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APPLICATION OF CLASSICAL AND MODERN TECHNIQUES IN ATTITUDE CONTROL OF A SATELLITE MOCKUP

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Abstract. *Controlling spacecraft attitude is critical to mission success and usually deep nonlinear, application-specific techniques are employed to achieve it. The intent in this work is to successfully apply the well-known classical and modern approaches to control a spacecraft mockup, obtaining satisfactory stability and performance. The setup consists of a single reaction wheel (RW) working as the actuator of the control system, and attitude determination is provided by a gyroscope. Also, the mockup contains a cubic body with two panels acting as solar array wings, and all aforementioned components are installed on a spin table to mimic spacecraft behavior. Classical control design included: frequency domain curve fitting; compensator design; and hardware implementation. Modern control application comprised: finding a minimal state-space representation of the model; frequency domain curve fitting; full-state feedback control design; full-state observer design; and hardware implementation.*

Keywords: *Attitude control, Spin table, Classical control, Modern control.*

1. INTRODUCTION

Maneuvering satellites in space is critical to mission success due to the high-precision requirements demanded from the attitude control system (ACS), varying from 20 degrees to arcseconds. The system relies on attitude determination, which is the attitude measurement compared to the desired value, resulting in the satellite's attitude error. The purpose of the ACS is to generate a corrective torque to null this error (Snider, 2010).

The present work features the application of both classical and modern approaches to control the attitude of a satellite mockup. The setup comprises a single reaction wheel that creates torque around the yaw axis, working as the actuator of the control system. Rotation is allowed around a single axis (one degree of freedom), with the attitude determined by a gyroscope and then fed back to the control system. The mockup also contains a cubic body with two panels acting as solar array wings (SAW) featured in satellites. The aforementioned components are installed on a spin table to mimic spacecraft behavior in space.

The classical control was developed upon frequency response analysis by means of Fourier and Laplace transforms, which brought about complex variable methods such as root locus, and Nyquist and Bode plots. Powerful tools such as transfer functions provide a broad understanding of systems, but these are frequently assumed to be linear, stationary, and internal structures are disregarded. Besides, the single input, single output (SISO) characteristic of transfer functions is a major constraint. Therefore, the advent of digital computers and the need for more robust, comprehensive controllers paved the way for modern control, a theory hardly novel, but overlooked due to hard manual realization (Bennett, 1993) (Ogata, 2002).

Modern control techniques apply to the vast majority of the real systems, which are nonlinear, non-deterministic and have to be assumed otherwise in classical control. Based on time-domain approach, they also apply to multiple input, multiple output (MIMO) structures and provide analysis of all inputs and outputs at once, bringing about a thorough description of the system, including the internal energy flow. The mathematical modeling tool is the state-space representation, which describes dynamical systems as input, output, and state variables related by differential equations. The state-space representation for the satellite mockup is

$$[\boldsymbol{x}] = [\omega_b \quad v_1 \quad v_2 \quad T_1 \quad T_2 \quad \theta_b]^T$$

$$[\boldsymbol{y}] = \theta_b$$

$$[\boldsymbol{u}] = T$$

$$\mathbf{A} = \begin{bmatrix} 0 & 0 & 0 & 2.86 & 2.86 & 0 \\ 0 & 0 & 0 & -1.01 & 0 & 0 \\ 0 & 0 & 0 & -1.01 & 0 & 0 \\ -5.89 & 4.48 & 0 & 0 & 0 & 0 \\ -5.89 & 0 & 4.48 & 0 & 0 & 0 \\ 1 & 0 & 0 & 0 & 0 & 0 \end{bmatrix}$$

$$\boldsymbol{B} = [2.86 \quad 0 \quad 0 \quad 0 \quad 0 \quad 0]^T$$

$$\boldsymbol{C} = [0 \quad 0 \quad 0 \quad 0 \quad 0 \quad 1]$$

$$\boldsymbol{D} = [0]$$

Despite the performance and robustness of modern design, most industrial feedback control systems are nevertheless based on classical methods, because they provide good designs in the face of uncertainty in the plant model and experimental information can be used directly for design purposes (Dixon *et al*., 2005).

