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Enhancing the Performance of Microsatellite Yaw-axis Attitude Control System Using PID Tuned Compensator

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Abstract: *The essence of efficient control unit for satellite attitude control (SAC) is that it makes sure that both quality and reliable data acquisition are achieved. This paper designs a proportional integral and derivative (PID) tuned compensator (PID-TC) for microsatellite yaw-axis attitude control system (ACS). The objective is to meet the performance specification of a microsatellite with respect to its yaw-axis attitude (or angle) dynamics using a suitable control unit. The dynamic of the microsatellite yaw-axis ACS was established. A PID-TC was designed using MATLAB control system designer tool. The MATLAB/Simulink simulation of the designed control system indicated that the performance of the system was largely enhanced and the stated design specifications were met having achieved settling time of 0.54 s, maximum overshoot of 2.48% and steady state error of 0. Comparison with previous PID and PD based control systems revealed that the PID-TC offered the best performance. With this performance, the proposed control system has largely enhanced the microsatellite yaw-axis ACS performance.*

Keywords— Attitude control system, Microsatellite, PID tuned compensator, Yaw-axis

1. INTRODUCTION

Generally, the conditions exiting above the earth's atmosphere is regarded as space environment. There is no predetermined condition to describe the edge of space given that the atmosphere gradually dissipates with increase in altitude [1]. A classical definition for the edge of atmosphere marks the beginning of space to be 100 km above the surface of the earth [1]. The satellite operates in a vacuum once it is out the atmosphere. In the vacuum environment, several challenges are encountered by the satellite such as cold welding, out gassing, and absence of convention means of heat transfer. In the absence of protection of the atmosphere, spacecraft are also at risk of micro-meteors. Satellite is also protected from electromagnetic radiation and charged particles by the earth's magnetosphere. Even though staying in the atmosphere comes with numerous benefits, there is need for satellites to leave the relatively comfort or safety of the atmosphere so as to reach their missions' required altitude.

Attitude in relation to spacecraft communication means satellite's orientation in space. Attitude control can be defined as the control of the orientation axis of an on-orbit flight satellite. An on-orbit flight satellite is one that is orbiting in space. Therefore, attitude control system (ACS) consists of

set of components forming a system (with controller inclusive, which is a subsystem) that aids in analyzing and

control of satellite orientation in space. The main task involve in attitude control is to enable the accurate pointing of satellite antenna at a particular region of interest on the ground-based stations and solar panels towards the direction of the sun.

There are several control techniques that have been used in satellite attitude control (SAC) because of its critical demand for high-precision and the demand for stability, accuracy, and reliability during on flight operation taking into account the rapid growth in aerospace industry [2,3]. Also, since satellite's attitude angle can be displaced as result of different natural disturbance sources such as solar the radiation pressure, earth's gradient gravity and the earth's magnetic field, and including the fact that the success of a satellite mission relies on it being able to keep a referenced orientation with respect to earth [4], many controllers have been put forward for attitude motion stabilization. For instance, yaw angle control of satellite system was achieved using classical proportional integral and derivative (PID) controller tuned by Ziegler-Nichols method [5]. The stabilization of yaw-axis angle of microsatellite was realized using integral time absolute error (ITAE) based PID and proportional and derivative (PD) controllers separately in [6]. In the study conducted by [2], PID and fuzzy-PID controllers were separately used to achieve satellite attitude control of satellite. Conventional PID controller, fuzzy logic controller (FLC), and adaptive PID controller were separately designed for attitude control of nanosatellite [7]. Selectable gains of PID control system for a generic model of nanosatellite attitude control and stabilization system was presented in [8]. Using variable structure PID controller, the convergence rate of ACS was improved in [3]. Linear quadratic regulator and PID control systems were used for on-orbit stabilization of a Low Earth Satellite (LEO) by applying each of the controller respectively [9].

