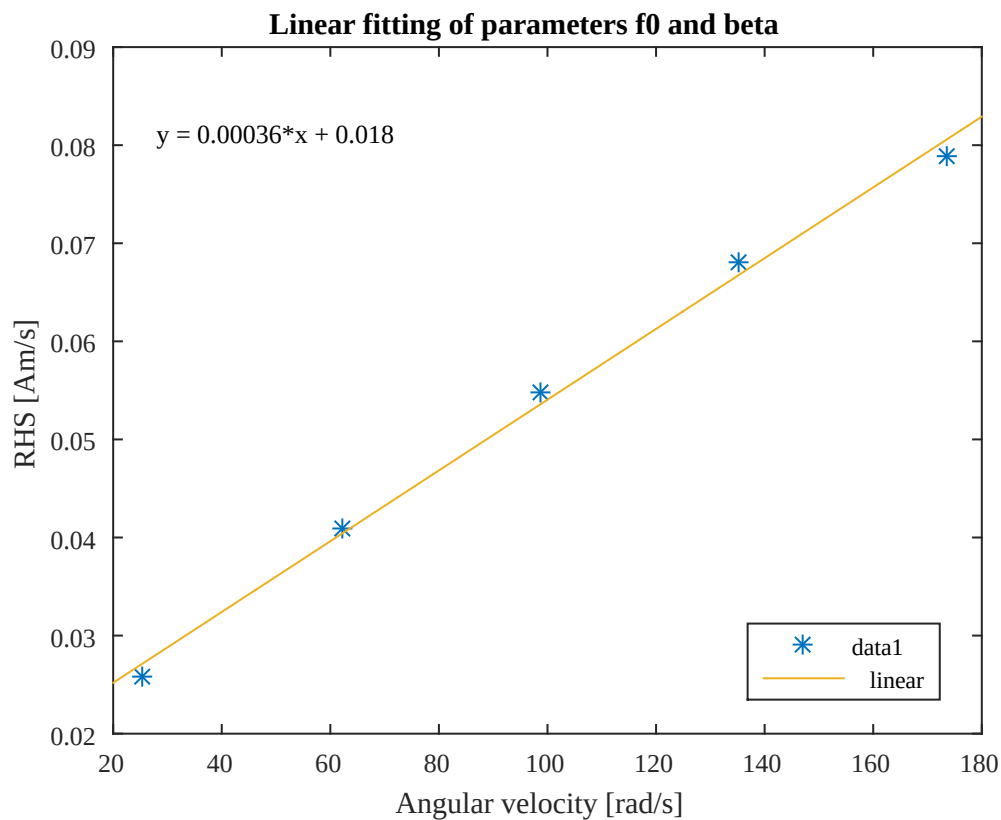
f_0 - static friction coefficient

After combining the equations, we have got:

$$f_0 + \beta\omega = \frac{k}{R}v - \frac{k^2}{R}\omega$$

The right side we have signed as RHS and on the left we have got linear function of ω . Now, the task was to find the coefficients of the function. We have used the data from the experiment described above in 'Tachometer' part. After choosing 5 points, we have calculated RHS for appropriate values of v and ω . Then we have used Basic Fitting tool to find the coefficients of the linear function.

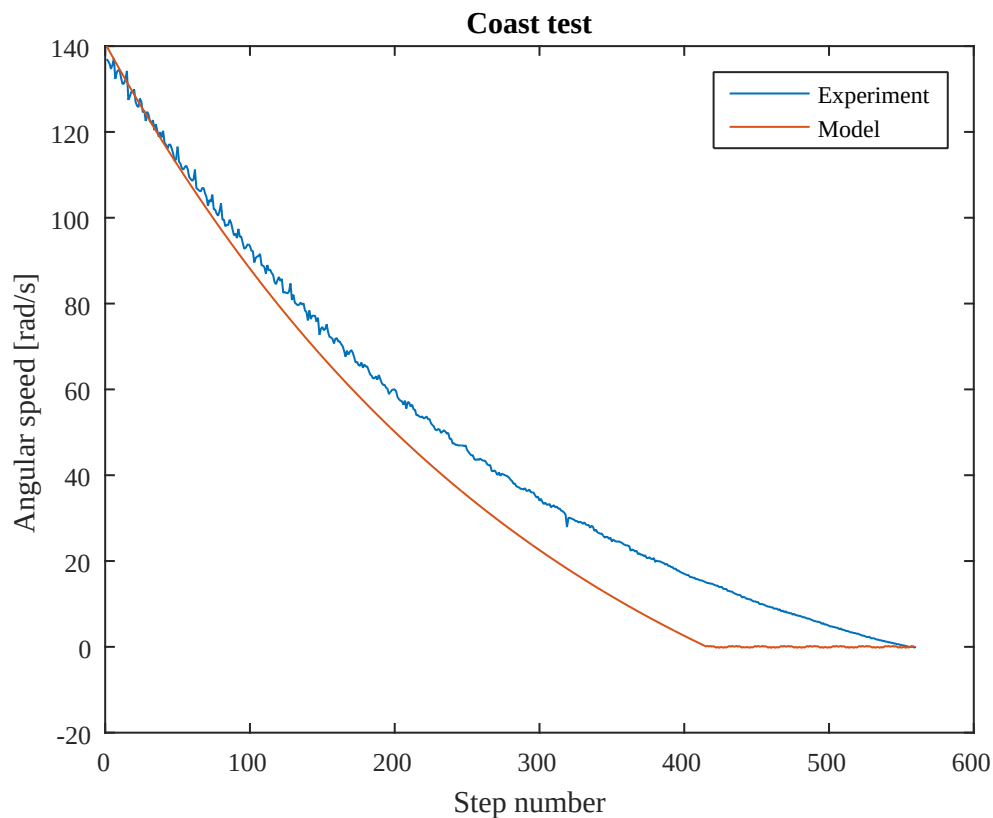
We have got:



