2–DOF PID Control of the Angular Position of an Industrial Plant Emulator

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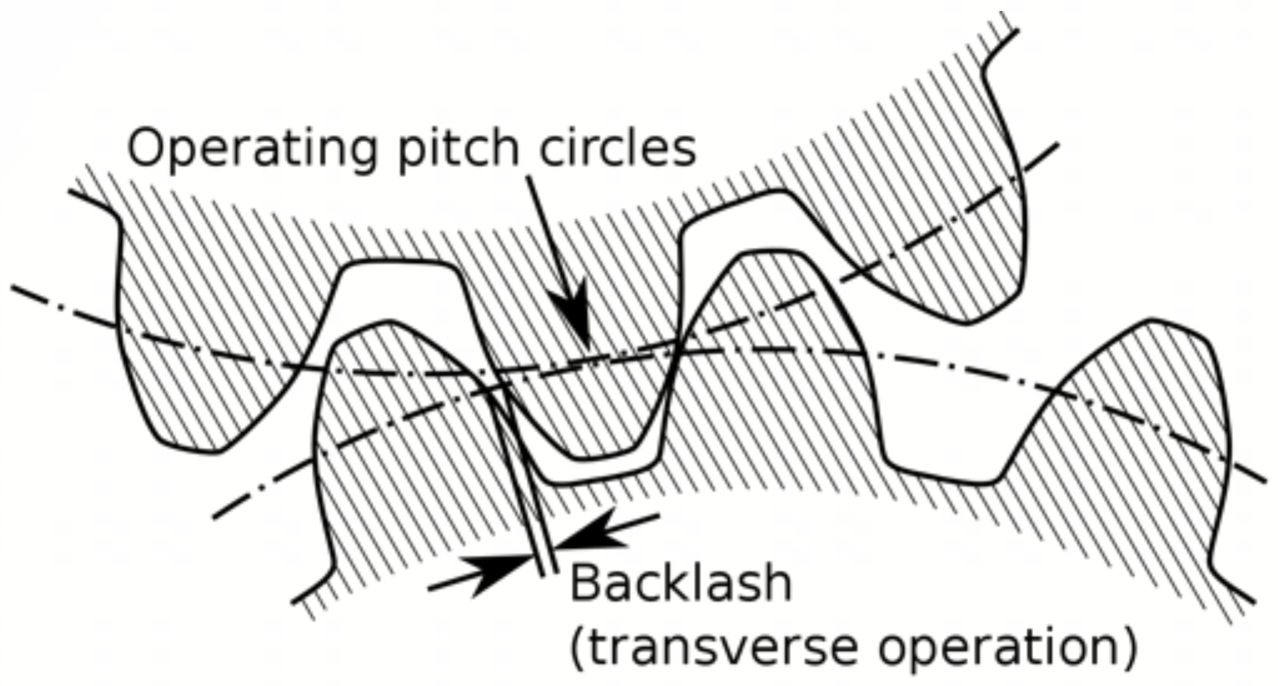
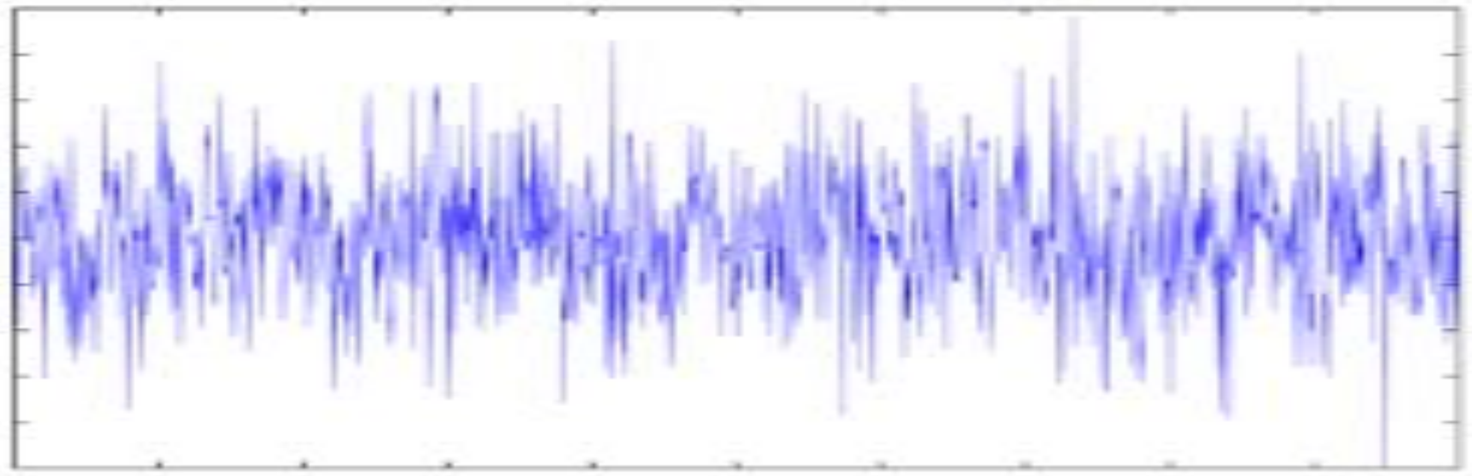
Introduction

PID Controllers don't perform well when subjected to multiple sources of disturbance, such as:

Backlash



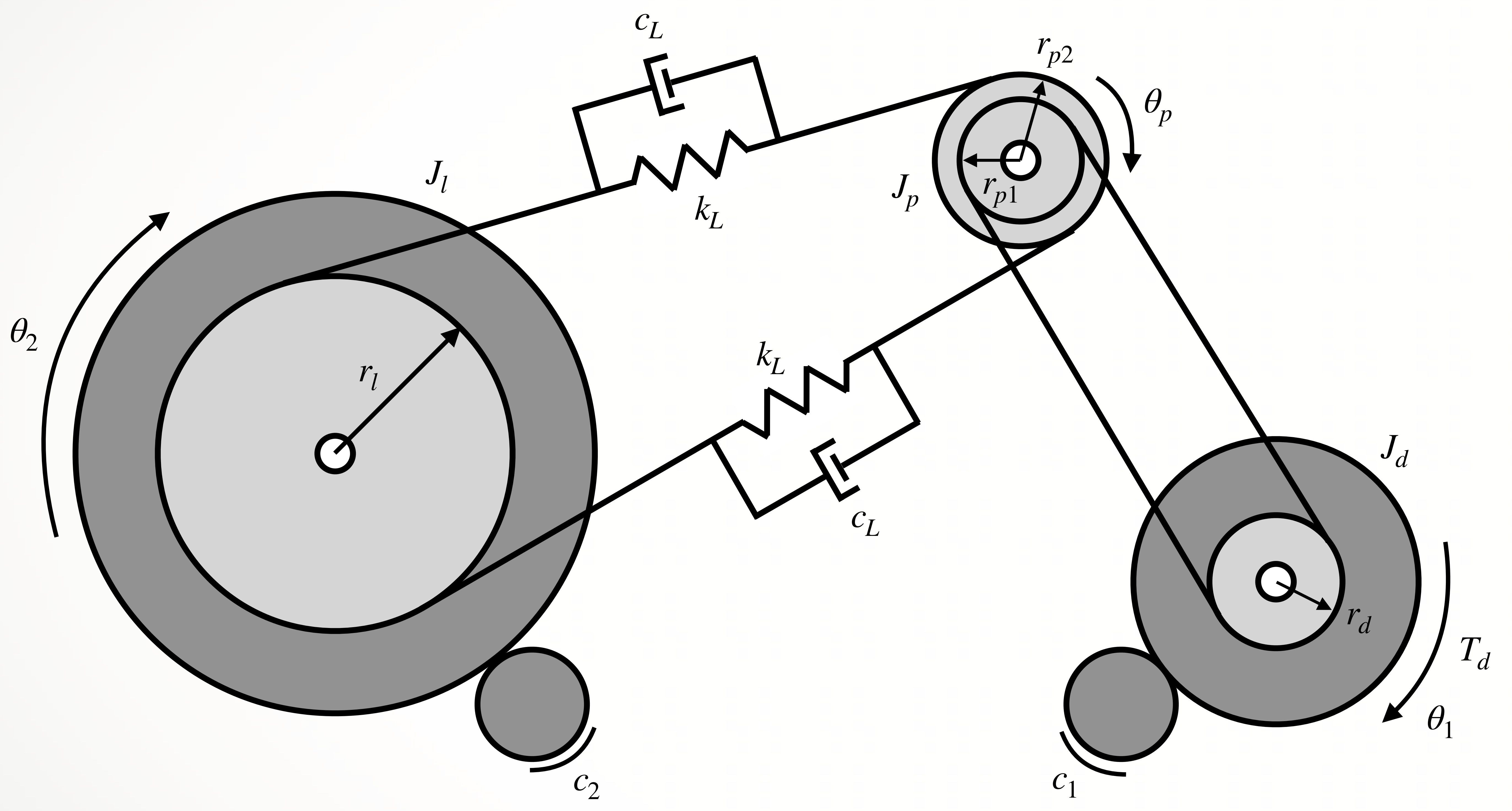
Vibration



Industrial Emulator Plant

Electromechanical system which consists of a brushless DC servo motor that drives a rotational load

Industrial Emulator Plant Modeling



Equivalent terms used to simplify the equations of motion:

$$J_d^* = J_d + \left(\frac{r_{p1}}{r_d}\right)^2 J_p \qquad gr = \frac{r_l r_{p1}}{r_{p2} r_d}$$

$$c_{12} = 2c_L r_l^2 \qquad k = 2k_L r_l^2$$

Equations of motion:

$$J_d^* \ddot{\theta}_1 + \left(c_1 + \frac{1}{gr^2} c_{12}\right)\dot{\theta}_1 - \frac{1}{gr} c_{12}\dot{\theta}_2 + \frac{k}{gr^2}\theta_1 - \frac{k}{gr}\theta_2 = T_D$$

$$J_l \ddot{\theta}_2 + \left(c_2 + c_{12}\right)\dot{\theta}_2 - \frac{1}{gr} c_{12}\dot{\theta}_1 + k\theta_2 - \frac{k}{gr}\theta_1 = 0$$

Industrial Emulator Plant Modeling

Equations of motion

$$J_d^*\ddot{\theta}_1 + \left(c_1 + \frac{1}{gr^2}c_{12}\right)\dot{\theta}_1 - \frac{1}{gr}c_{12}\dot{\theta}_2 + \frac{k}{gr^2}\theta_1 - \frac{k}{gr}\theta_2 = T_D$$

$$J_l\ddot{\theta}_2 + (c_2 + c_{12})\,\dot{\theta}_2 - \frac{1}{gr}c_{12}\dot{\theta}_1 + k\theta_2 - \frac{k}{gr}\theta_1 = 0$$

where:

$$J_d^* = J_d + \left(\frac{r_{p1}}{r_d}\right)^2 J_p \qquad gr = \frac{r_l r_{p1}}{r_{p2} r_d}$$

$$c_{12} = 2c_L r_l^2 \qquad k = 2k_L r_l^2$$

→

State vectors

$$\mathbf{x} = \left[\theta_1\ \dot{\theta}_1\ \theta_2\ \dot{\theta}_2\right]^T \qquad \dot{\mathbf{x}} = \left[\dot{\theta}_1\ \ddot{\theta}_1\ \dot{\theta}_2\ \ddot{\theta}_2\right]^T$$

State equations

$$\dot{\mathbf{x}} = \mathbf{A}\mathbf{x} + \mathbf{B}u \qquad y = \mathbf{C}\mathbf{x}$$

$$\mathbf{A} = \begin{bmatrix} 0 & 1 & 0 & 0 \\ a_{21} & a_{22} & a_{23} & a_{24} \\ 0 & 0 & 0 & 1 \\ a_{41} & a_{42} & a_{43} & a_{44} \end{bmatrix} \quad \mathbf{B} = \begin{bmatrix} 0 \\ b_{21} \\ 0 \\ 0 \end{bmatrix} \quad \mathbf{C} = \begin{bmatrix} 0 & 0 & 1 & 0 \end{bmatrix}$$