In this paper the objective is to meet the performance criteria of a microsatellite yaw-axis ACS using simplified control structure of PID-tuned compensator (PID-TC) that enhances the tracking and time response performance.

2. CONCEPT OF ATTITUDE CONSTROL SYSTEM

Attitude in relation to spacecraft communication means to satellite's orientation in space. Attitude control can be defined as the control of the orientation axis of an on-orbit flight satellite. An on-orbit flight satellite is one that is orbiting in space. Therefore, ACS consists of set of components forming a system (with controller inclusive, which is a subsystem) that aids in analyzing and control of satellite orientation in space. The main task involve in attitude control is to enable the accurate pointing of satellite antenna at a particular region of interest on the ground-based stations and solar panels towards the direction of the sun.

2.1 Satellite Attitude

Generally, the description for attitude is presented from the perspective of angle instead of distance. For satellite, attitude means angular rotation about the satellite's centred coordinate frame. There are three axes that are used to describe the attitude of satellite. These are: pitch, roll, and yaw. These axes are represented as shown in Fig. 1 with respect to the earth.

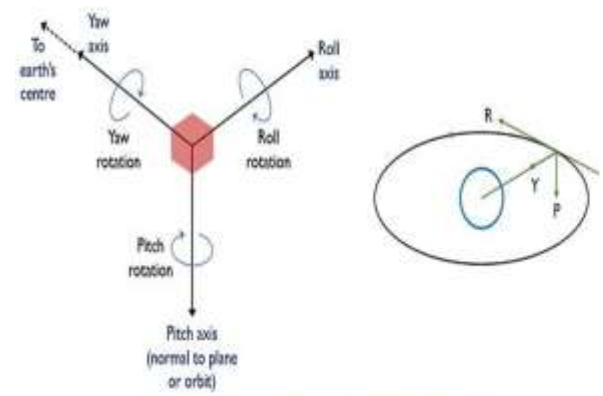

Fig. 1. Roll, pitch, and yaw axis representation [10]

It can be seen from the figure that the three axes pass through the centre of gravity of the body (box).The angle corresponding to each axis is called roll angle, pitch angle, and yaw angle respectively. The roll angle is formed from the rotation about the x-axis, while the pitch angle and the yaw angle are formed from the rotation in y-axis and z-axis respectively.

The rotation of the satellite about the x-axis (roll axis) leads to North and South track motion considering an equatorial orbit. For rotation of satellite about y-axis (pitch axis), the track movement occurs East and West. In the case of rotation due to antenna tracking, the satellite movement is about the z-axis (yaw-axis). Important parameters to determining the attitude control requirements are the accuracy and the rate with which the attitude is changing [10]. The ability of a satellite to properly point or focus the emitted radiation towards an earth station (or desired target on the ground) is corresponds to its accuracy. This implies that regardless of the slight shift experienced by the satellite, it must be able to focus or centre the beam on the target. The emitted beam towards the target makes a cone. Thus, the accuracy of the attitude is measured by the angular size of the coned formed and this is called attitude accuracy. Therefore, the control objective is that the control system ensures that satellite properly operates so that the emitted beam is focused toward the target.

The movement of satellite in space requires that sometimes a need arise to shift its focus among various target on the earth. The shift from one target to another must be a fast process. This described as slew rate and it is regarded as the angular speed by which the satellite has altered its focus from one target to another on the earth.

2.2 Factors Influencing Satellite Attitude

The need for precision considering the focusing of satellite from one point to another comes with enormous challenges. Despite the fact that satellite can be fixed to aim at a target at a given attitude, there are many factors or parameters that can still change its position. They are called disturbance forces (or torques). These parameters can unnecessarily alter the satellite attitude. Figure 2 shows the disturbance forces that can impact on the satellite attitude.