$$f_0 = 1.8 \cdot 10^{-3}$$
$$\beta = 3.6 \cdot 10^{-4}$$

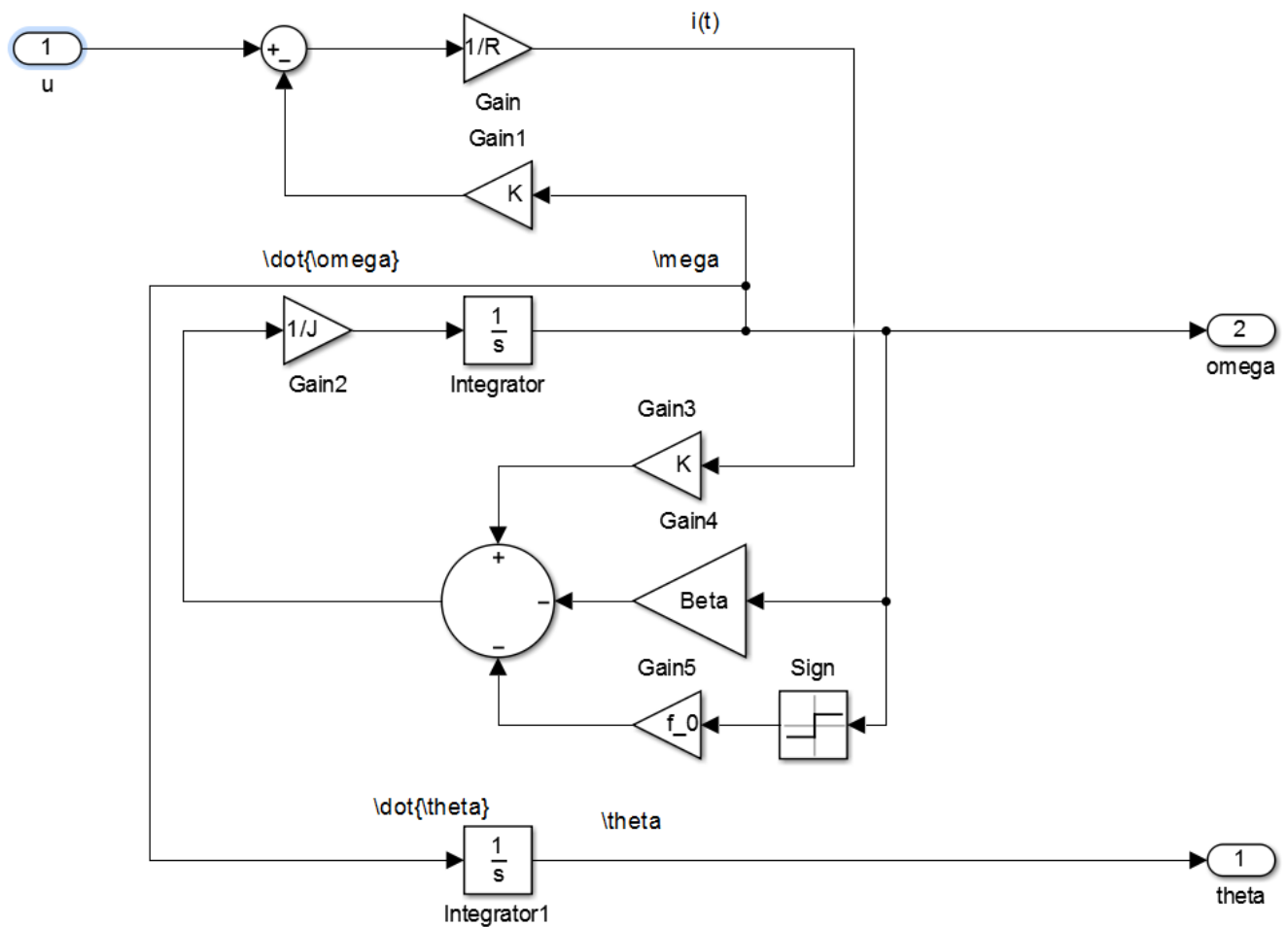
Coast test

In order to check the validity of friction coefficients we have conducted an experiment, called coast test. Then, we compared it with model simulation. The results, presented below, show that the coefficients were calculated correctly.

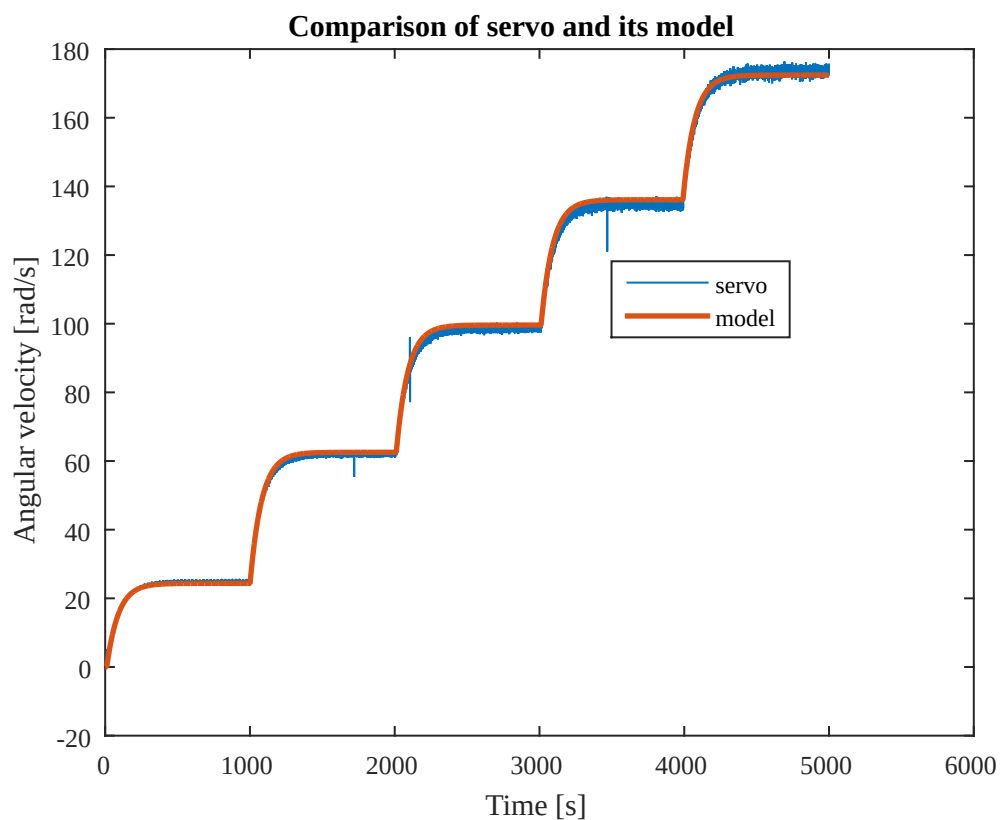


Model evaluation

We have created following model of servo, according to Equation 1:



The comparison of acquired data and model yields the following results:



Controller

PID regulator can be implemented for control of plant. This method can be easily introduced as long as it require little knowledge of system dynamics.

There is a better idea. Considering system dynamics, one can employ cascaded control system. The diagram below shows idea of such control system:

The structure is as follows:

Controller	Controlled variable	Implemented
primary, outermost, master	position	yes
secondary controller	velocity	yes
tertiary, inner-most	current	no

Secondary PID controller tuning

Using Ziegler–Nichols method, we found out that $P = 2, 5$ causes instability in system response. $P = 1.25$ therefore.

However, test on the plant showed instability of system. Using heuristic/empirical method we found out optimal gain value: $P = 0.03$.

