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FULL-AND REDUCED- ORDER COMPENSATOR FOR INNOSAT ATTITUDE CONTROL

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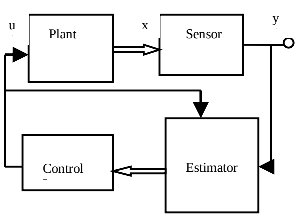
Graphical abstract



Abstract

This paper presents a study on the estimator based on Linear Quadratic Regulator (LQR) control scheme for Innovative Satellite (InnoSAT). By using LQR control scheme, the controller and the estimator has been derived for state space form in all three axes to stabilize the system's performance. This study starts by converting the transfer functions of attitude control into state space form. Then, the step continues by finding the best value of weighting matrices of LQR in order to obtain the best value of controller gain, K. After that, the best value of L is obtained for the estimator gain. The value of K and L is combined in forming full order compensator and in the same time the reduced order compensator is also formed. Lastly, the performance of full order compensator is compared to reduced order compensator. From the simulation, results indicate that both types of estimators have presented good stability and tracking performance. However, reduced order estimator has simpler equation and faster convergence to zero than the full order estimator. This property is very important in developing a satellite attitude control for real-time implementation.

Keywords: InnoSAT, LQR, miniature satellites, attitude control, estimator

Abstrak

Kertas kerja ini membentangkan kajian berasaskan skim kawalan penganggar linear kuadratik (LQR) untuk Satelit Inovatif (InnoSAT). Dengan skim kawalan LQR, pengawal dan estimator yang telah diperolehi dalam bentuk keadaan ruang di ketiga-tiga paksi untuk menstabilkan prestasi sistem. Kajian ini bermula dengan menukar rangkap pindah kawalan sikap ke bentuk keadaan ruang. Kemudian, nilai terbaik matriks pemberat LQR untuk mendapatkan nilai terbaik gandaan pengawal, K diperolehi. Seterusnya, nilai terbaik diperolehi untuk gandaan estimator, L. Nilai K dan L digabungkan bagi membentuk pemampas tertib penuh dan pemampas tertib berkurang serentak. Akhir sekali, pelaksanaan tertib pemampas penuh dibandingkan dengan pemampas tertib berkurang. Dari simulasi, keputusan menunjukkan kedua-dua jenis estimator mempunyai kestabilan dan prestasi pengesanan yang baik. Walau bagaimanapun, penganggar tertib berkurang mempunyai persamaan yang lebih mudah dan penumpuan yang lebih cepat kepada sifar. Ciri-ciri ini adalah sangat penting dalam membangunkan kawalan atitud satelit untuk pelaksanaan masa sebenar.

Kata kunci: InnoSAT, LQR, satelit kecil, kawalan atitud, estimator

1.0 INTRODUCTION

Miniature satellites become more popular in the last few decades due to their low cost during design, development, launching, power consumption and size and mass reduction. The fast development of technology has created the possibility in building miniature satellite. Miniature satellite can be divided into two types which are nano and pico satellite. These satellites are differentiated based on the weight and size of the satellite1. An example of nano satellite is the Innovative Satellite (InnoSAT) where the development of this satellite was organized by Agensi Angkasa Negara (ANGKASA) to attract the interest of Malaysian universities in satellite development studies [2].

Attitude control systems (ACS) play a fundamental role in satellite operation and in achieving mission goals. The satellite attitude control problem has been studied extensively where a number of possible approaches have been developed through the years [3-6]. Many approaches have been developed to control the attitude of satellite such as LQR and LQG, linear matrix inequality(LMI), gain scheduling/linear parameter varying [3], adaptive control/model following, variable structure, sliding mode control, fault tolerant control system (FTCS) and model-based predictive control (MPC) [4]. Nowadays, artificial intelligence techniques such as neural networks [5] and fuzzy logic are also used for obtaining better performance of attitude control.

The LQR method has been chosen in this paper for several reasons. LQR is an optimal controller that can provide smallest possible error to its input that can be obtained from a full state feedback. Moreover, LQR control scheme is simpler and straightforward for multivariable systems application. Besides that, the controller is capable to be generated automatically by simply selecting a few parameters where loop-shaping does not need to be done. Furthermore, in terms of robustness, LQR approach is more accurate since it considers the uncertainties noise of satellite system that cannot be seen in the Kalman filter [7].