where

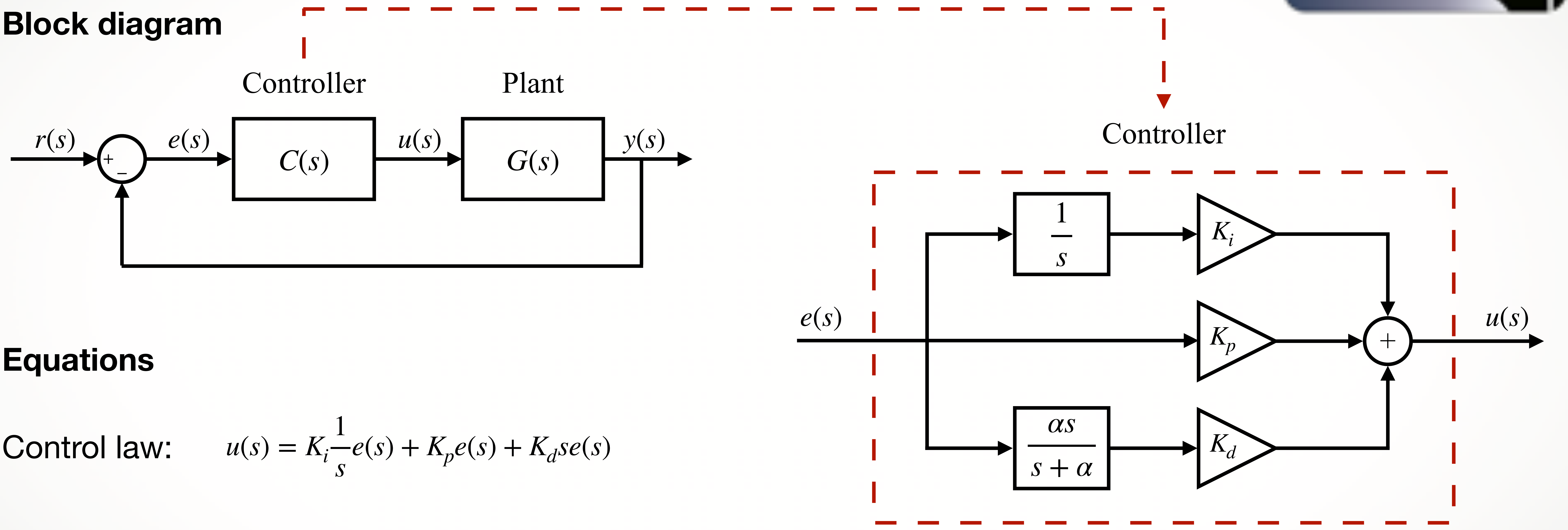
$$a_{21} = -\frac{k}{gr^2 J_d^*} \qquad a_{22} = -\frac{c_1 + \frac{c_{12}}{gr^2}}{J_d^*} \qquad a_{23} = \frac{k}{grJ_d^*}$$

$$a_{24} = \frac{c_{12}}{grJ_d^*} \qquad a_{41} = \frac{k}{grJ_l} \qquad a_{42} = \frac{c_{12}}{grJ_l}$$

$$a_{43} = -\frac{k}{J_l} \qquad a_{44} = -\frac{c_2 + c_{12}}{J_l} \qquad b_{21} = \frac{1}{J_d^*}$$

PID Controller Algorithm

Block diagram



Equations

Control law: $u(s) = K_i \frac{1}{s} e(s) + K_p e(s) + K_d s e(s)$

Error: $e(s) = r(s) - y(s)$

2-DOF PID Controller Algorithm

Equations

Control law: $$u(s) = K_i \frac{1}{s} e_i(s) + K_p e_p(s) + K_d \frac{\alpha s}{s+\alpha} e_d(s)$$

Weighted error terms:

$$e_p(s) = \beta r(s) - y(s)$$

$$e_i(s) = r(s) - y(s)$$

$$e_d(s) = \gamma r(s) - y(s)$$

If $\gamma = 0$:

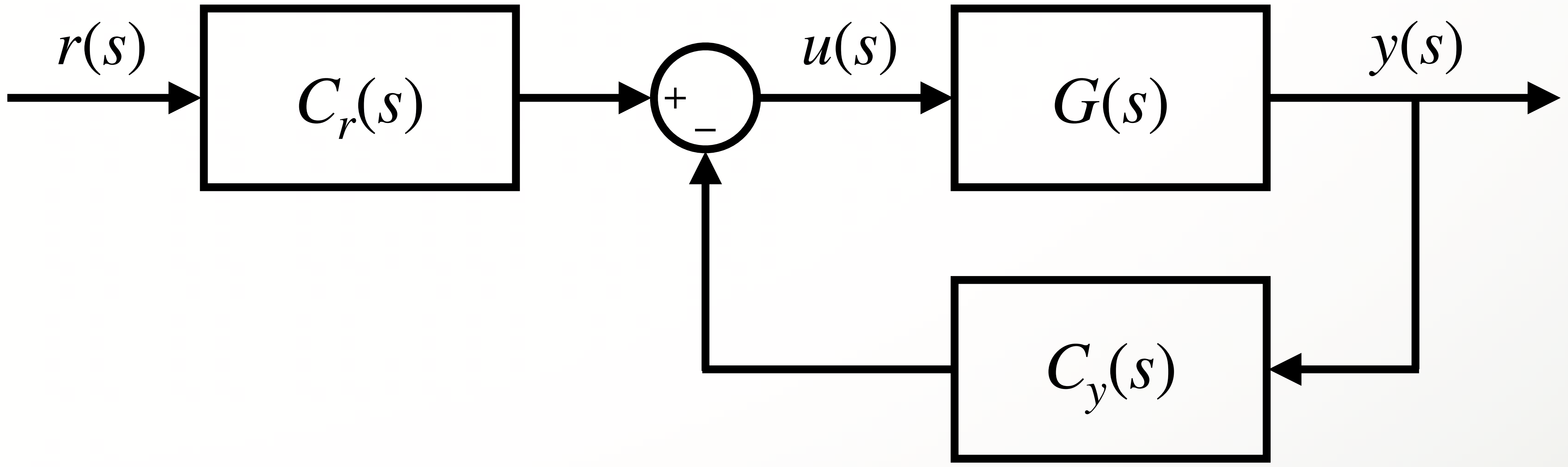
$$u(s) = \underbrace{\left[K_i \frac{1}{s} + K_p \beta\right]}_{C_r(s)} r(s) - \underbrace{\left[K_i \frac{1}{s} + K_p \beta + K_d \frac{\alpha s}{s+\alpha}\right]}_{C_y(s)} y(s)$$

Two new controllers:

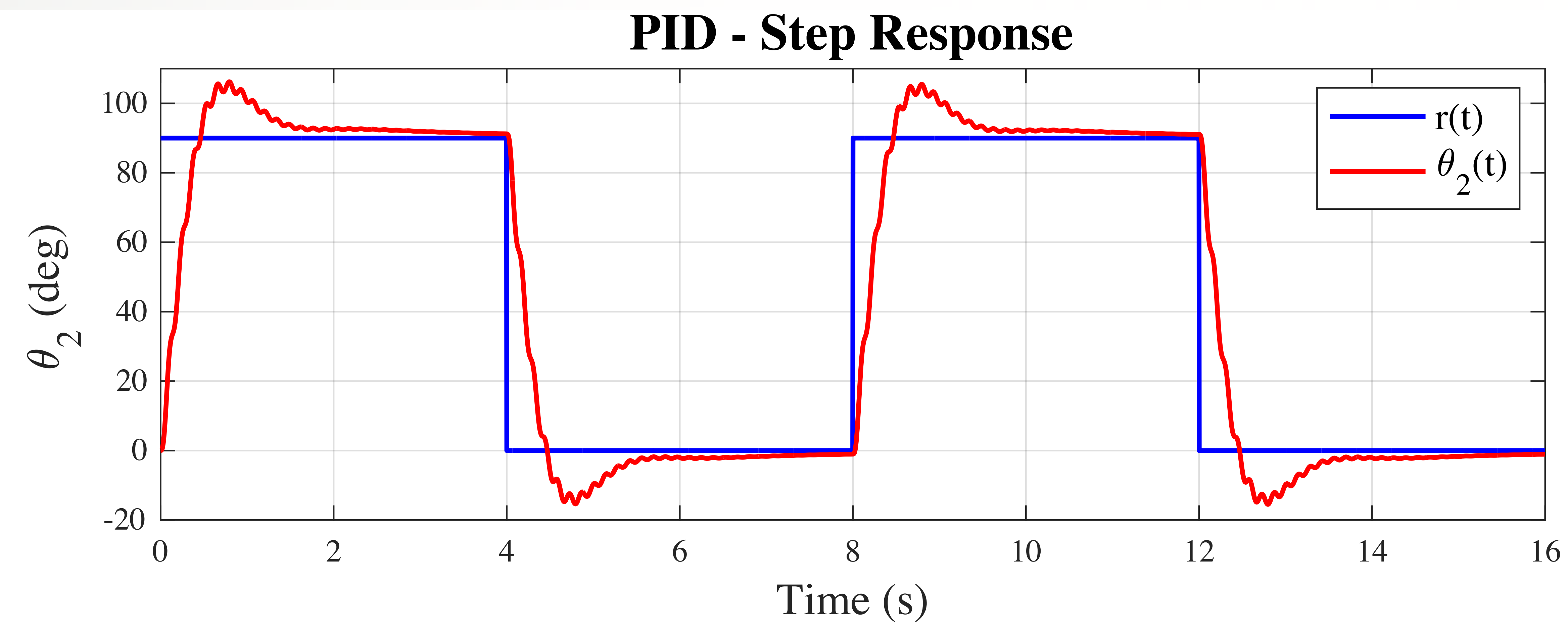
$$C_r(s) = \left[K_i \frac{1}{s} + K_p \beta\right]$$

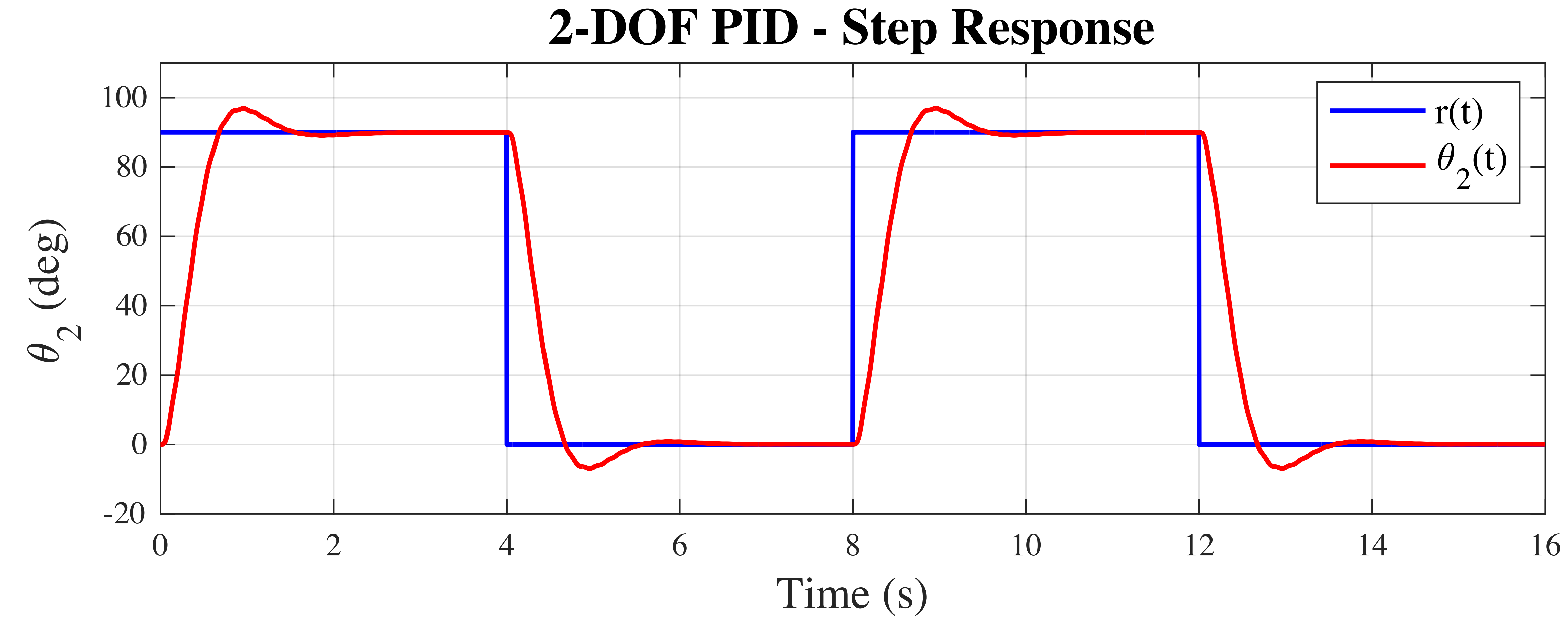
$$C_y(s) = \left[K_i \frac{1}{s} + K_p \beta + K_d \frac{\alpha s}{s+\alpha}\right]$$

Block diagram of 2-DOF PID controller:



Controller Simulation





CONTROL PARAMETERS FOR SIMULATION STUDIES

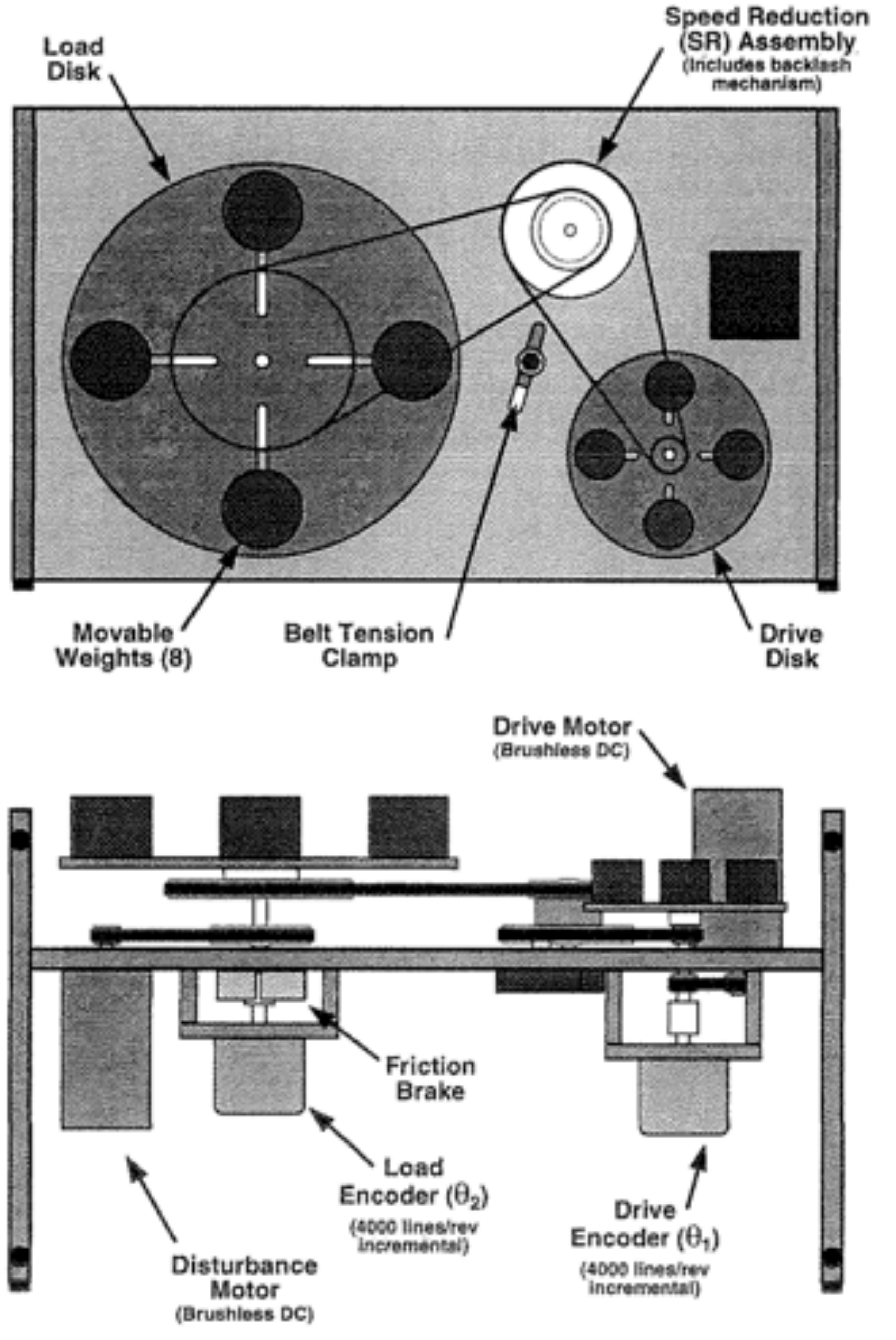
Controller	K_p	K_i	K_d	α	β	γ
PID	0.015	0.003	0.0035	–	–	–
2–DOF PID	0.015	0.003	0.0035	50	0.8769	0

SIMULATION RESULTS

Controller	e_{ss} (%)	t_s (s)	OS (%)
PID	1.37	3.16	18.0
2–DOF PID	0.13	1.37	7.68

The 2-DOF PID controller has less steady state error, settling time, overshoot and oscillations than the PID controller.