Primary PID controller tuning

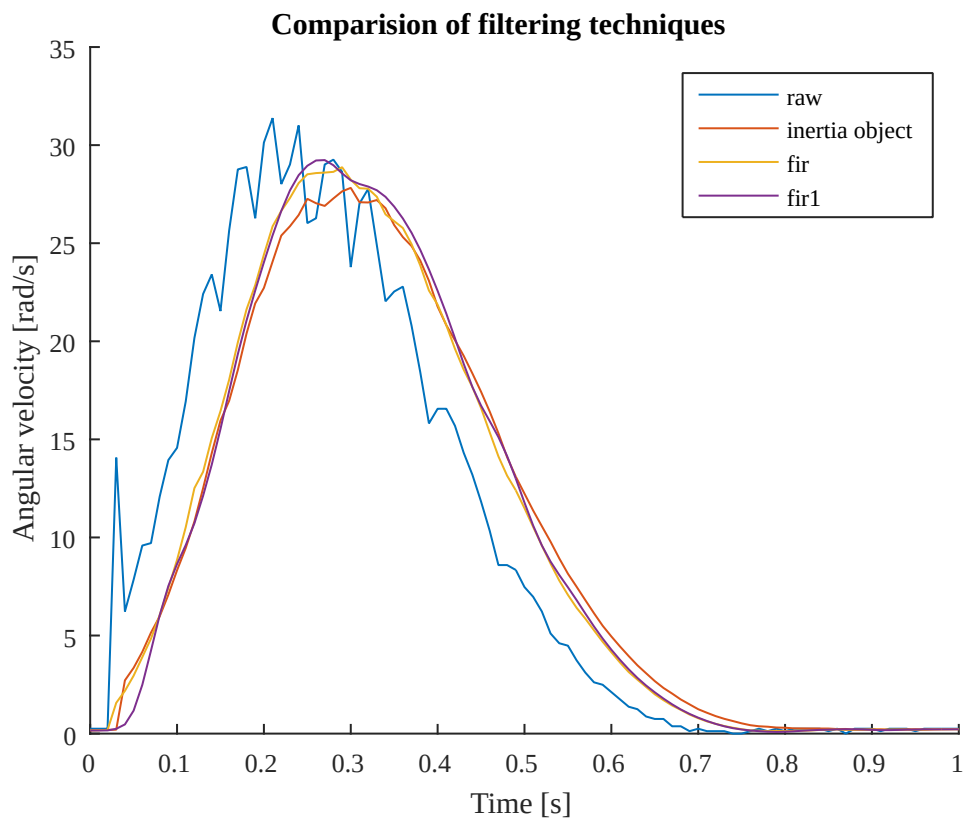
using method as above we found optimal setting for PID:

$$P = 5$$
$$I = 0.1$$

Filtering consideration

The tests on real plant showed that filtering of velocity signal is critical to quality of regulation.

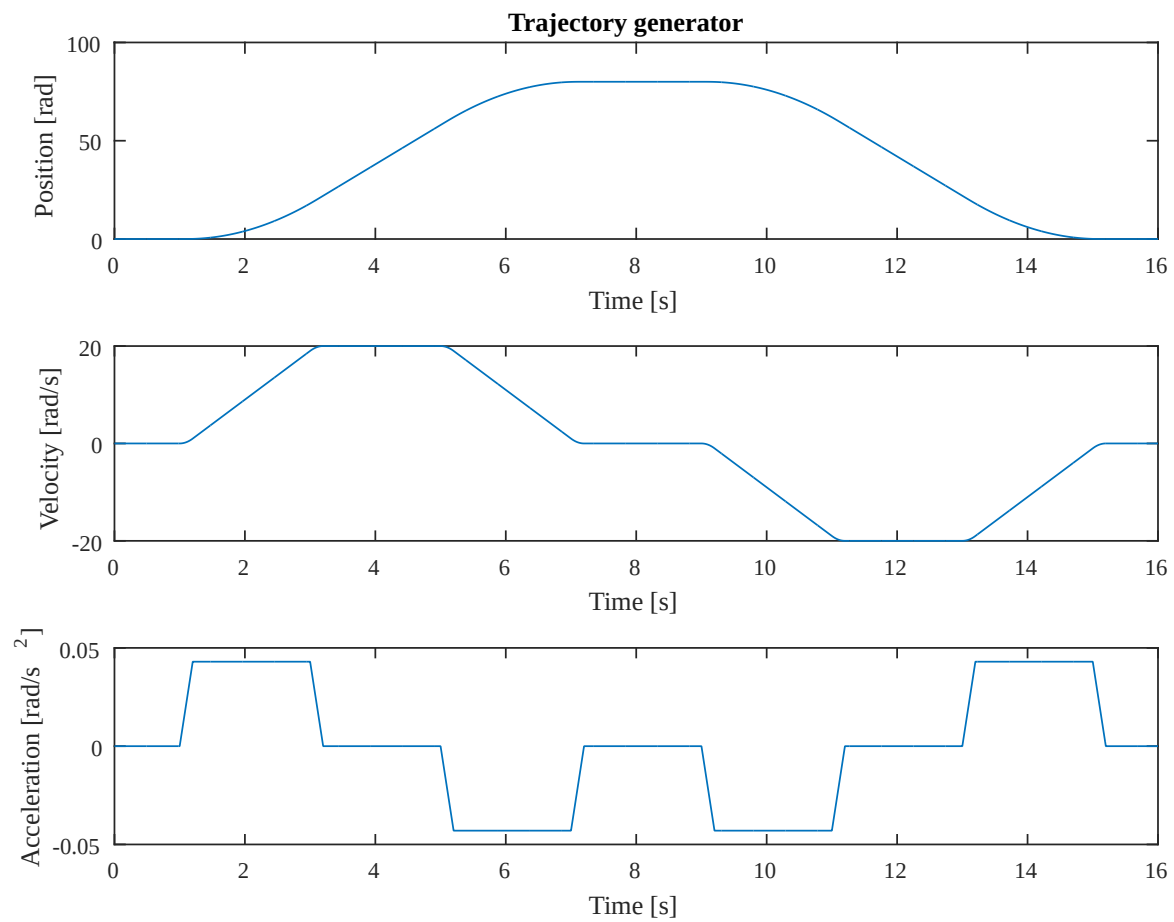
The figure below shows comaprision of filtering techniques, compared to raw signal:



- inertia object $G(S) = \frac{1}{0.05s+1}$
- fir coefficients $fc_1 = [1, 1, 1, 1, 1, 1, 1, 1, 1, 1]$
- fir1 coefficients $fc_2 = \text{fir1}(10, 0.15)$