In order to improve the stability of the system and error characteristics, compensation is typically added to feedback controlled system. This is due to the process itself that cannot be made to have acceptable characteristics with proportional feedback alone [8]. One type of compensator that is usually used is full-order compensator [9-13]. Based on the study in [14], a full order estimator using linear state variable feedback was used in designing ACS of space satellite in stationary orbits. As for [16], this study has proposed the use of full-order estimator for thrust-limited rendezvous in near-circular orbits. The method design in this study is able to be applied into various routine rendezvous missions for fault isolation and cost effective in the future.

In [13] it is shown that the design problem of full order estimator for linear systems with unknown inputs can be reduced to a simplified form where the unknown input vector does not interfere in the estimator equations. The estimator is known as reduced-order estimator. This estimator reduces the order of the estimator by the number of sensed outputs. Due to the presence of a direct transmission, the reduced order estimator has higher bandwidth from sensor to control when compared with full order estimator. Moreover, reduced-order estimator required less number of sensors and less number of feedback loops for corresponding feedback control applications [15]. Therefore, this current research focuses on finding the best compensator for ACS based on LQR control scheme for the application of InnoSAT.

2.0 METHODOLOGY

2.1 InnoSAT Model

Since LQR is used as the control scheme, the transfer function needs to be converted into state space. This transfer function is represented by yaw (ϕ), pitch (θ) and roll (ψ) such as in (1), (2) and (3) [2].

$$\phi(s) = \frac{s^2 + 0.3051s + 0.2040}{s^4 + 1.1050s^2 + 0.1650} \quad (1)$$

$$\theta(s) = \frac{1}{s^2 - 7.1138x10^{-3}} \quad (2)$$

$$\psi(s) = \frac{s^2 - 0.3023s + 0.8088}{s^4 + 1.1050s^2 + 0.1650} \quad (3)$$

The general form of state-space is given by (4) and (5) below.

$$\dot{x} = Ax + Bu \quad (4)$$

$$y = Cx + Du \quad (5)$$

where x is called the "state vector", y is called the "output vector", u is called the "input (or control) vector", A is the "state (or system) matrix", B is the "input matrix", C is the "output matrix", D is the feedforward matrix (in cases where the system model does not have a direct feedforward, D is the zero matrix).

The state space representation for yaw, pitch and roll axes are shown below. The matrices A, B and C of yaw axis are respectively obtained as:

$$A_Y = \begin{bmatrix} 0 & -1.1050 & 0 & -0.1650 \\ 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 1 & 0 \end{bmatrix} \quad (6)$$

$$B_Y = [1 \quad 0 \quad 0 \quad 0]^T \quad (7)$$

$$C_Y = [0 \quad 1.0000 \quad 0.3051 \quad 0.2040] \quad (8)$$

Similarly, the matrices A, B and C of pitch axis are respectively obtained as:

$$A_P = \begin{bmatrix} 0 & 0.0071 \\ 1 & 0 \end{bmatrix} \quad (9)$$

$$B_P = [1 \quad 0]^T \quad (10)$$

$$C_P = [0 \quad 1.0000] \quad (11)$$

Lastly, the matrices A, B and C of roll axis are respectively obtained as:

$$A_R = \begin{bmatrix} 0 & -1.1050 & 0 & -0.1650 \\ 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 1 & 0 \end{bmatrix} \quad (12)$$

$$B_R = [1 \quad 0 \quad 0 \quad 0]^T \quad (13)$$

$$C_R = [0 \quad 1 \quad -0.3023 \quad 0.8088] \quad (14)$$

However, for all yaw, pitch and roll axes, D_Y, D_P and D_R are equal to zero.

2.2 Linear Quadratic Regulator (LQR)

The full order compensator calculation start with finding the controller gain value, K. Figure 1 shows the basic mechanism of control law that is used in this study. Based on this mechanism, the optimal value of K is determined by using state-space in (4) and (5).

