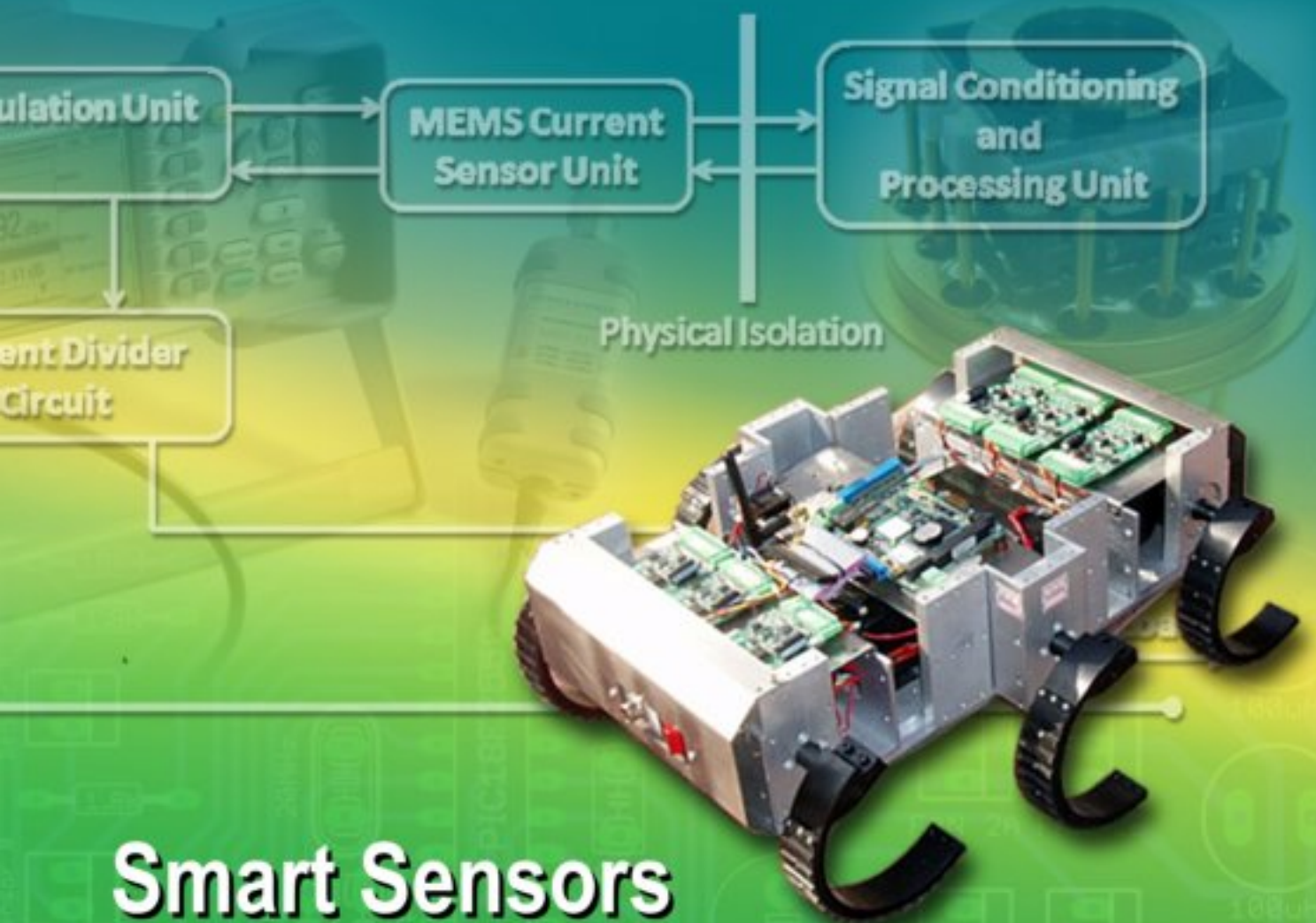


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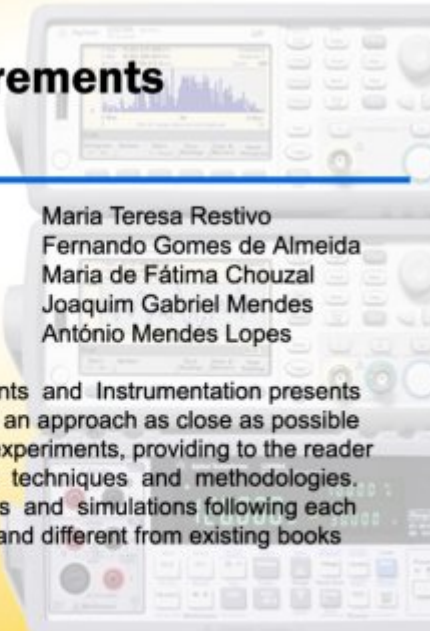





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Stability Analysis and Design of PI Controller Using Kharitnov Polynomial for Rotary Inverted Pendulum

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Abstract: Stability analysis of linear and non linear control systems is one of the major requirements of modern manufacturing plants, biomedical systems, aerospace systems, automobile systems and in industry. By assessment of stability only we can predict whether the system will work in desired conditions or not. This paper deals with mathematical modeling and design of swing up controller for a rotary inverted pendulum system which is non linear and unstable plant. In this system, the stabilization point considered is the inverted position of pendulum at inverted position while in rotation. *Copyright © 2012 IFSA.*

Keywords: Rotary inverted pendulum, System modeling, Kharitnov polynomial, PI controller, Stability analysis).

1. Introduction

A rotary Inverted Pendulum System (RIP) consists of a pendulum attached to a rotating arm driven by a motor. The aim of this paper is to design PI controller for the RIP system which is a single input single output system, so that pendulum at the end of the rotating arm remains in the inverted position while in rotation.