In order to get satisfactory stability and tracking, the requirements of the unity feedback system include: at least 30 degrees of phase margin; 10 dB of gain margin, maximum overshoot of 40%, settling time for the observer equal or less than 3 seconds, and a closed-loop (-3 dB) bandwidth between 1 and 3 rad/s.

2. EXPERIMENTAL PROCEDURE

To apply classical control theory, the following procedure was adopted: transforming the state-space model into a transfer function and changing zero and pole locations to match empirical data; designing a lead compensator so as to fulfill stability and performance requirements; simulating designed compensator; and testing it in the hardware to check if it complies with the requirements.

For modern control theory application the steps were: finding minimal state-space representation of the model and changing pole and zero locations to match empirical data; designing a full state feedback control system by doing closed-loop pole placement in order to achieve stability and performance requisites; designing a full-state observer to minimize errors between the model and the mockup; simulating the designed control/observation system with the same model with arbitrary initial conditions to simulate the physical system; and testing the design in the mockup.

3. RESULTS AND DISCUSSION

In classical control, after transforming the state-space model into a transfer function and fitting its frequency response to empirical data, the resulting transfer function was

$$H(s) = \frac{s^4 + 9s^2 + 20.26}{s^6 + 42.66s^4 + 171.78s^2 - 1.485 \cdot 10^{-14}s} \tag{1}$$

and a comparison between empirical and analytical frequency responses is shown in Fig. 1. It can be noticed that both responses are quite similar in frequencies lower than 10 rad/s, and since satellites are usually not expected to rotate at higher frequencies, the result was considered as satisfactory.

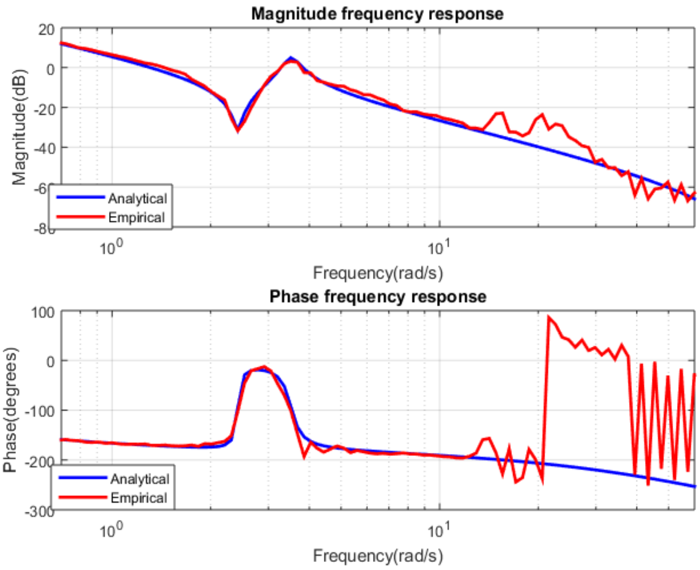
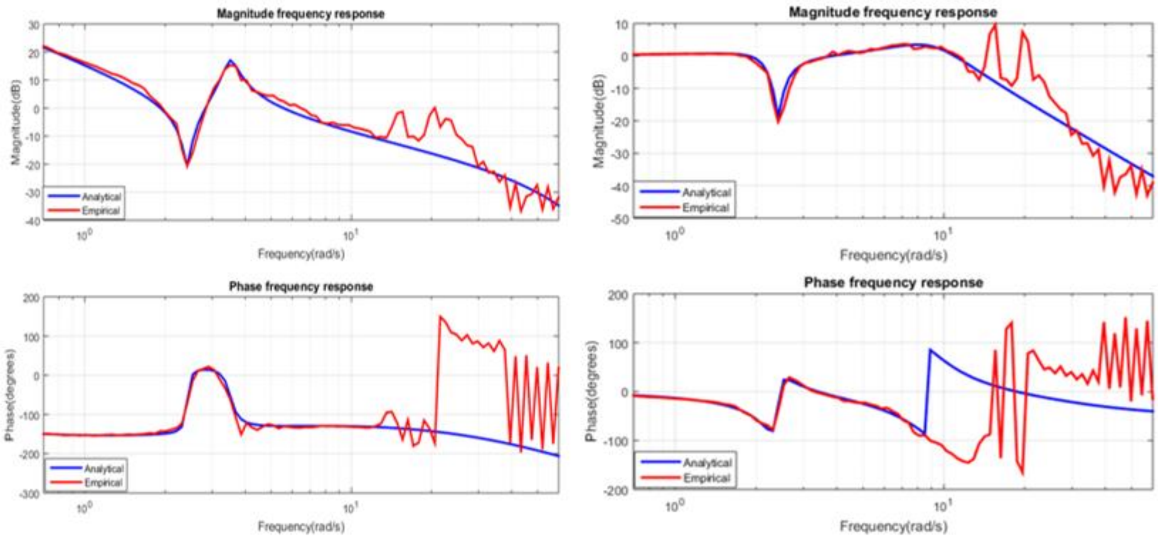