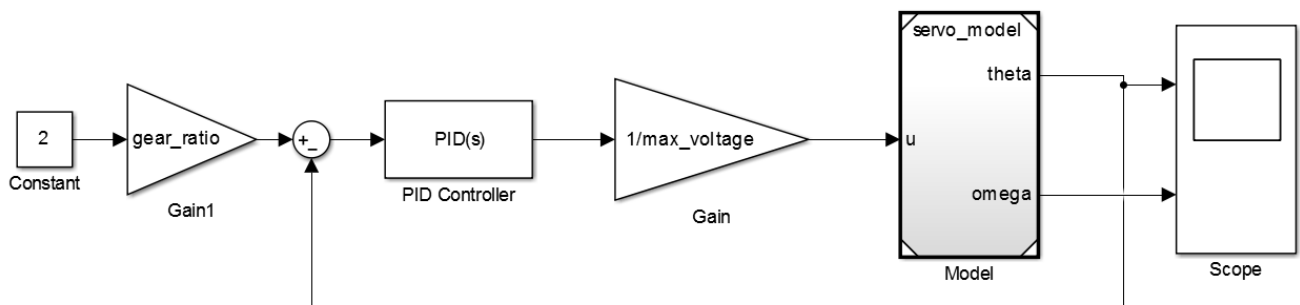
Feedforward control - trajectory generator

In order to improve quality of control the simple trajectory generator was implemented. It uses pre-defined time series of acceleration to create velocity and position references. The figure below shows time series that was generated for position, velocity and acceleration.

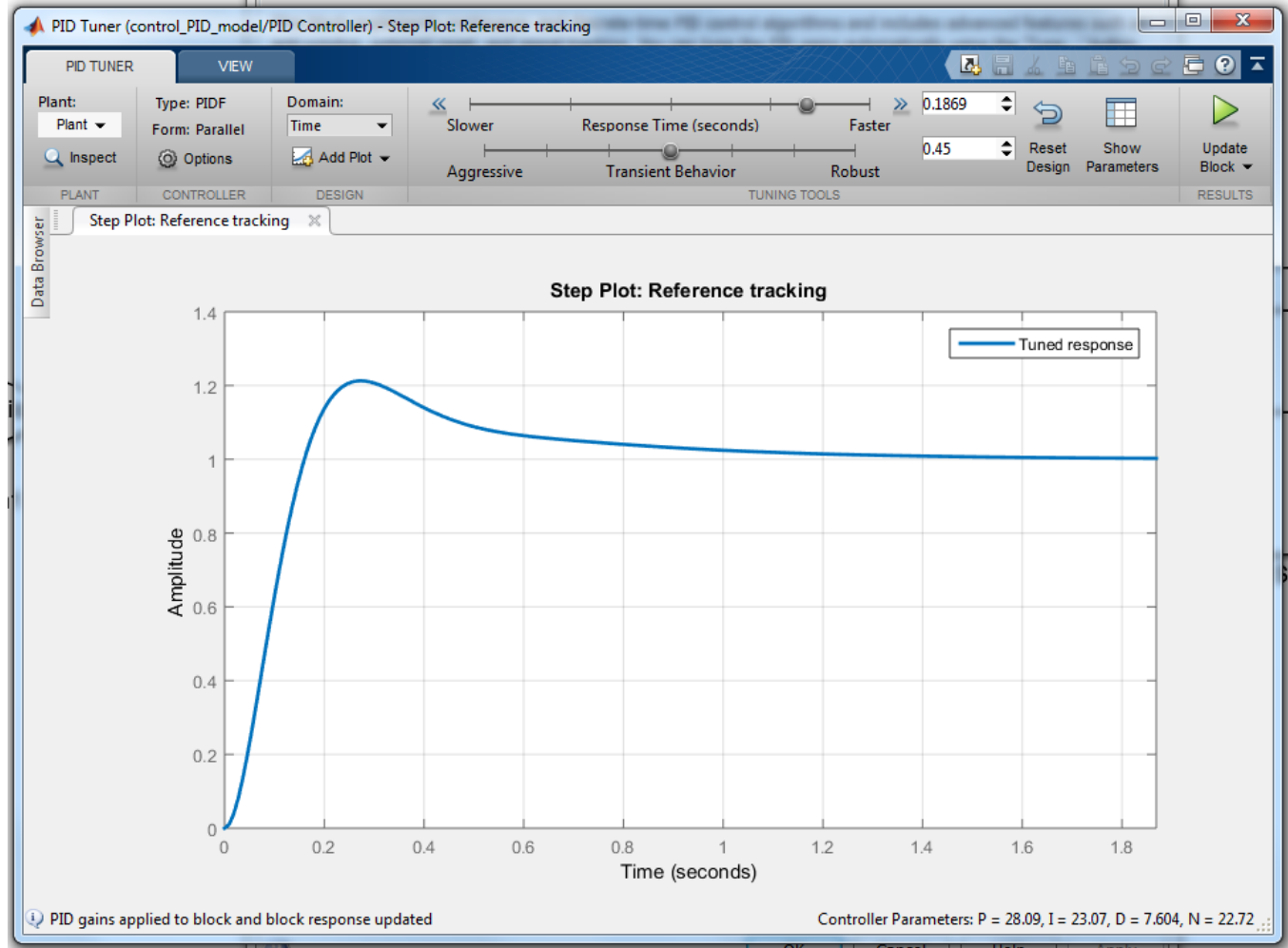


PID tuning

The following test stand was implemented to tune PID controller:



The results of PID tuning:



Transfer function of PID:

$$G(s) = P + I \frac{1}{s} + D \frac{N}{1 + N \frac{1}{s}}$$

Coefficients:

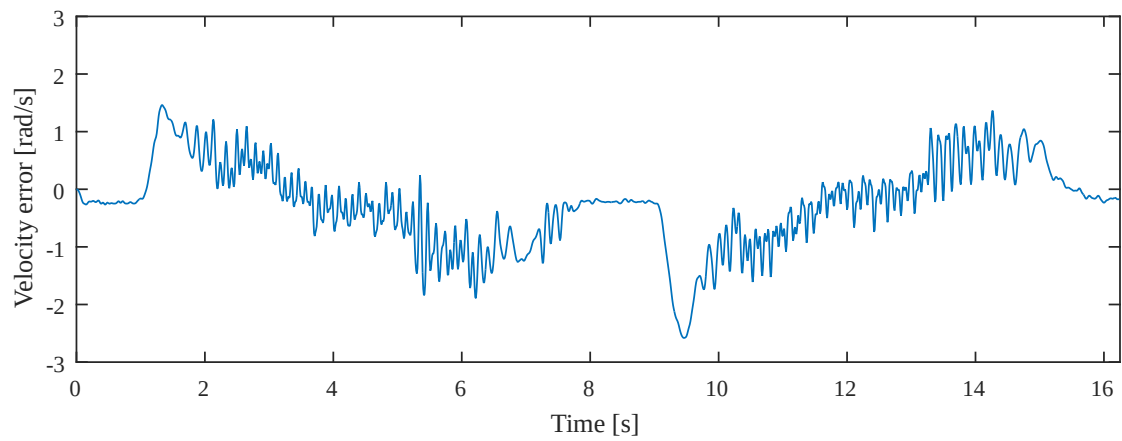
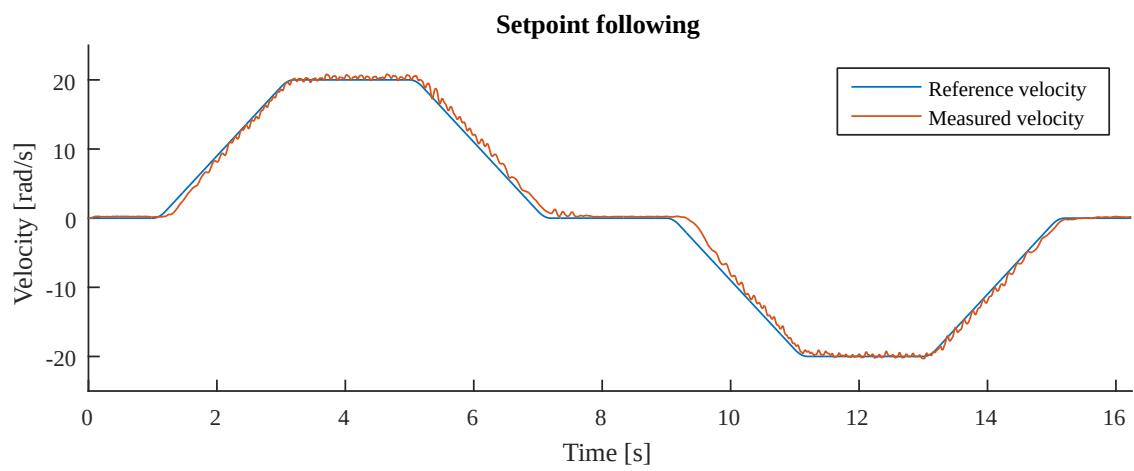
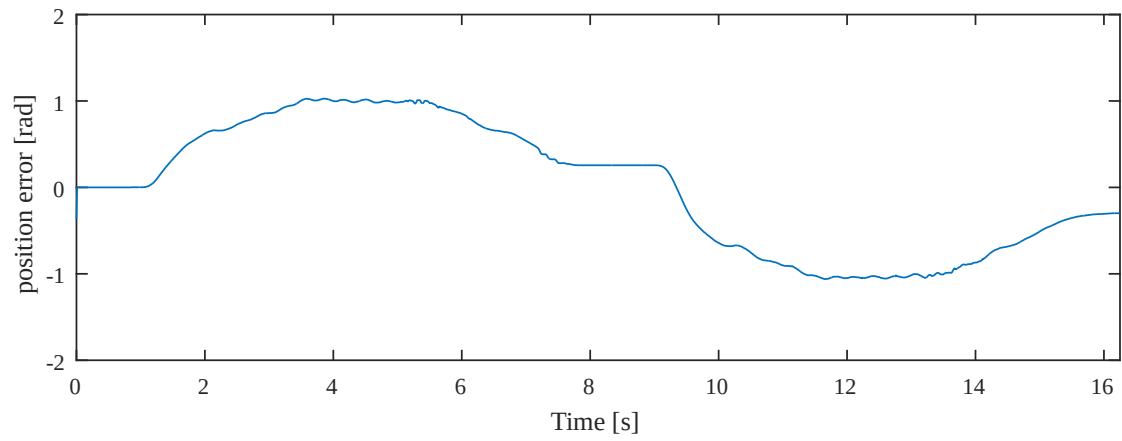
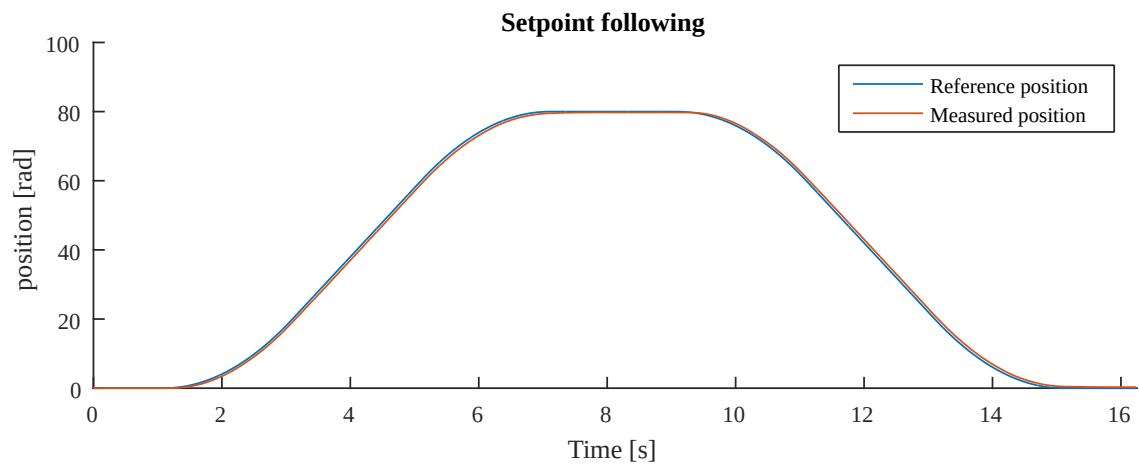
$$\begin{aligned} P &= 28 \\ I &= 23 \\ D &= 7.6 \\ N &= 22.7 \end{aligned}$$