2. Rotary Inverted Pendulum

The structure of rotary inverted pendulum is given below. The rotational inverted pendulum consists of a driven arm which rotates in the horizontal plane and a pendulum attached to that arm which is free to rotate in the vertical plane.

The Rotary Inverted Pendulum consists of (see Fig. 1):

- a) DC servomotor;
- b) Rotating arm;
- c) Pendulum.



Fig. 1. Rotary Inverted Pendulum.

3. System Modeling

3.1. DC Servomotor and its Modeling

DC servomotor is an electromechanical system which converts electrical energy to mechanical energy. In RDIP it is used for rotating the rotating arm.

The model of the dc servomotor is shown below in Fig. 2:

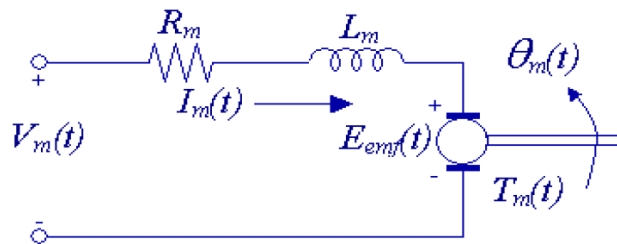


Fig. 2. Equivalent model of armature controlled dc servomotor.

R_m is the resistance of the armature circuit;

L_m is the inductance of the armature circuit;

E_{emf} is the back emf developed;

θ_m is the angular displacement of the motor shaft or angular displacement of the rotating arm;

T_m is the torque developed.

By Kirchoff's voltage law:

$$V_m - R_m I_m - L_m \dot{I}_m - E_{emf} = 0 \quad (1)$$

By torque current relationship,

$$T \propto I_m \quad (2)$$

The above proportionality can be written as:

$$T = K_t I_m, \quad (3)$$

where K_t is the torque constant.

The torque equation can be written as:

$$T = J\dot{\omega} + B\omega \quad (4)$$

where: J is moment of inertia, B is rotational frictional coefficient.