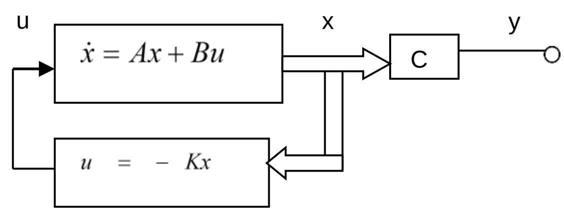


Figure 1 Predicted Control Law Mechanization of a close loop system

The control law is defined as in (15):

$$u = -Kx \quad (15)$$

By substituting (15) into the system described in (1) gives:

$$\dot{x} = (A - BK)x \quad (16)$$

The optimum value of K is important to obtain stable eigenvalues or poles. The eigenvalues are obtained using LQR control scheme. The general form of performance index is as shown in (17) below.

$$J = \int_0^\infty (x^T Q x + u^T R u)dt \qquad Q \geq 0, \ R > 0 \quad (17)$$

Before the optimum value of K is obtained, the weighting matrices which are R and Q need to be adjusted. This is because the smallest settling time and overshoot need to be achieved. In this study, the value of R is set as 1. Therefore, weighting matric Q is adjusted by varying the value from 0.1 until 10. The values for Q and R are calculated based on Bryson's rule such as in (18) and (19) 17.

$$Q_{ii} = \frac{1}{maximum\ acceptable\ value\ of [x_i^2]} \quad (18)$$

$$R_{ii} = \frac{1}{maximum\ acceptable\ value\ of\ [u_i^2]} \quad (19)$$

where i ∈{1,2,...}.

2.3 Full-Order Compensator

The output obtained from LQR is then used to obtained eigenvalues or poles. From here, the gain values of estimator, L is obtained. By combining the values of controller and estimator, the full order compensator in state-space form is obtained in Figure 2.

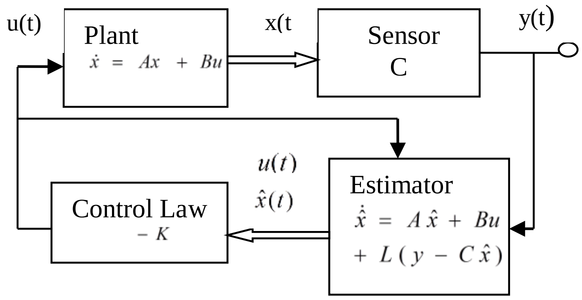


Figure 2 Estimator and Controller Mechanization

The error in the estimate is defined as

$$\tilde{x} \triangleq x - \hat{x} \tag{20}$$

Then, the dynamics of this error is given by:

$$\dot{\tilde{x}} = A\tilde{x} \tag{21}$$

A full order estimator has the form [9-13]:

$$\dot{\hat{x}} = A\hat{x} + B_2u + L(y - C\hat{x}) \tag{22}$$

The dynamics of the error can be obtained by subtracting the estimate (22) from the state (4):

$$\dot{\tilde{x}} = (A - LC)\tilde{x} \tag{23}$$

The selected L should make $A - LC$ stable and reasonably fast eigenvalues, then will decay to zero and remain there. This means that $\hat{x}(t)$ will converge to $x(t)$ without considering the value of $\hat{x}(0)$. Then, the dynamics of the error to be stable faster than the open loop dynamics.

The plant equation with feedback is defined as:

$$\dot{x} = Ax - BK\hat{x} \tag{24}$$

which can be rewritten in terms of the state error $\tilde{x}$ as:

$$\dot{x} = Ax - BK(x - \tilde{x}) \tag{25}$$

The overall system dynamics in state form are obtained by combining (25) with the estimator error (23):

$$\begin{bmatrix} \dot{x} \\ \dot{\tilde{x}} \end{bmatrix} = \begin{bmatrix} A - BK & BK \\ 0 & A - LC \end{bmatrix} \begin{bmatrix} x \\ \tilde{x} \end{bmatrix} \tag{26}$$

2.4 Reduced-Order Compensator

The reduced order compensator calculation starts by assuming that the output equals the first state where $y = x_1$. The state vector is then partition into two parts: x_1 and x_2. The full description is as in (27) and (28).