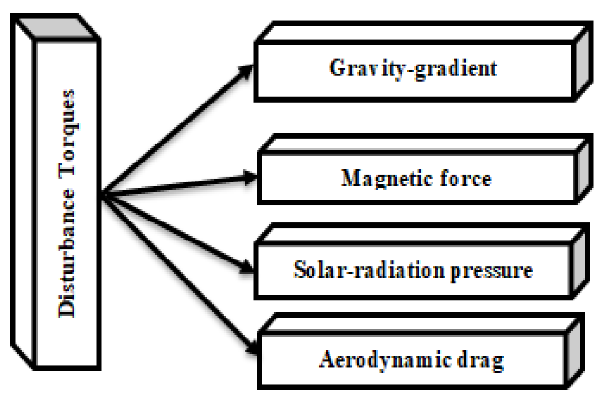

Fig. 2. Description of factors affecting satellite attitude

2.3 Description of Attitude Control System

Figure 3 is a simplified block diagram that describes the basic concept of ACS. As shown, the attitude of the satellite and the output fed to a comparator are detected by the sensors. Comparison of the actual attitude of the satellite and a reference or desired value is carried out at the comparator. This comparison results in generation of error signals based on which needed correctional action is executed.

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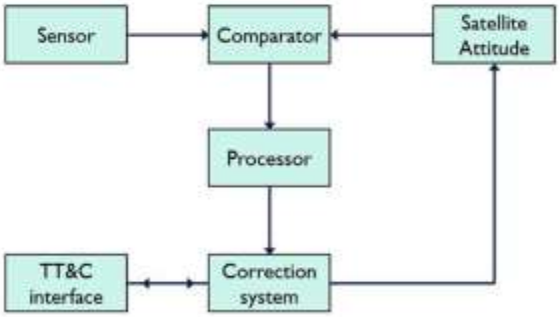

Fig. 3. Block diagram description of ACS [10]

In carrying out attitude control, the method of adding a potential detector is relatively important. This method involves the use of infrared sensors to enable the detection of the earth's circumference relatively to background of the space. In this approach, four sensors are incorporated such that a quadrant is covered by each while the centre of the earth is made the point of reference. Hence, one or more sensor detects the changes in satellite orientation and subsequently, a restoring torque corresponding to the detected change is generated by the system. Control signals can be sent from ground stations with respect to the attitude information received from the space orbiting satellite despite the fact that changes in take place in the space region of the satellite. At any time the attitude is altered, the control signals are sent from the ground station to implement attitude maneuvers.

The following are ways of generating the torque that controls the attitude and are: passive attitude control and active attitude control.

In the passive attitude control, the control system action is rather similar to that of open loop control system. This allows the satellite to maintain the referenced attitude such that its position is kept using little torque or in some cases at no torque. The satellite is stabilized by this method without impeding satellite energy supplies. Examples of passive attitude control are: gravity gradient stabilization, spin stabilization, and dampers.

For the second method, active attitude control, the control action is considered that of a closed loop control system, which requires a feedback to ensure necessary adjustments are made. In contrary to the passive attitude control, which does not provide the overall torque for stabilization to compensate for disturbance torques; the active attitude control produces the overall corrective torques required to adequately address the effect of disturbance torques.

3. System Design and Configuration

The dynamic of the considered microsatellite yaw-axis attitude control system is presented in this section including the design of the PID tuned compensator and the proposed closed loop configuration of the ACS.

3.1 Dynamic Modelling

The microsatellite yaw-axis ACS can be described by a simple single-input single-output (SISO) closed loop control model shown in Fig. 4 with the mathematical description of the various elements subsequently defined.