Experimental Setup



Experimental Results

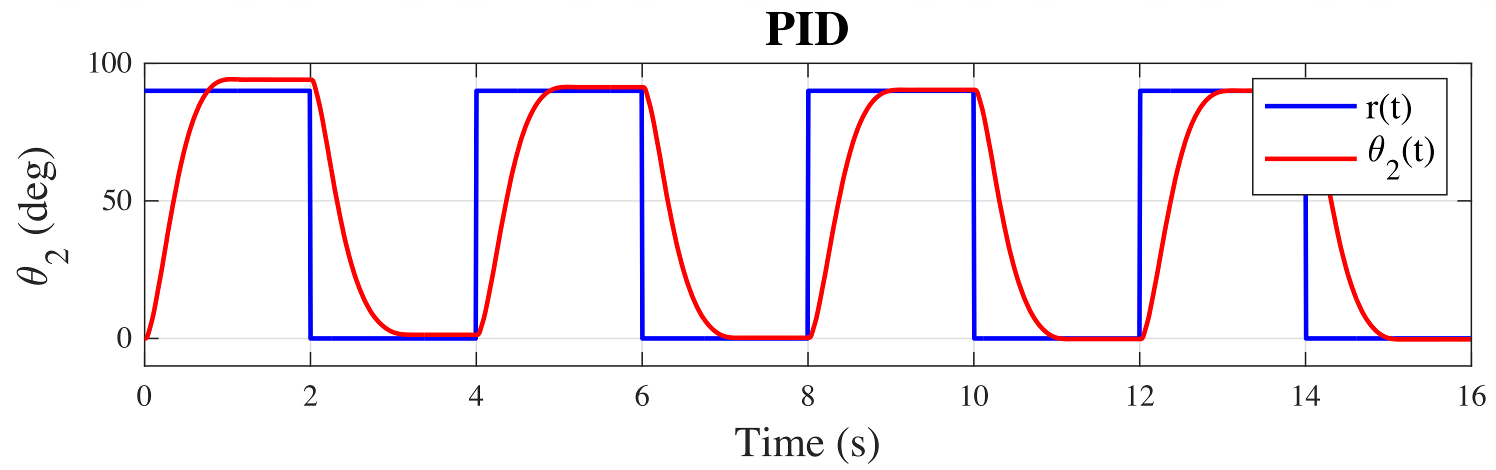
Without disturbances

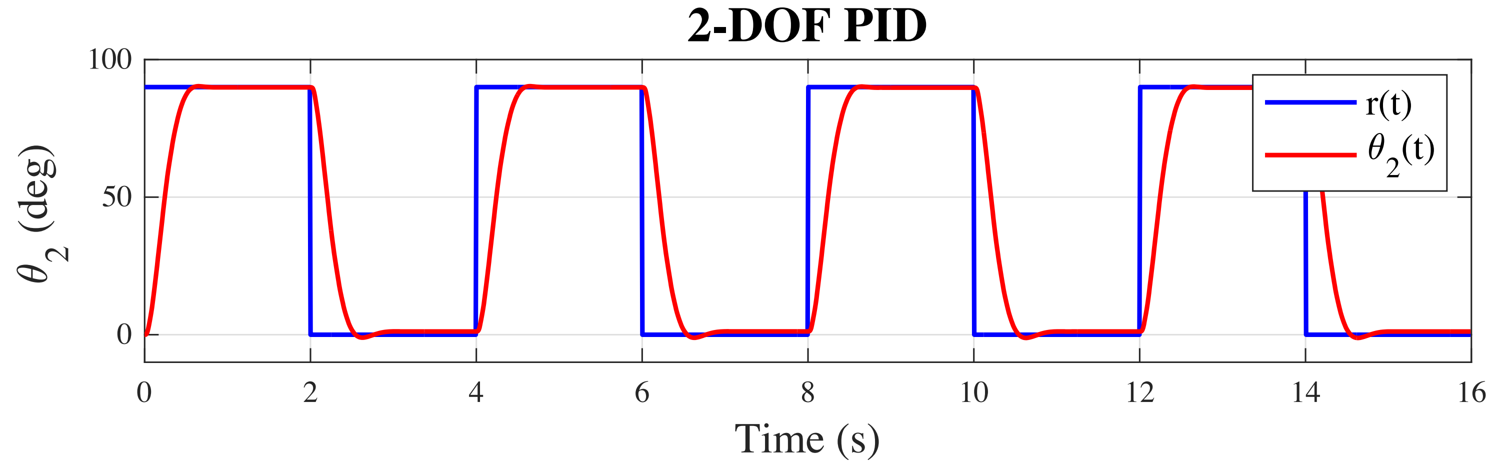
CONTROLLER PARAMETERS

Controller	K_p	K_i	K_d	α	β	γ
PID	0.06	0.02	0.02	–	–	–
2–DOF PID	0.1	0.02	0.02	50	0.95	0

IMPLEMENTATION RESULTS

Controller	e_{ss} (%)	t_s (s)	OS (%)
PID	1.61	0.87	0
2–DOF PID	0.22	0.43	0.22





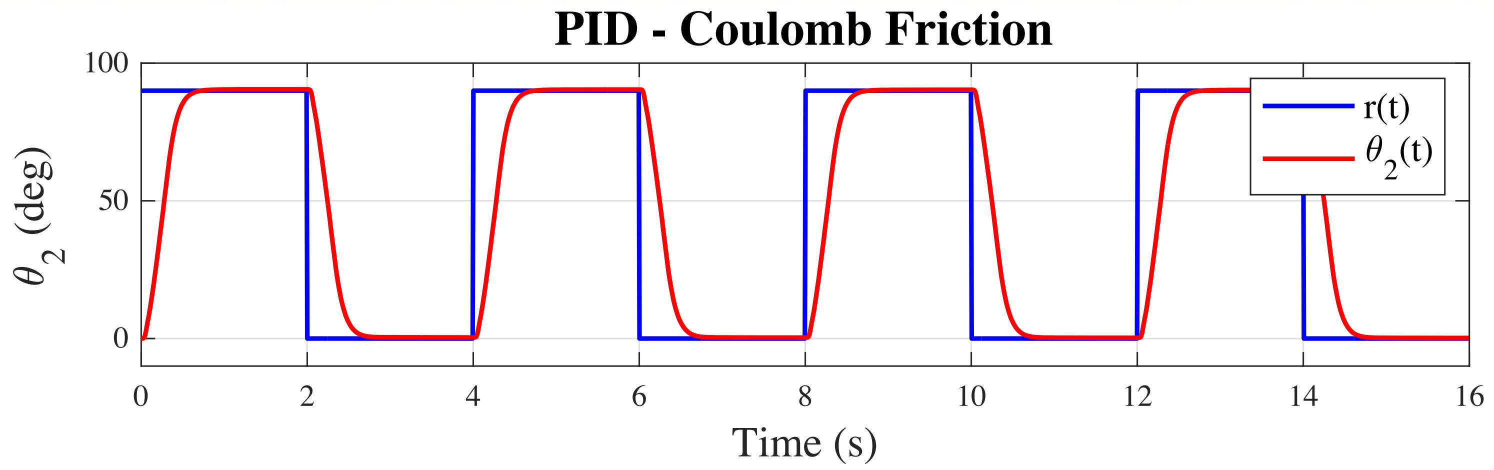
With Coulomb friction

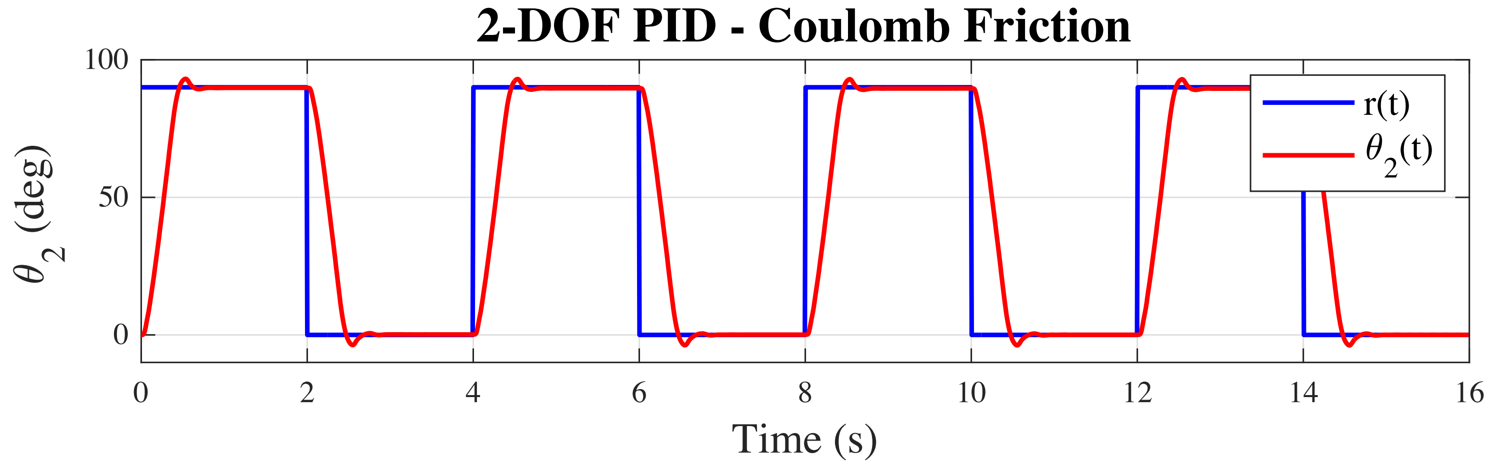
CONTROLLER PARAMETERS

Controller	K_p	K_i	K_d	α	β	γ
PID	0.5	0.05	0.02	–	–	–
2–DOF PID	0.5	0.09	0.02	50	0.95	0