$$\begin{bmatrix} \dot{x}_1 \\ \dot{x}_2 \end{bmatrix} = \begin{bmatrix} A_{11} & A_{12} \\ A_{21} & A_{22} \end{bmatrix} \begin{bmatrix} x_1 \\ x_2 \end{bmatrix} + \begin{bmatrix} B_1 \\ B_2 \end{bmatrix} u \tag{27}$$

$$y = [1 \quad 0] \begin{bmatrix} x_1 \\ x_2 \end{bmatrix} \tag{28}$$

The dynamics of the unmeasured state-variables are given by:

$$\dot{x}_2 = A_{22}x_2 + A_{21}x_1 + B_2u \tag{29}$$

where $A_{21}x_1 + B_2u$ is known input and can be considered as an input into $\dot{x}_2$ dynamics. Let $\dot{x}_1 = y$, the measured dynamics are given by a scalar (30):

$$\dot{x}_1 = \dot{y} = A_{11}y + A_{12}x_2 + B_1u \tag{30}$$

By collecting the known terms in (30) on one side, (31) is written as:

$$\dot{y} - A_{11}y - B_1u = A_{12}x_2 \tag{31}$$

Based on (31), the substitutions of reduced order estimator can be written as in (32) until (36).

$$x \rightarrow x_1 \tag{32}$$

$$A \rightarrow A_{22} \tag{33}$$

$$Bu \rightarrow A_{21}y + B_2u \tag{34}$$

$$y \rightarrow \dot{y} - A_{21}y - B_1u \tag{35}$$

$$C \rightarrow A_{12} \tag{36}$$

The reduced order estimator equations are obtained by substituting (32) until (36) into full order estimator (22):

$$\dot{x}_2 = A_{22}\hat{x}_2 + A_{21}y + B_2u + L(\dot{y} - A_{11}y + B_1u - A_{12}\hat{x}_2 \tag{37}$$

The error in the reduced order estimator is defined as

$$\tilde{x}_2 \triangleq x_2 - \hat{x}_2 \tag{38}$$

The dynamics of the error can be obtained by subtracting the estimate (29) from the state (37):

$$\dot{\tilde{x}}_2 = (A_{22} - LA_{12})\hat{x}_2 \tag{39}$$

The reduced order estimator equations can be rewritten as:

$$\dot{\hat{x}}_2 = (A_{22} - LA_{12})\hat{x}_2 + (A_{22} - LA_{12})\hat{x}_2 + B_2 u + \dot{y} \qquad (40)$$

From equation (40) it is known that differentiation amplifies noise, hence, if y is noisy the use of the dynamics of the error can be obtained by subtracting the estimate (29) from the state (37): is unacceptable. Thus, the new controller state is defined as:

$$x_3 \triangleq \hat{x}_2 - Ly \qquad (41)$$

The new implementation of the reduced order estimator is given by

$$\dot{x}_3 = (A_{22} - LA_{12})\hat{x}_2 + (A_{21} - LA_{11})y + (B_2 - LB_1)u \qquad (42)$$

$$u = [K_1 \quad K_2]\begin{bmatrix} x_a \\ x_b \end{bmatrix} = K_1 y - K_2 y\hat{x}_b \qquad (43)$$

Substituting (43) into (4) and using (42) as well as some algebra, the state space equations for reduced order compensator are determined:

$$\dot{x}_c = A_r x_c + B_r y \qquad (44)$$

$$u = C_r x_c + D_r y \qquad (45)$$

where

$$A_r = A_{22} - LA_{12} + (B_2 - LB_1)K_2 \qquad (46)$$

$$B_r = A_r L + A_{21} - LA_{11} - (B_2 - LB_1)K_2 \qquad (47)$$

$$C_r = -K_2 \qquad (48)$$

$$D_r = -K_1 - K_2 L \qquad (49)$$

3.0 SIMULATION RESULTS

Condition of controllability and observability play an important role in representing a system in state space. The concept was introduced by Kalman [7-11]. The solution of control problem will not exist if a system is not controllable. Then to obtained a control on system, it is essential to find the conditions where system can be controllable and observable. The general controllability and observability matrices for the system are defined respectively as:

$$C = [B \quad AB \ldots A^{n-1} \quad B] \qquad (50)$$

$$O = \begin{bmatrix} C \\ CA \\ \vdots \\ CA^{n-1} \end{bmatrix} \qquad (51)$$

From (50), the system is controllable if and only if this matrix has rank equal to the size n of the state vector. Meanwhile, (51) shows that the system is observable if and only if this matrix has rank equal to the size n of the state vector.

Here for InnoSAT only yaw axis numerical results have been considered to illustrate the proposed design procedures of this paper where the matrices for A, B and C as given in (6), (7) and (8) respectively.