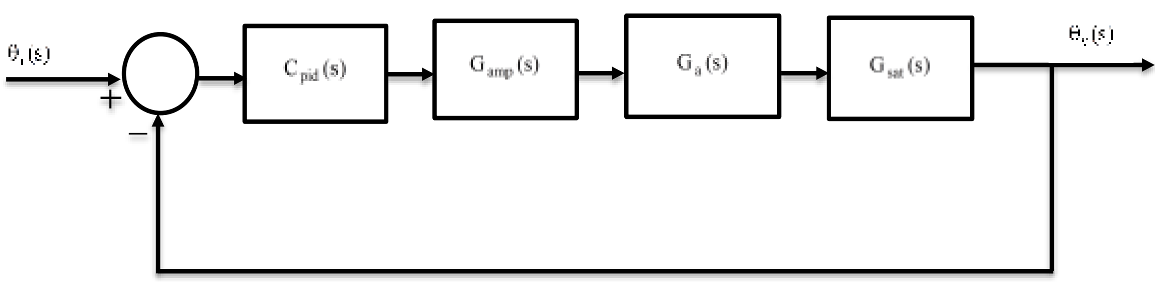

Fig. 4. Closed loop control block diagram of microsatellite yaw-axis ACS

The block diagram of the closed loop control of microsatellite yaw-axis ACS shown in Fig. 4 consists of a compensator $C_{pid}(s)$, amplifier $G_{amp}(s)$, actuator, $G_a(s)$, and the satellite structure $G_{sat}(s)$. The mathematic model of each element in the closed loop block diagram except the compensator is given by [6]:

$$G_{sat}(s) = \frac{1}{0.8\,s^2} \tag{1}$$

$$G_a(s) = \frac{78.3\,s}{s^2 + 1815.4\,s + 24466} \tag{2}$$

$$G_{amp}(s) = \frac{240}{0.1\,s + 1} \tag{3}$$

where $G_{sat}(s)$, $G_a(s)$, and $G_{amp}(s)$ are the satellite structure, actuator dynamic, and the amplifier dynamic. The closed loop transfer function of Fig. 4 without the compensator is given by:

$$\frac{\theta_y(s)}{\theta_d(s)} = \frac{G_{amp}(s) \times G_a(s) \times G_{sat}(s)}{1 + [G_{amp}(s) \times G_a(s) \times G_{sat}(s)] \times H(s)} \tag{4}$$

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where is unity feedback gain element (usually a measurement sensor). Substituting the expression in (1) through (3) into (4) gives:

$$\frac{\theta_y(s)}{\theta_r(s)} = \frac{18792\,s}{0.08\,s^5 + 146\,s^4 + 3410\,s^3 + 1.957\times10^4 s^2 + 18792\,s} \quad \text{…. (5)}$$

The design object objective is to meet the performance criteria defined as maximum overshoot of ($M_p \le 5\%$), settling time ($t_s \le 2\,s$) with 2% criterion, zero steady-state error for a microstatellite yaw angle control system.

3.2 Design of PID Tuned Compensator

The design of PID tuned compensator is presented in this section. The compensator is developed using robust response time PID tuning method of the control system designer of the MATLAB. This method is used in order to develop a control system with fast response time and robust transient behaviour. PID-TC compensator has been used to provide robust and fast response in [11]-[13]. The graphical user interface (GUI) of the tuning method in MATLAB is shown in Fig. 5.