The expression for back emf can be written as:

$$E_{emf} = K_b \omega \quad (5)$$

where: K_b is the back emf constant, ω is the angular velocity.

$$\omega = \dot{\theta} \quad (6)$$

From the above equations, the transfer function of the dc servomotor is obtained as:

$$\frac{\theta(s)}{V_m(s)} = \frac{K_t K_b}{s(s^2 J L_m + s(B L_m + J R_m) + R_m B + K_t K_b)} \quad (7)$$

Taking into account, efficiencies of gear box and motor.

The transfer function can be written as:

$$\frac{\theta(s)}{V_m(s)} = \frac{\eta_m \eta_g K_t K_b}{s(s^2 J L_m + s(B L_m + J R_m) + R_m B + \eta_m \eta_g K_t K_b)} \quad (8)$$

where:

$$K_b = K_m K_g \quad (9)$$

Since

$$L_m \ll R_m$$

$$\frac{\theta(s)}{V_m(s)} = \frac{\eta_m \eta_g K_t K_b}{s^2(JR_m) + s(R_m B + \eta_m \eta_g K_t K_b)}, \quad (10)$$

where,

η_m is the efficiency of the motor, η_g is the efficiency of the gear box.

3.2. Modeling of Rotating Arm and Pendulum

Fig. 3 depicts the rotary inverted pendulum in motion.

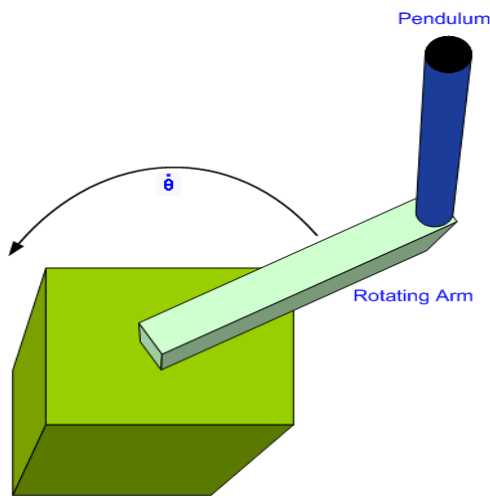


Fig. 3. Topview of rotary inverted pendulum.

Let the pendulum be considered as lump mass at half the length of the pendulum.

The side view of the pendulum on motion can be shown as (see Fig. 4):

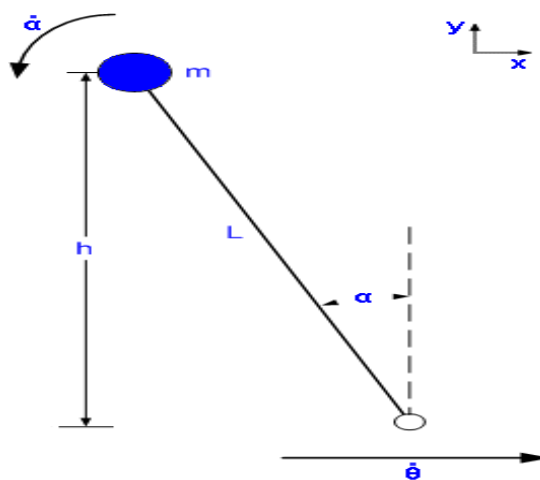


Fig. 4. Side view of pendulum in motion.

L is the length to pendulum's centre of mass (half the pendulum length);

m is the mass of the pendulum;

r is the half the length rotating arm;

α is the pendulum deflection;

θ is the servo load gear angle.