The whole system is setup by connecting the PI camera module to the CSI port on the Raspberry PI board via ribbon cable while the LCD screen is connected to the board via HDMI cable. The wireless keyboard and mouse is connected to the board using wireless USB adapter. This is only needed when manipulation of code is required. The power is supplied to the board by connecting a micro USB to USB cable to a wall socket USB adapter or power bank.

$$A_c = \begin{bmatrix} -1.1790 & -1.8001 & -0.5148 & -0.2624 \\ 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 1 & 0 \end{bmatrix} \qquad (52)$$

The eigenvalues of controller are:

$$P_c = \begin{bmatrix} -0.4675 + 1.0786i \\ -0.4675 - 1.0786i \\ -0.1220 + 0.4183i \\ -0.1220 - 0.4183i \end{bmatrix} \qquad (53)$$

The gain matrix for compensated system is:

$$L = [\,2.1935 \;\; 2.1925 \;\; 0.8943 \;\; 0.0118]^T \qquad (54)$$

The state space form of compensator system is:

$$A_{ce} = \begin{bmatrix} -2.358 & -2.495 & -1.030 & -0.360 & 1.179 & 0.696 & 0.515 & 0.097 \\ 1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 1 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & -1.179 & -3.994 & -1.184 & -0.710 \\ 0 & 0 & 0 & 0 & 0 & -2.193 & -0.669 & -0.447 \\ 0 & 0 & 0 & 0 & 0 & 0.106 & -0.273 & -0.182 \\ 0 & 0 & 0 & 0 & 0 & -0.012 & 0.996 & -0.002 \end{bmatrix} \qquad (55)$$

$$B_{ce} = [\,1 \;\; 0 \;\; 0 \;\; 0 \;\; 0 \;\; 0 \;\; 0 \;\; 0]^T \qquad (56)$$

$$C_{ce} = [0 \;\; 1 \;\; 0.3051 \;\; 0.2040 \;\; 0 \;\; 0 \;\; 0 \;\; 0] \qquad (57)$$

From (6), the values of separated matrices of A are:

$$A_{11} = 0 \qquad (58)$$

$$A_{12} = [-1.1050 \quad 0 \quad -0.1650] \qquad (59)$$

$$A_{21} = \begin{bmatrix}1 & 0 & 0\end{bmatrix}^T \quad (60)$$

$$A_{22} = \begin{bmatrix}0 & 0 & 0\\ 1 & 0 & 0\\ 0 & 1 & 0\end{bmatrix} \quad (61)$$

From (7), the values of separated matrices of B are:

$$B_1 = 1 \quad (62)$$

$$B_2 = \begin{bmatrix}0 & 0 & 0\end{bmatrix}^T \quad (63)$$

The values of separated matrices of K are:

$$K_1 = 1.1790 \quad (64)$$

$$K_2 = \begin{bmatrix}0.695 & 0.5147 & 0.0974\end{bmatrix} \quad (65)$$

Substituting (28) to (45) into (46) to (49), the state space equations for reduced order compensator are determined as:

$$A_r = \begin{bmatrix}-5.352 & -1.531 & -0.780\\ -38.557 & -11.313 & -5.766\\ 10.540 & 4.014 & 1.536\end{bmatrix} \quad (66)$$

$$B_r = \begin{bmatrix}42.475 & 3.036e+02 & -1.037e+02\end{bmatrix} \quad (67)$$

$$C_r = \begin{bmatrix}-0.695 & -0.515 & -0.0974\end{bmatrix} \quad (68)$$

$$D_r = 11.6302 \quad (69)$$

Figures 3 to 5 show the step response plots produced by full order compensator and the reduced order compensator of yaw, pitch and roll axes for InnoSAT respectively.