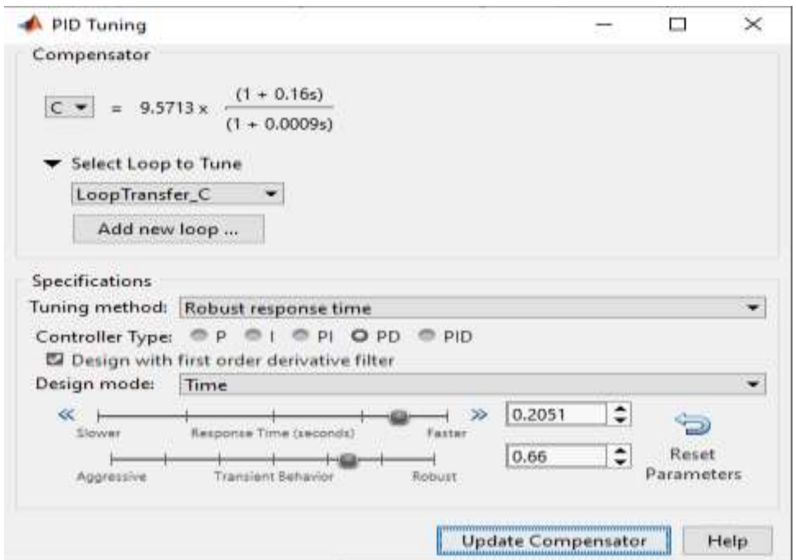

Fig. 5. Graphical user interface of the PID tuning

The designed compensator is given by the transfer function:

$$C_{pid}(s) = 1670\frac{(s+6.387)}{(s+1114)} \qquad (6)$$

The configuration of the proposed system in MATLAB/Simulink is shown in Fig. 6.

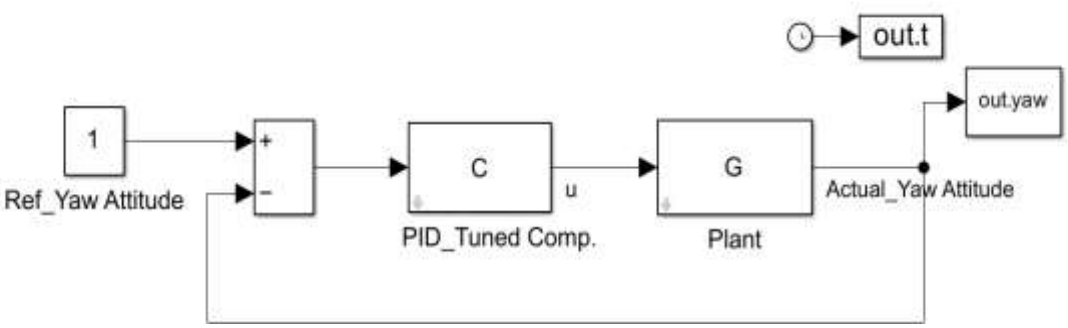

Fig. 6. Designed control system for microsatellite yaw-axis ACS

The performance of the designed system is compared with that of existing PID based control systems in Ajiboye et al., 2020 whose dynamics are defined in terms of PID (G_{Pid}), PID with pre-filter (G_{pidf}), PD (G_{pd}), and PD with pre-filter G_{pdf}. The dynamic expression of each PID and PD based control system in the previous work is given by (Ajiboye et al., 2020):

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$$G_{pid} = \frac{189200(s+11.34)(s+3.3630)}{s^5+1825s^4+42625s^3+43380s^2+2783000s+7219000} \quad (7)$$

$$G_{pidf} = \left(\frac{38.16}{s^2+14.71s+38.16}\right)\left(\frac{189200(s+11.34)(s+3.3630)}{s^5+1825s^4+42625s^3+43380s^2+2783000s+7219000}\right) \quad (8)$$

$$G_{pd} = \frac{98870(s+13.07)}{s^4+1825s^3+42625s^2+343500s+1292000} \quad (9)$$

$$G_{pdf} = \left(\frac{13.07}{s+13.07}\right)\left(\frac{98870(s+13.07)}{s^4+1825s^3+42625s^2+343500s+1292000}\right) \quad (10)$$

The overall Simulink model for comparing the designed PID-TC and the previous PID/PD based control systems by Ajiboye et al. (2020) is shown in Fig. 7. The figure is a composite diagram used to carry out performance comparison of the system for different control conditions.