Controller evaluation

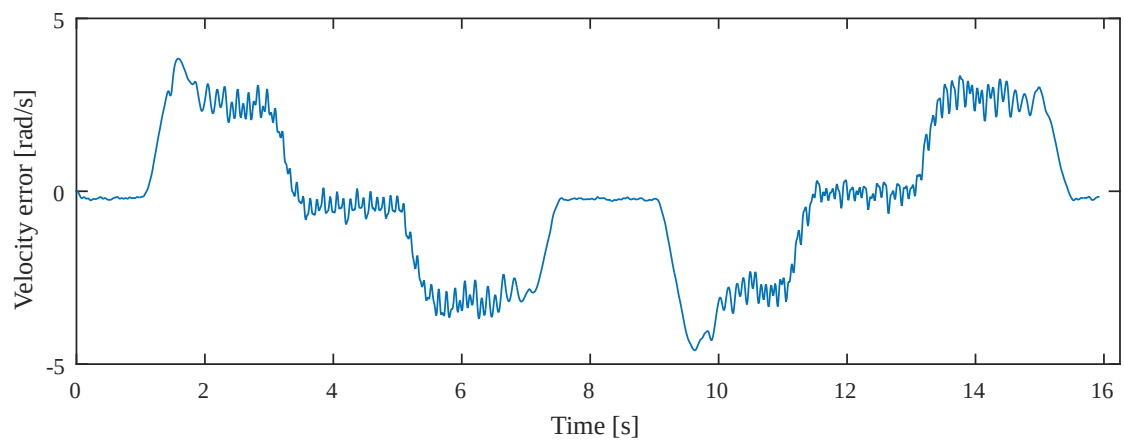
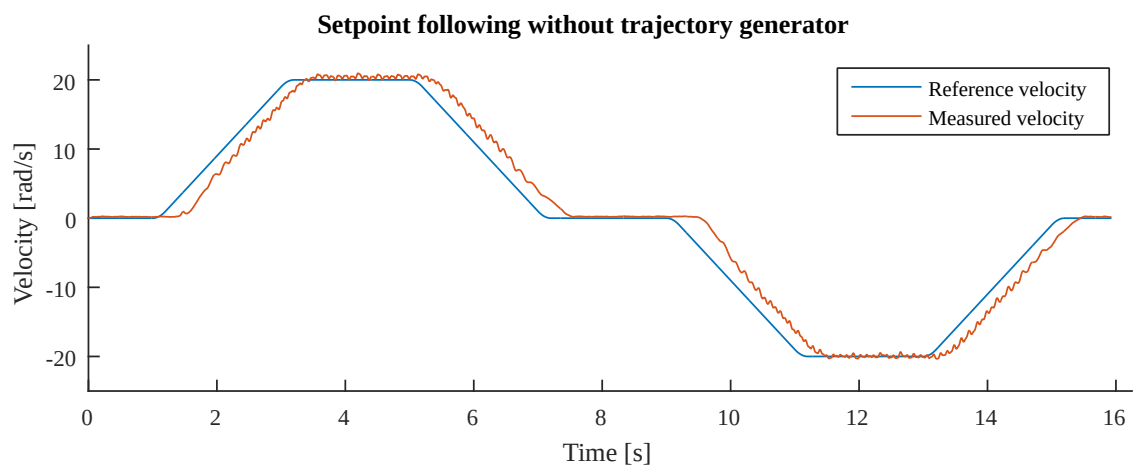
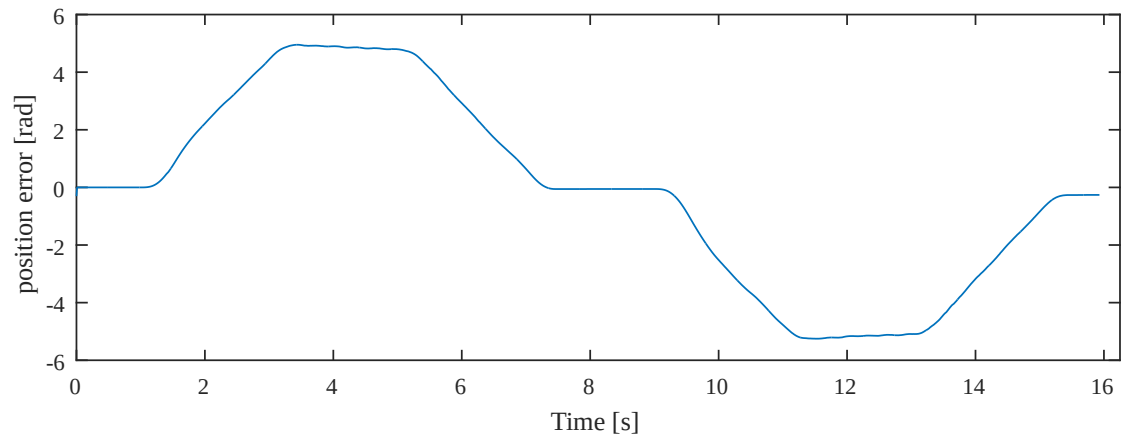
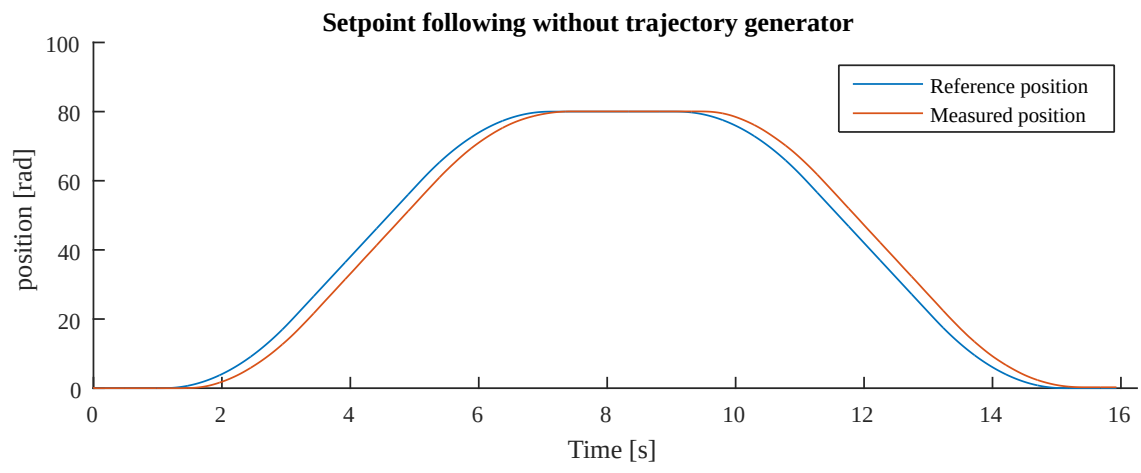
The following test were conducted in order to check control quality of system:

1. setpoint following
2. setpoint following without trajectory generator
3. disturbance rejection
4. robustness