IMPLEMENTATION RESULTS

Controller	e_{ss} (%)	t_s (s)	OS (%)
PID	0.44	0.58	0
2–DOF PID	0.22	0.49	3.33





Experimental Results

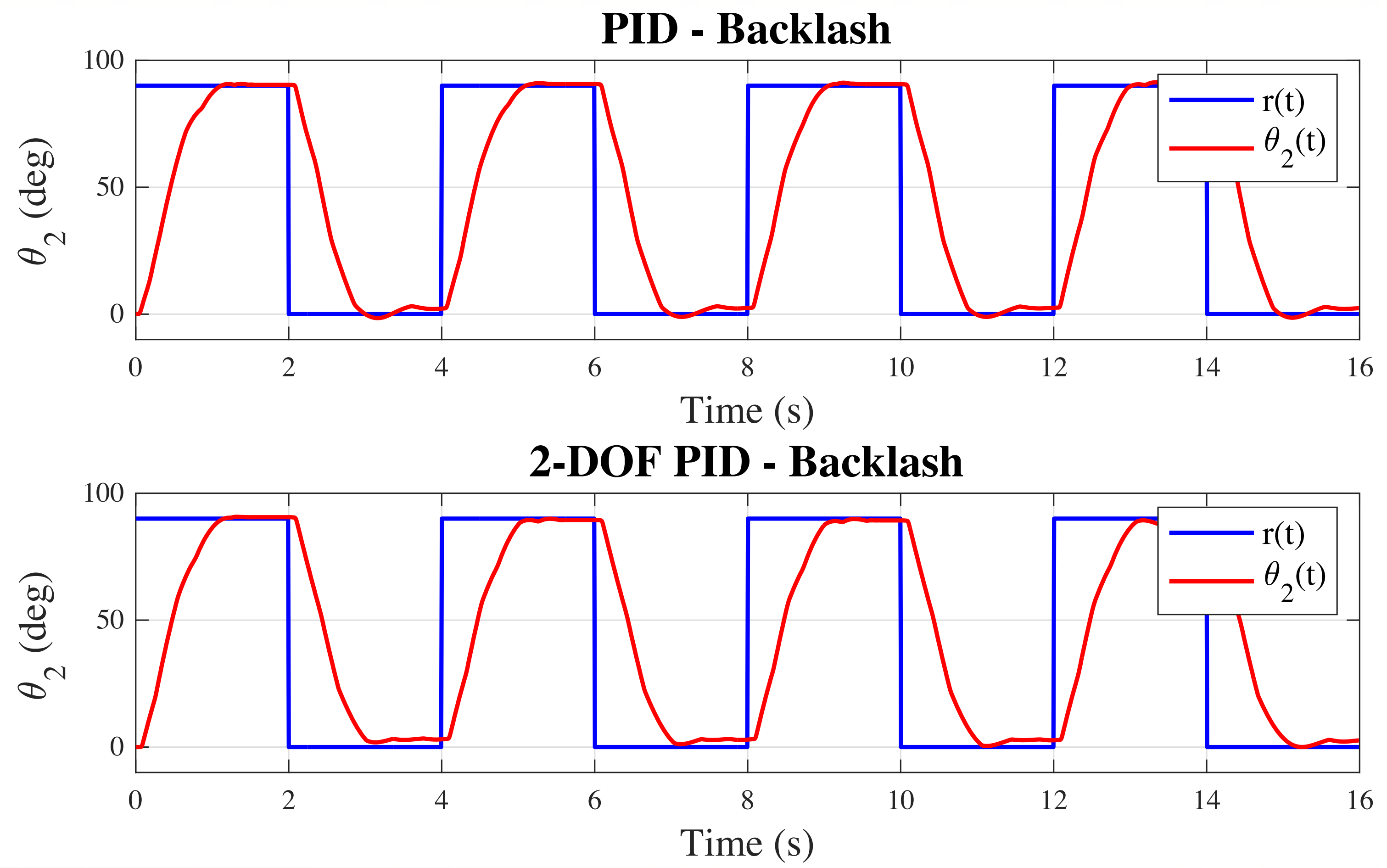
With backlash

CONTROLLER PARAMETERS

Controller	K_p	K_i	K_d	α	β	γ
PID	0.03	0.01	0.003	–	–	–
2–DOF PID	0.03	0.015	0.01	50	0.85	0