From Fig. 4, there are two components for velocity of the pendulum lumped mass:

$$V_{\text{pendulum centre of mass}} = -L\cos\alpha(\dot{\alpha})\hat{x} - L\sin\alpha(\dot{\alpha})\hat{y} \quad (11)$$

Velocity of the rotating arm:

$$V_{\text{arm}} = r\dot{\theta} \quad (12)$$

Taking the x and y components:

$$V_x = r\dot{\theta} - L\cos\alpha(\dot{\alpha}) \quad (13)$$

$$V_y = -L\sin\alpha(\dot{\alpha}) \quad (14)$$

3.3. System Dynamic Equations

Potential Energy is only due to gravity.

$$PE_{\text{pendulum}} = mgh = mgL\cos\alpha \quad (15)$$

Kinetic Energy arises from the moving hub, the velocity of point mass in the x-direction, the velocity of the point mass in the y-direction and the rotating pendulum about its center of mass:

$$T = KE_{\text{Hub}} + KE_{V_x} + KE_{V_y} + KE_{\text{pendulum}} \quad (16)$$

The moment of inertia of a rod about its centre of mass is:

$$J_{\text{cm}} = \frac{1}{12}MR^2 \quad (17)$$

Taking : $R = 2L$

$$J_{\text{cm}} = \frac{1}{3}ML^2 \quad (18)$$

$$KE_{\text{Hub}} = \frac{1}{2}J\dot{\theta}^2 \quad (19)$$

$$KE_{V_x} = \frac{1}{2}mV_x^2 \quad (20)$$

$$KE_{V_y} = \frac{1}{2}mV_y^2 \quad (21)$$

$$KE_{pendulum} = \frac{1}{2}J_{cm}\dot{\alpha}^2 \quad (22)$$

The Lagrangian is given by:

$$L = T - PE_{pendulum} \quad (23)$$

$$\frac{\delta}{\delta t} \left(\frac{\delta L}{\delta \dot{\theta}} \right) - \frac{\delta L}{\delta \theta} = T_{output} - B_{eq} \dot{\theta} \quad (24)$$

$$\frac{\delta}{\delta t} \left(\frac{\delta L}{\delta \dot{\alpha}} \right) - \frac{\delta L}{\delta \alpha} = 0 \quad (25)$$

Output torque on the load of the motor is:

$$T_{output} = \frac{n_m n_g K_t K_m (V_m - I_m R_m)}{R_m} \quad (26)$$

3.4. State Space Model of the System

The state space model of one sided rotary inverted pendulum can be deduced from the above expressions as shown below,

$$\begin{bmatrix} \dot{\theta} \\ \dot{\omega} \\ \dot{\phi} \\ \dot{\alpha} \end{bmatrix} = \begin{bmatrix} 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \\ 0 & \frac{b\omega}{E} & \frac{rG}{E} & 0 \\ 0 & \frac{\omega\phi}{E} & \frac{-bG}{E} & 0 \end{bmatrix} \begin{bmatrix} \theta \\ \omega \\ \phi \\ \alpha \end{bmatrix} + \begin{bmatrix} 0 \\ 0 \\ \frac{r n_m n_g K_t K_m}{R_m E} \\ \frac{b n_m n_g K_t K_m}{R_m E} \end{bmatrix} V_m \quad (27)$$

where:

$$a = J + m r^2$$

$$b = mLr$$

$$c = \frac{4}{3}mL^2$$

$$d = mgL$$

$$E = ac - b^2$$

$$G = \frac{n_m n_g K_t K_m K_g^2 + BR_m}{R_m}$$

4. Kharitnov Polynomial

In the project simulation, we employ the method of Kharitonov's Theorem to determine the region for stabilizing controller-parameters (of polytypic polynomials). The main advantage of using this method is that it can be adopted or not only SISO, but also for MIMO system of any order; even if having perturbations in them. The Generalized Kharitonov Theorem given here provides a constructive solution to this problem by reducing it to the Hurwitz stability of a prescribed set of extremal line segments. The number of line segments in this test set is independent of the dimension of the parameter space. This test set has many important extremal properties that are useful in control systems.

In the problem, K_p and K_i are the unknown parameters.

The aim is to find a stabilizing range these values.