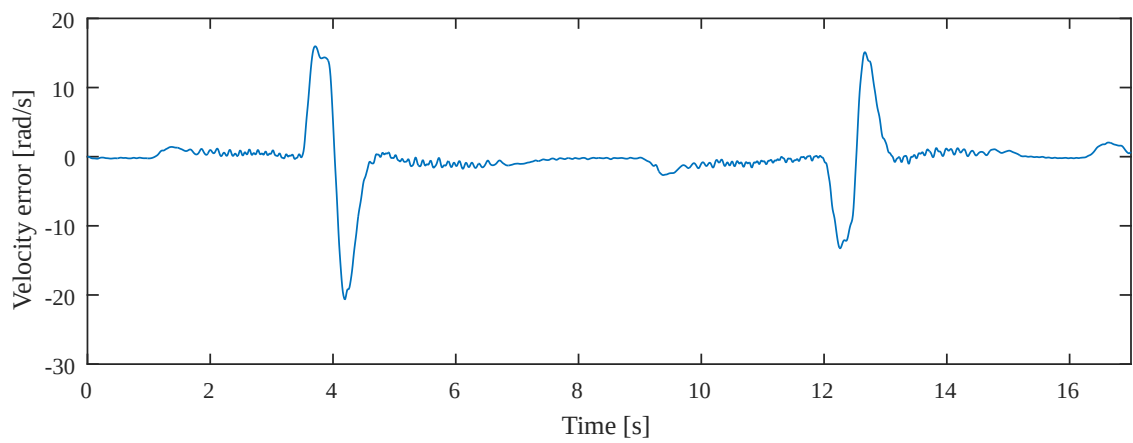
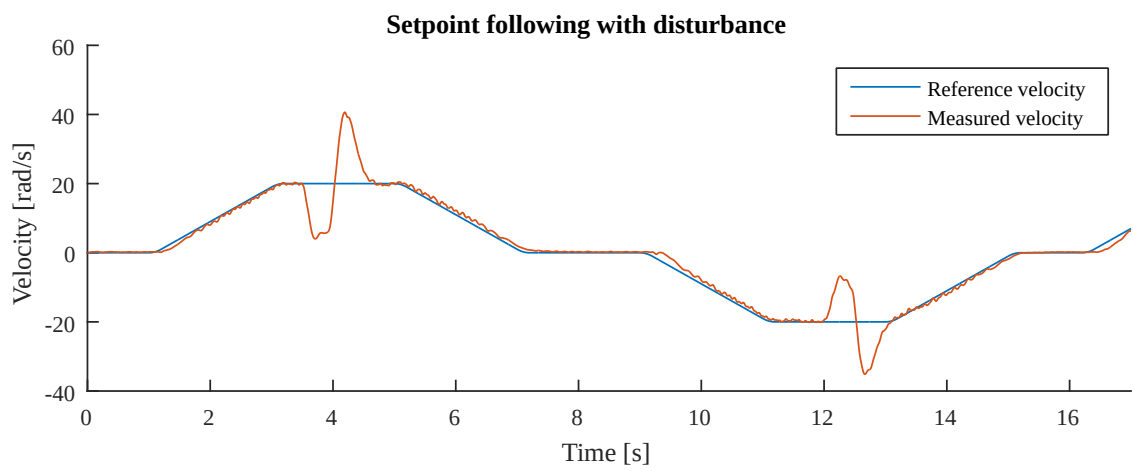
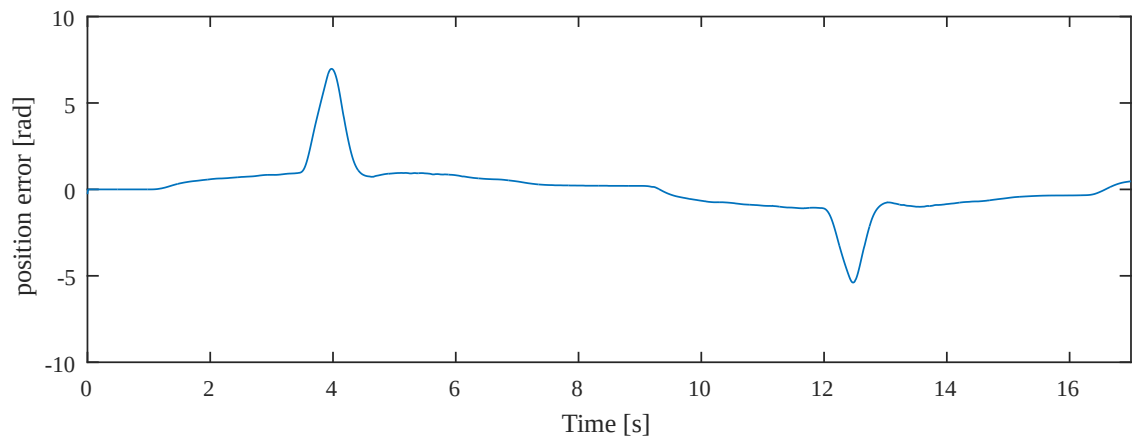
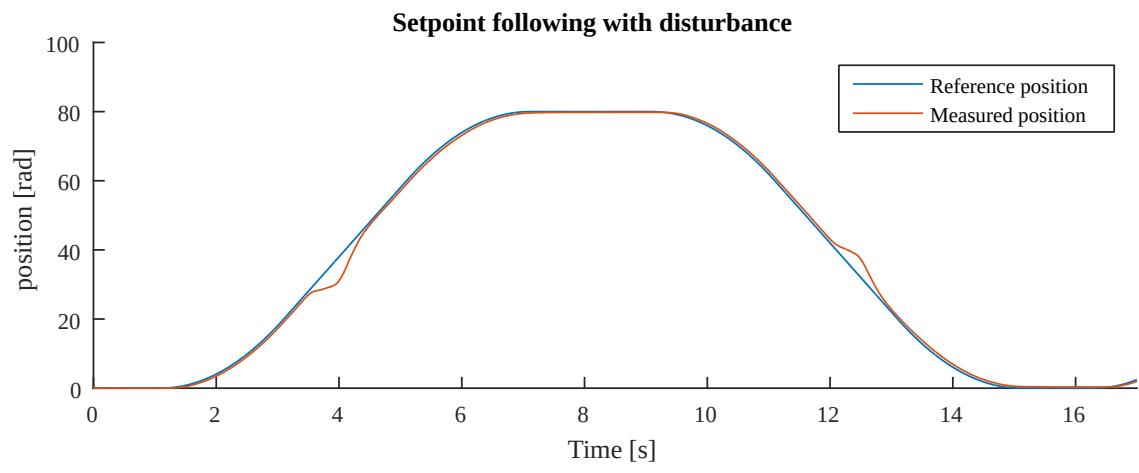
Setpoint following