IMPLEMENTATION RESULTS

Controller	e_{ss} (%)	t_s (s)	OS (%)
PID	0.44	0.95	1.5
2–DOF PID	0.55	1.02	0



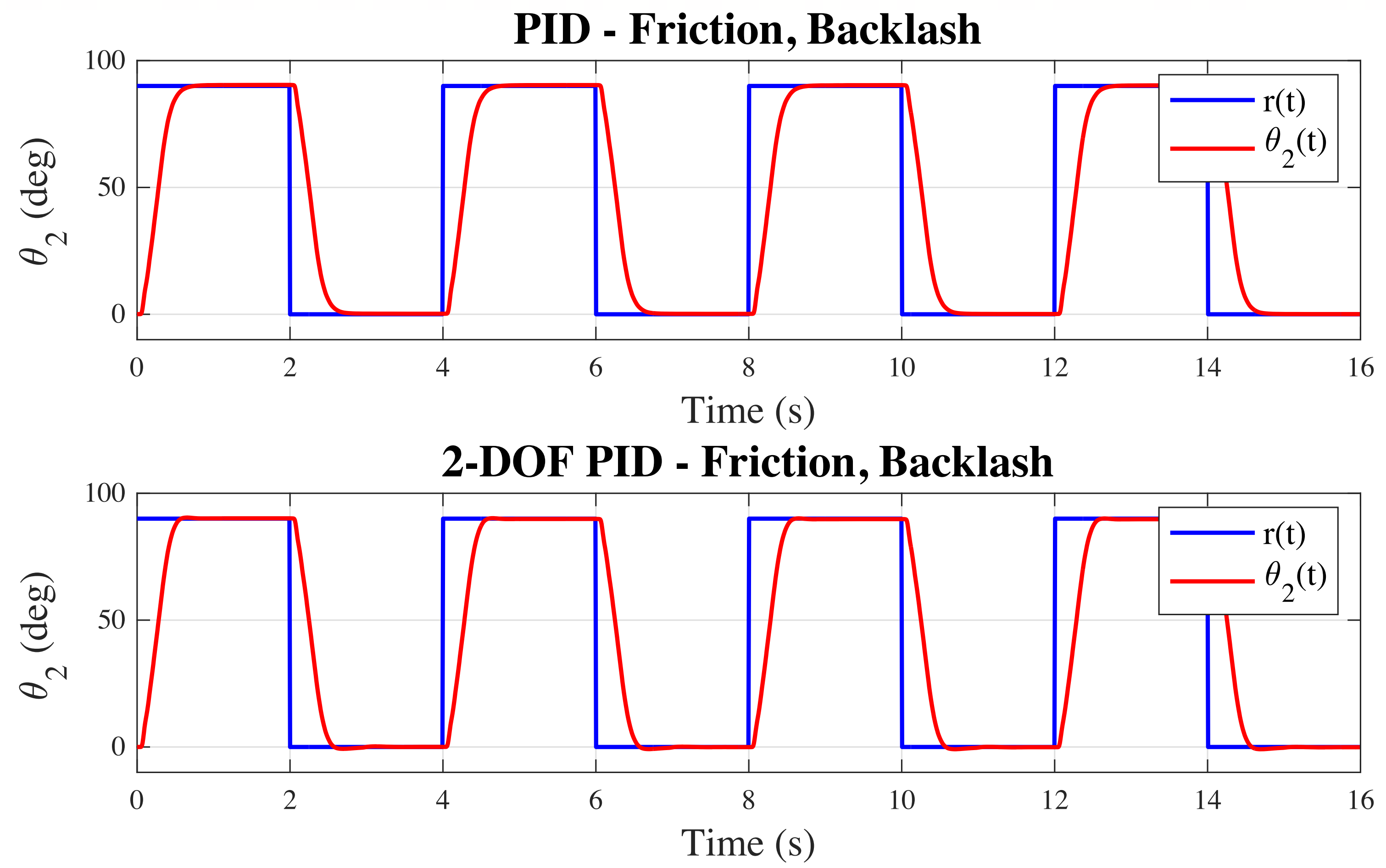
With Coulomb friction and backlash

CONTROLLER PARAMETERS

Controller	K_p	K_i	K_d	α	β	γ
PID	0.5	0.05	0.018	–	–	–
2–DOF PID	0.3	0.095	0.02	50	0.92	0

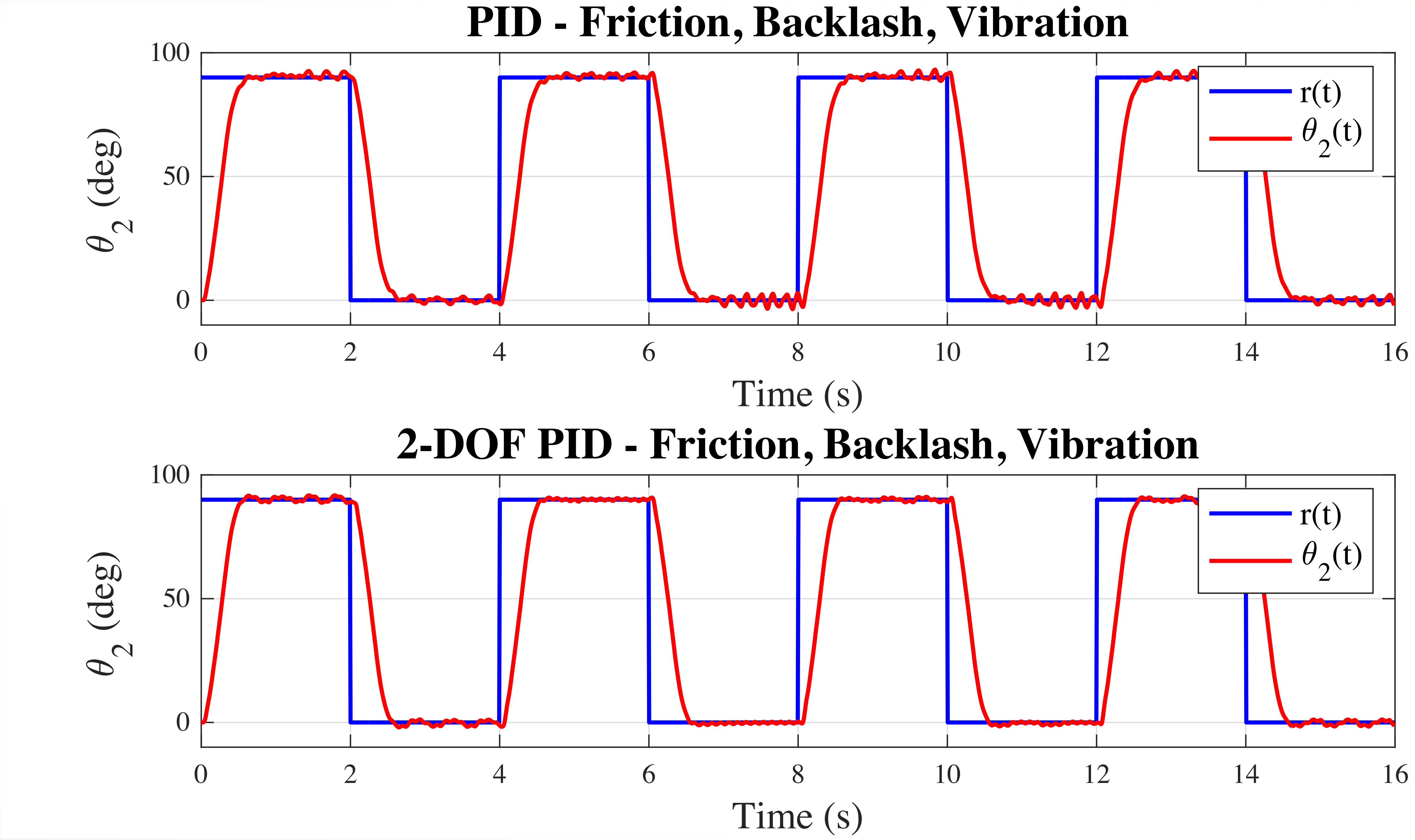
IMPLEMENTATION RESULTS

Controller	e_{ss} (%)	t_s (s)	OS (%)
PID	0.27	0.59	0
2–DOF PID	0.11	0.52	0.48



Experimental Results

With Coulomb friction and backlash and sinusoidal vibration



CONTROLLER PARAMETERS

Controller	K_p	K_i	K_d	α	β	γ
PID	0.5	0.05	0.018	–	–	–
2–DOF PID	0.3	0.095	0.02	50	0.92	0

IMPLEMENTATION RESULTS

Controller	e_{ss} (%)	t_s (s)	OS (%)
PID	2.81	0.58	4.02
2–DOF PID	0.11	0.52	0.93

Concluding Remarks

- Both controllers achieved similar performance in experimental the first four experimental tests, although the PID controller was slightly better without disturbances and with Coulomb friction, while the 2–DOF PID controller was slightly better with backlash and Coulomb friction + backlash.

- However, there was a notable difference in test five due to the presence of Coulomb friction, backlash and vibration. In that case, the step response of the 2–DOF PID controller showed significantly less overshoot, steady state error and oscillations and similar settling time.

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