Let $(1+GH)$ forms the characteristic polynomial for the system given by:

$$G = (PI \text{ controller}) * \text{system TF}$$

$$H = 1(\text{unity feedback})$$

5. Determination of Range of K_P and K_I which Stabilizes the System

For a typical pendulum system:

For pendulum 1:

$m = .2 \text{ kg}$

$L = .3 \text{ m}$

$K_f = K_m = .00767$

$K_p = 70$

$B = .004$

$\eta_p = .9$

$\eta_m = .69$

$R_m = 2.6 \text{ ohm}$

$E = .000096$

$G = .07285$

Here output considered is pendulum angle:

$$\frac{\alpha(s)}{V_m(s)} = \frac{16.02s + .06292}{s^3 + 18.21s^2 - 61.31s - 446.9}$$

The characteristic polynomial of the system with PI controller can be given as:

$$P(s) = s^4 + 18.21s^3 + (16.02K_p - 61.31)s^2 + (16.02K_i + .0692K_p - 446.9)s + .0692K_i$$

Here there is polynomial inside a polynomial. We have to find a range of K_p and K_i for which $P(s)$ have closed loop poles on left side of s -plane.

For $K_p = [20, 100)$ and $K_i = [25, 100)$, the closed loop poles lies on the left hand side of the s-plane.

The values K_p and K_i which stabilizes the system can be plotted as (see Fig. 5):

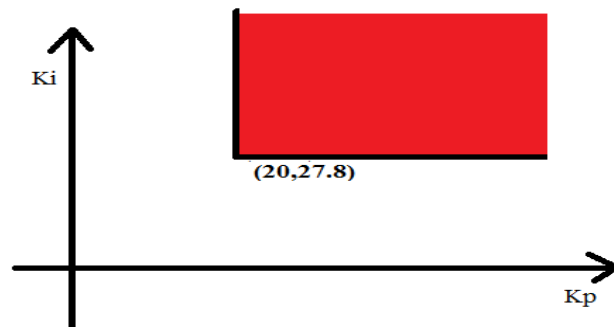


Fig. 5. Stabilizing values of K_p and K_i (shaded region).

6. Stability Analysis

The LabVIEW block diagram for stability analysis for both cases is shown in Fig. 6. Here we consider closed loop system with unity feedback that is the system obtained by the characteristic polynomial for both pendulums.