Setpoint following without trajectory generator

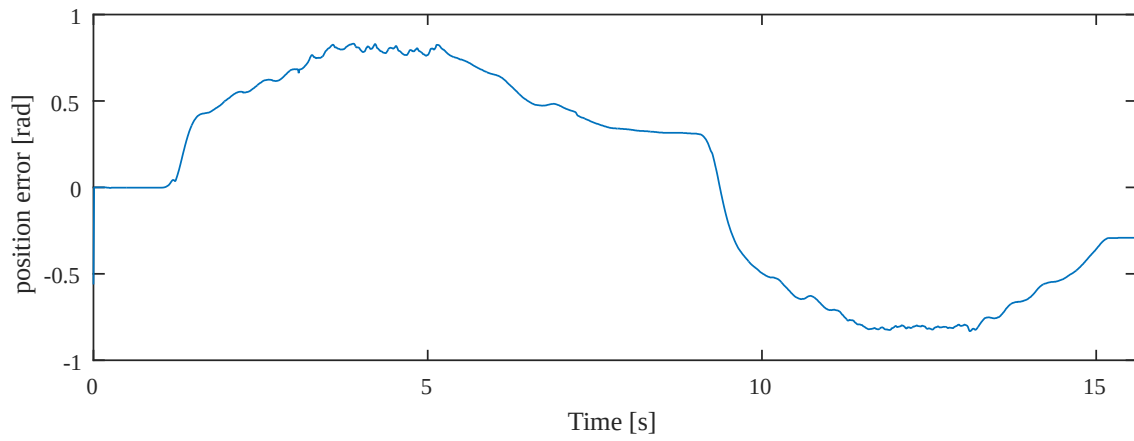
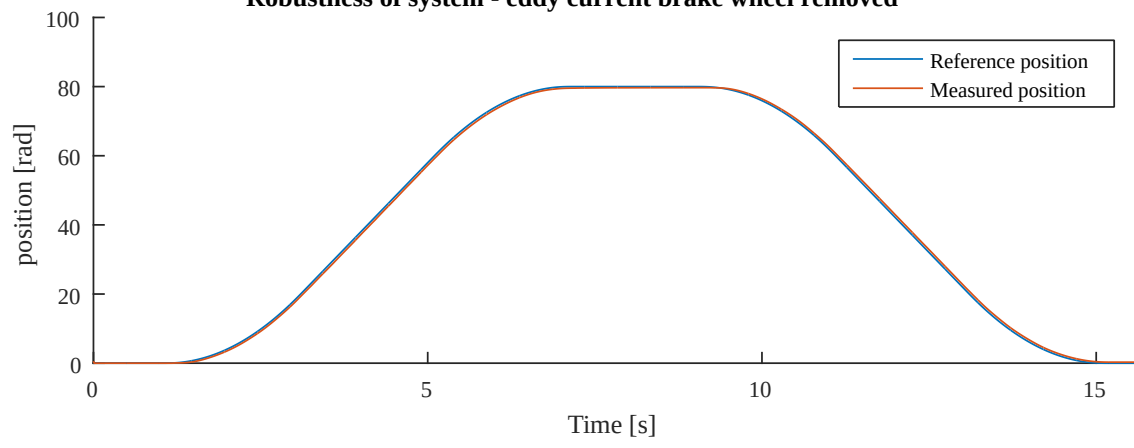


Disturbance rejection

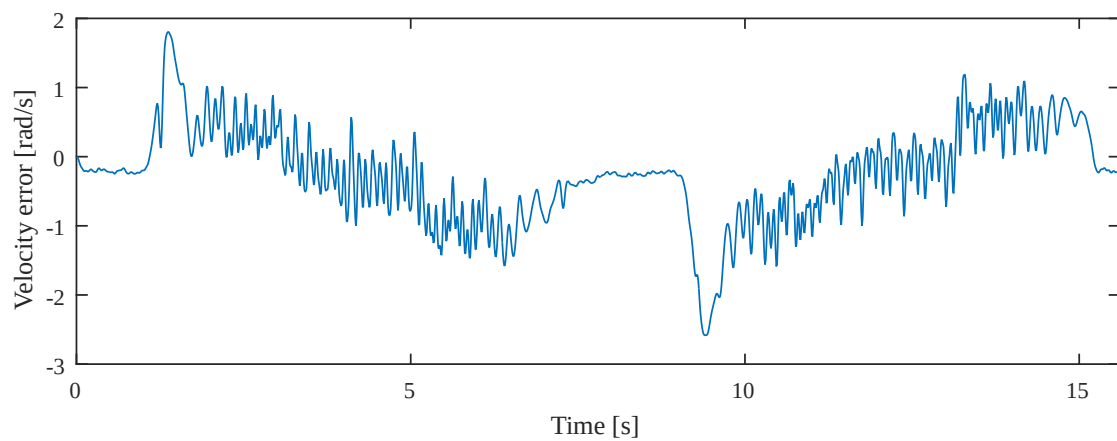
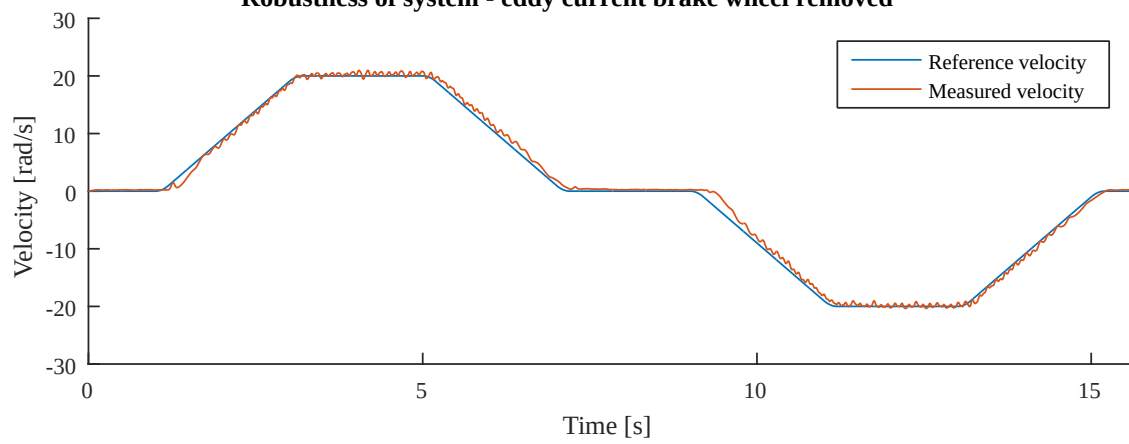


Robustness

Robustness of system - eddy current brake wheel removed



Robustness of system - eddy current brake wheel removed



Conclusions

We had issues with parameters estimation as long as the motor constant provided by manufacturer in datasheets was mistaken by order of magnitude. We have discovered this issue by series of two tests (steady-state friction force fitting and coast test).

After solving issue above, outputs of model and real system matches.

The PID tuning process brought a lot of surprises. In particular, the velocity controller was tuned in simulation to considerably high values of parameters. These values did not work on the plant. The identified root cause was filtering velocity signal. Having tested few methods of filtering we were able to establish a stable system with lower PID parameters.

The control system design is robust and non susceptible to considerably large disturbances.

We were not able to control system with inertia removed. However, this is drastic change to system dynamic. One could design controlled handling such change, however the control quality across all possible dynamic would suffer.

We were not able to control system with backlash inserted between encoder and inertia too. In such case one would have to probably change whole control strategy for system.

The trajectory generator brought significant improvement to the quality of the control. The system managed to catch up with the setpoint.

References

- [Manufacturer website](http://www.inteco.com.pl/products/modular-servo/) - <http://www.inteco.com.pl/products/modular-servo/>
- [Motor datasheet](http://www.buehler-motor.pl/download/DC_Motor_51_x_88_1.13.044.2XX.pdf) - [http://www.buehler-motor.pl/download/DC Motor_51 x 88_1.13.044.2XX.pdf](http://www.buehler-motor.pl/download/DC_Motor_51_x_88_1.13.044.2XX.pdf)