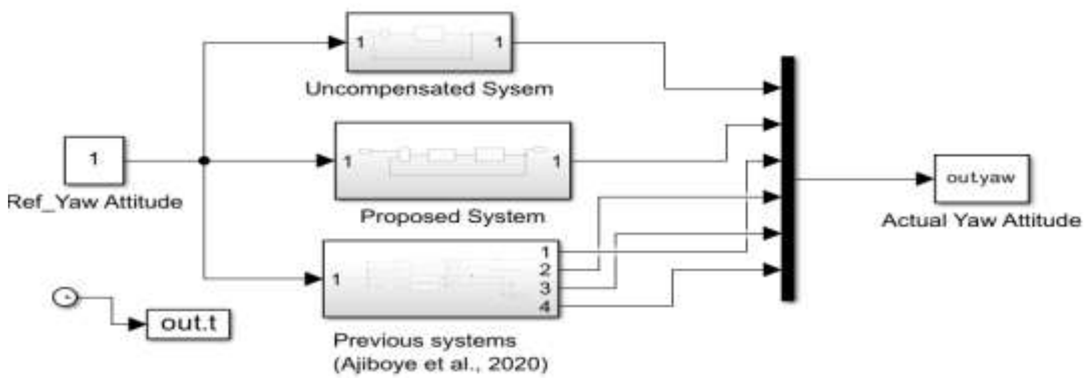

Fig. 7. MATLAB/Simulink model for different control system

4. RESULTS AND DISCUSSION

The transient and steady state characteristics of the designed control system were analyzed via simulations in MATLAB/Simulink environment in order to establish the significant of the study. Simulation was initially carried out examining the behaviour of the system when there was no controller or compensator introduced. This is called the uncompensated closed loop control system (Sys1) and its response to unit step input is shown in Fig. 8. Then the designed PID-TC was added as part of the closed loop control and the resulting step response is shown in Fig. 9. Plots of the step responses of PID-TC control system and uncompensated control system (Sys1) are shown in Fig. 10. Finally, simulation was conducted to compare the step response of the system for different control conditions as shown in Fig. 11. The numerical analysis of the response of the system for different control conditions is shown in Table 1.