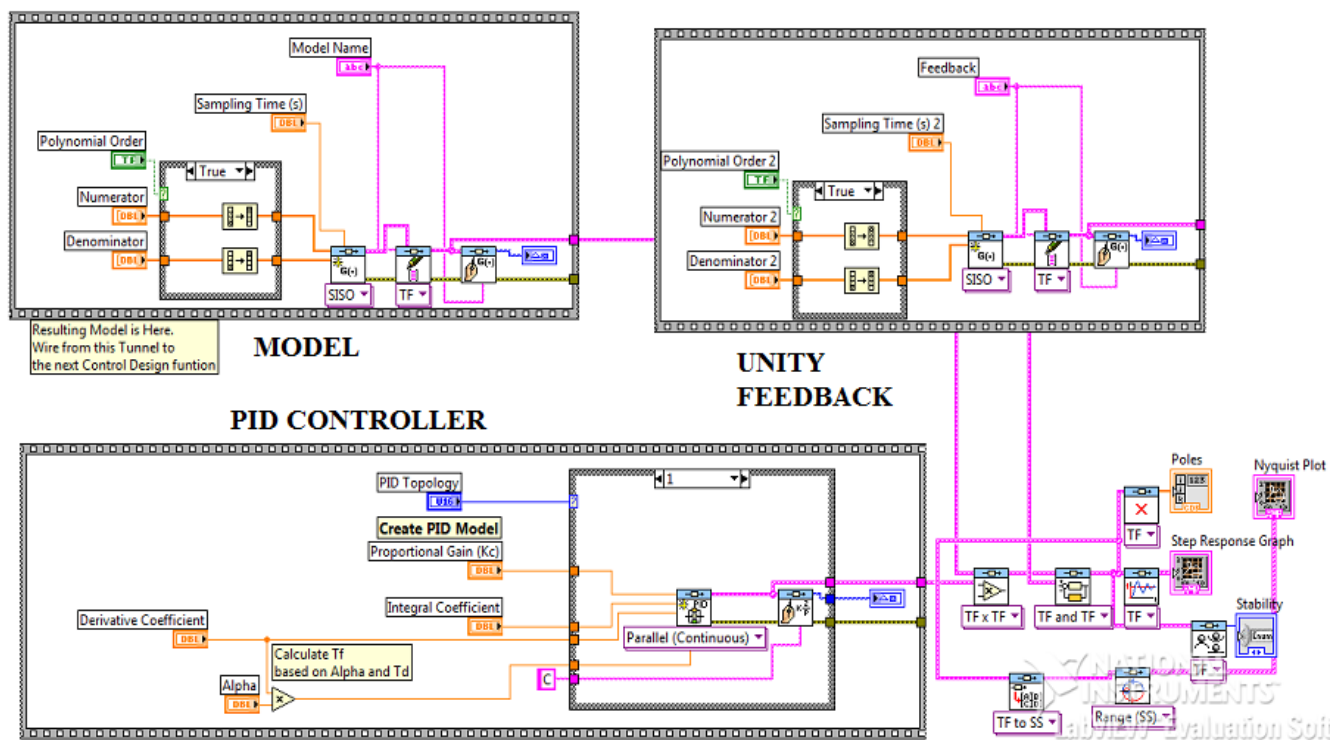


Fig. 6. LabVIEW block diagram for stability analysis.

Since the system under consideration is closed loop, stability analysis can be performed by plotting the Nyquist plot.

For pendulum, with $K_p=20$, $K_i=27.8$, the Nyquist plot is as shown below in Fig. 7.

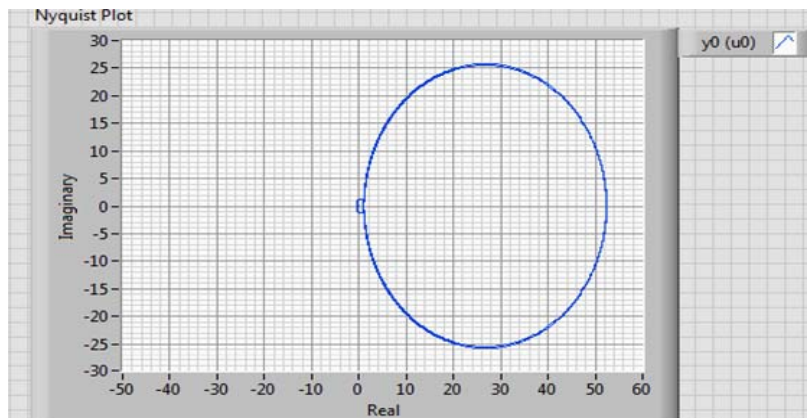


Fig. 7. Nyquist plot for pendulum 1 for $K_p=20$ and $K_i=27.8$.

The closed loop poles are given by:

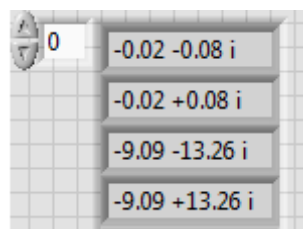


Fig. 8. Closed loop poles.

Number of anticlockwise encirclements of $(-1+j0)$ point is zero. All closed loop poles are on the left half of s plane, hence the system is stable for these PI values.

For pendulum1, with $K_p=15$, $K_i=10$, the Nyquist plot is as shown below in Fig. 9.