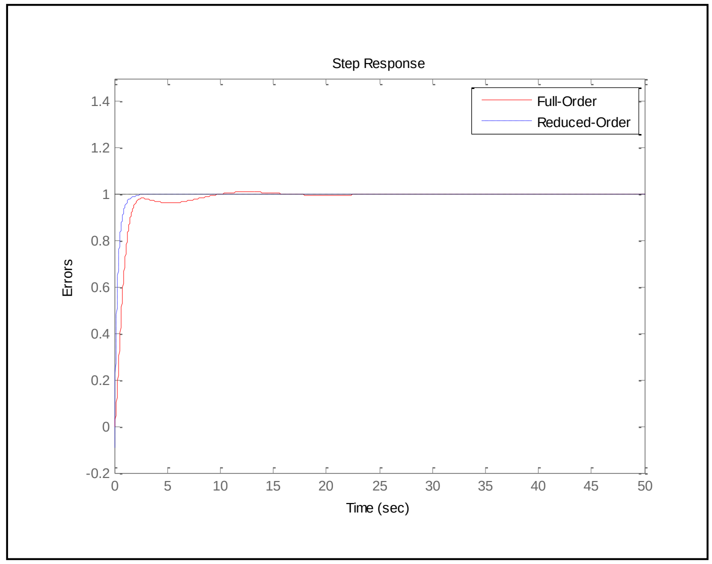


Figure 3 Step response of the full order compensator and reduced order compensator of yaw axis

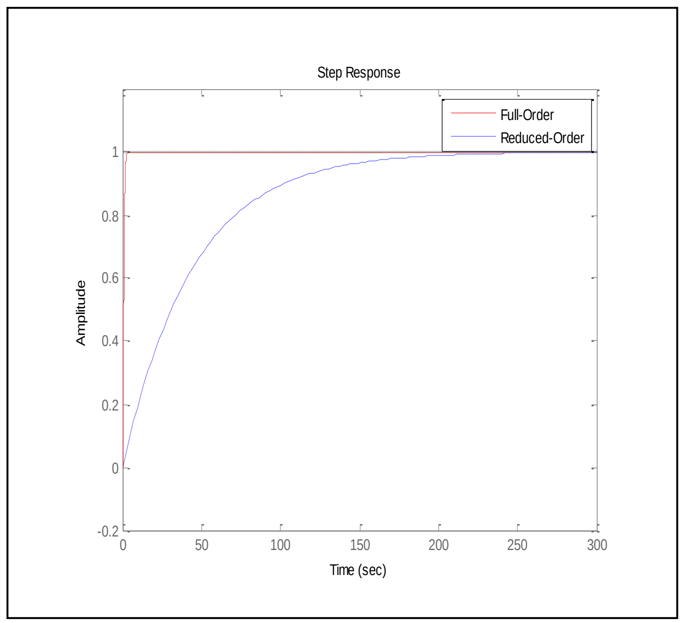


Figure 4 Step response of the full order compensator and reduced order compensator of pitch axis

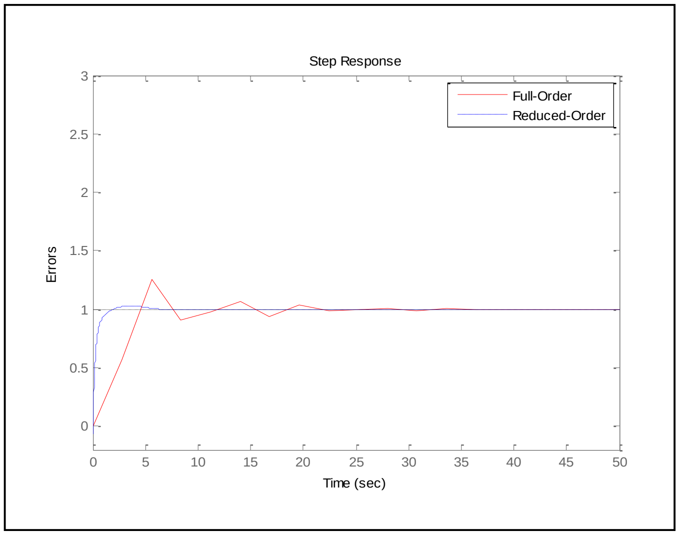


Figure 5 Step response of the full order compensator and reduced order compensator of roll axis

Referring to Figure 3 and Figure 5, reduced-order compensation for the yaw and roll axes converge faster to the steady state compared to the full-order compensation. However, the reduced-order compensation for the pitch axis cannot precede full-order compensation. From (2), the smallest order of the plant pole which is 0.007114 has been considered as zero, and there seem that the pole is at imaginary axis, so the stability has been affected and the system is slow to converge to the steady state. Therefore, in this case reduced-order compensated is not recommended.

4.0 CONCLUSION

The implementation of full- and reduced-order compensators have been shown and presented in detail. Yaw axis numerical results have been presented to illustrate the proposed design procedures. The simulation results show that the reduced-order compensations converge faster to the steady-state compared to the full-order compensations. However, the reduced-order compensation is not recommended to the pitch axis due to the very small pole in the transfer function.

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