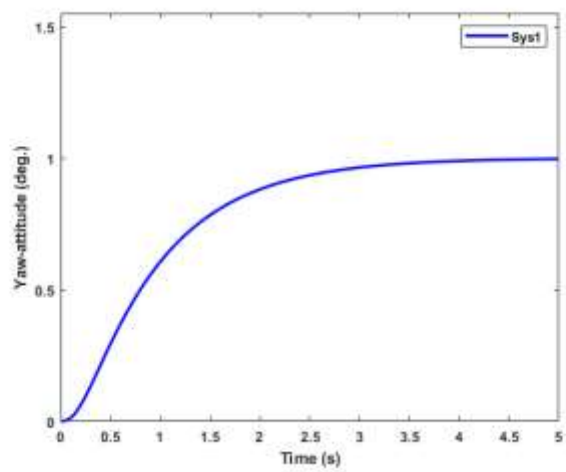

Fig. 8. Step response of uncompensated system

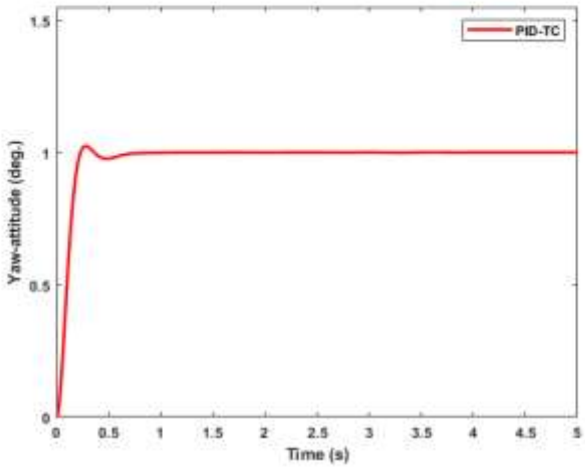

Fig. 9. Step response of PID-TC system

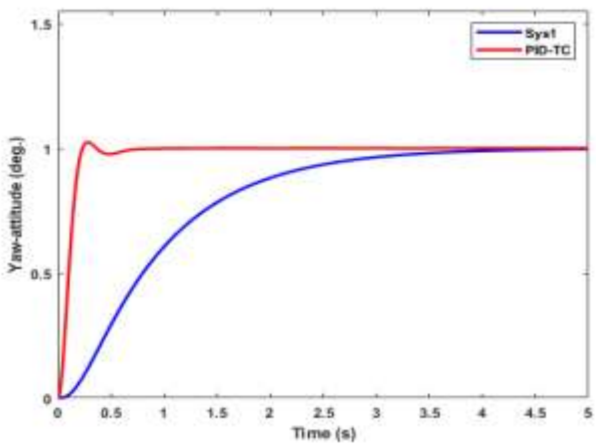

Fig. 10. Step responses of Sys1 and PID-TC control systems

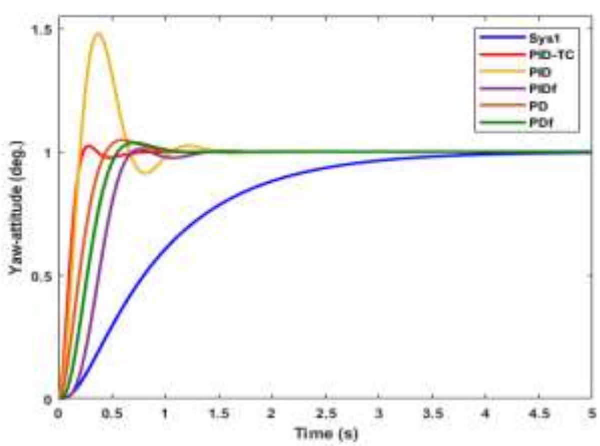

Fig. 10. Step responses of different control systems

Table 1: Numerical analysis of different control systems

Control condition	Time domain performance parameters				
	t_r	t_p	t_s	M_p	e_{ss}
Sys1	1.89 s	10 s	3.49 s	0	0
PID-TC	0.14 s	0.28 s	0.54 s	2.48%	0
PID	0.14 s	0.37 s	1.30 s	47.8%	0
PIDf	0.37 s	0.76 s	1.17	1.07%	0
PD	0.29 s	0.59 s	0.82 s	4.67%	0
PDf	0.33 s	0.71 s	0.67 s	3.59%	0

t_r is rise time, t_p is peak time, t_s is the settling time, M_p maximum overshoot, and e_{ss} is steady state error.

The design performance criteria of the microsatellite yaw-axis ACS is used to establish clear understanding of the results. It is obvious from the numerical analysis of the simulation plots stated in Table 1 that the control conditions that did not meet all the performance specifications were the uncompensated system (Sys1) and classical PID control system (PID). The introduction of the other control algorithms indicated that the performance criteria were met for PID-TC, PIDf, PD, and PDf. This is because all these control conditions provided settling time less than or equal to 2 s ($t_s \leq 2\,s$), maximum overshoot less than or equal to 5% ($M_p \leq 5\%$), and $E_{ss} = 0$. Generally, looking at the table, it can be seen that the designed PID-TC control outperformed all the other control systems in terms of settling time but was outperformed by the PIDf control system with respect to peak overshoot. However, looking at their rise time and peak time, the PID-TC will have a response of 0.23 s and achieve peak value of 0.48 s ahead before the PIDf control system. This performance gives the designed PID-TC control system advantage over the PIDf including the other control systems.

5. Conclusion

A PID-TC control system has been designed to provide control action for a microsatellite yaw-axis ACS. The mathematical equations representing the dynamic characteristics of the microsatellite yaw-axis ACS were established in terms of amplifier, actuator, and satellite structure transfer functions. Then a PID-TC was designed using the MATLAB control system designer tool to compensate the associated weakness of the system in order to meet the performance criteria. The simulation analysis conducted indicated that the proposed system meet all the design conditions and outperformed the other control systems previously implemented for the considered microsatellite yaw-axis ACS.

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