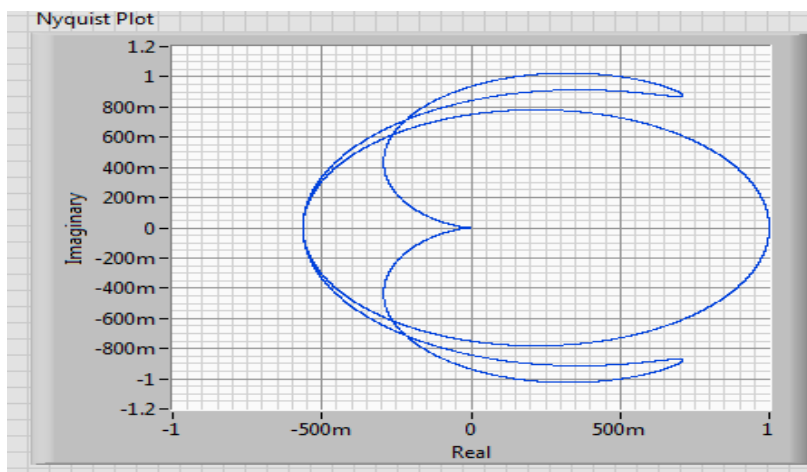


Fig. 9. Nyquist plot for pendulum 1 for $K_p=15$ and $K_i=10$.

The closed loop poles are given by:

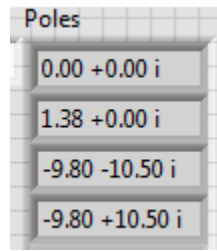


Fig. 10. Closed loop poles.

One pole is at origin and another one is at right half of s plane. Again number of anticlockwise encirclements of $(-1+j0)$ point is zero. Hence for this PI values, system is unstable for these PI values.

5. Conclusions

In the research the system is taken as rotary inverted pendulum. It is a highly non linear and unstable system. Linearization is done with the help of state space equations. From the linearised model, the transfer function of the system with pendulum angle as output and input voltage to the motor is taken. Then from the characteristic polynomial that is the Kharitnov polynomial is formed with PI controller transfer function. By giving different ranges for K_p and K_i , the range which stabilizes the system is found with the help of Routh Hurwitz criteria i.e. all closed loop poles lies on the left side of the s plane in that range. Stability analysis for the respective closed loop system is done by Nyquist stability criteria which gives an outlook to the stable range of K_p and K_i values for transfer function of the rotary inverted pendulum system.

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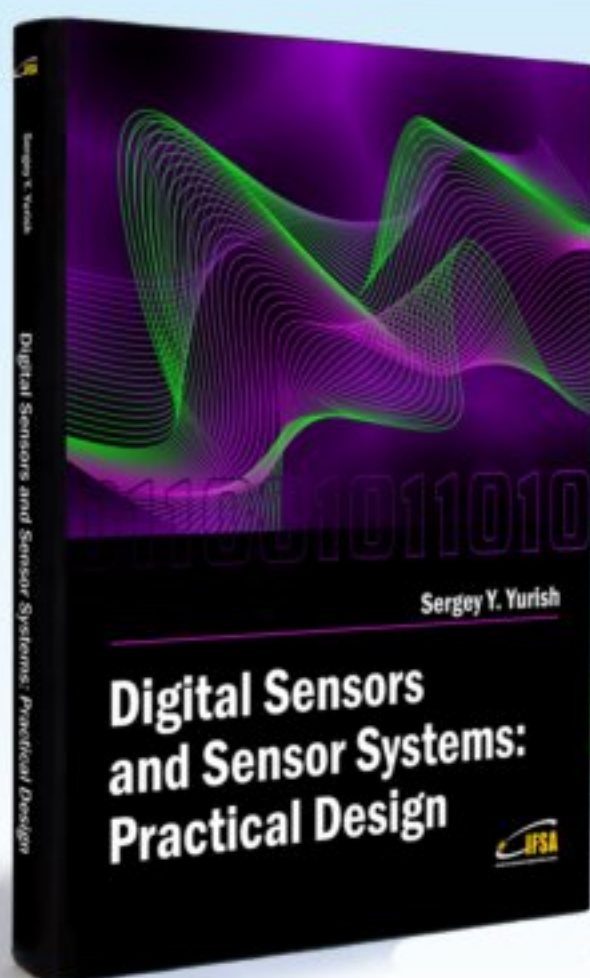
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