Figure 1: Frequency domain fitting.

Once a transfer function was found, a lead compensator was designed in the interest of achieving stability and performance specifications. The compensator chosen was

$$D(s) = \frac{3s + 7.5}{s + 47.619} \tag{2}$$

and the open-loop frequency response of the transfer function with the compensator, and the empirical data with compensator magnitude and phase added are shown in Fig. 2a. The closed-loop frequency response of the same systems is shown in Fig. 2b. The analytical response presented phase margin of 30.3° and gain margin of 26.7 dB, the empirical response showed phase margin of 37.3° and gain margin of 36 dB. Both systems have -3 dB bandwidth of around 2.05 rad/s. These results meet the specifications, which allowed hardware implementation. A plot showing step response of both analytical model and hardware is shown in Fig. 3. Their overshoots were 30% and 28%, respectively.



a) b)

Figure 2: Compensated frequency responses. (a) Open-loop; (b) Closed-loop.

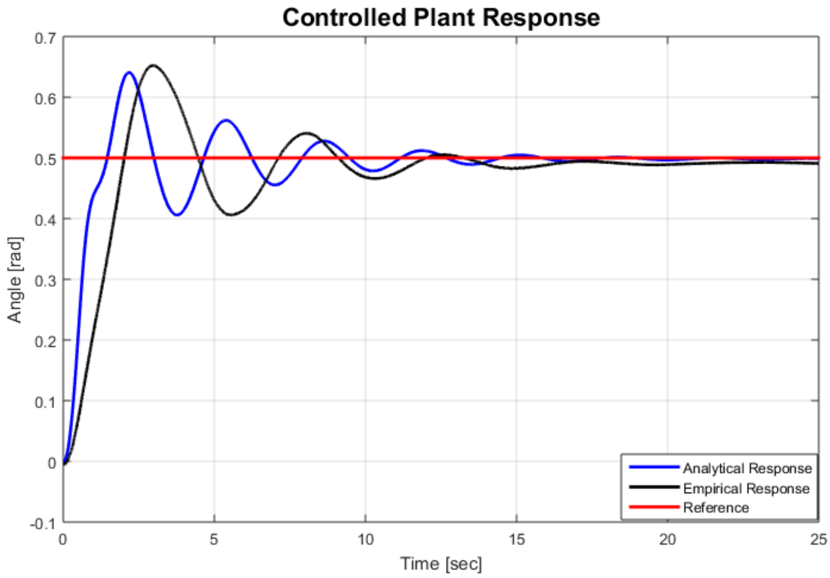


Figure 3: Step response.

The resulting minimal state-space model after fitting was:

$$\boldsymbol{A} = \begin{bmatrix} -1.0653 & -12.4419 & -2.4097 & -0.0550 \\ 1.0005 & 0.0057 & 0.0012 & 0.0001 \\ 0.2371 & 3.7882 & 0.5352 & 0.0068 \\ -0.0001 & -0.0013 & 0.9997 & 0 \end{bmatrix}, \ \boldsymbol{B} = \begin{bmatrix} 0.2166 \\ -0.0001 \\ -0.0481 \\ 0 \end{bmatrix}$$

$$\boldsymbol{C} = \begin{bmatrix} -0.4599 & -29.9118 & -2.0411 & -75.2727 \end{bmatrix}$$

$$\boldsymbol{D} = [0]$$

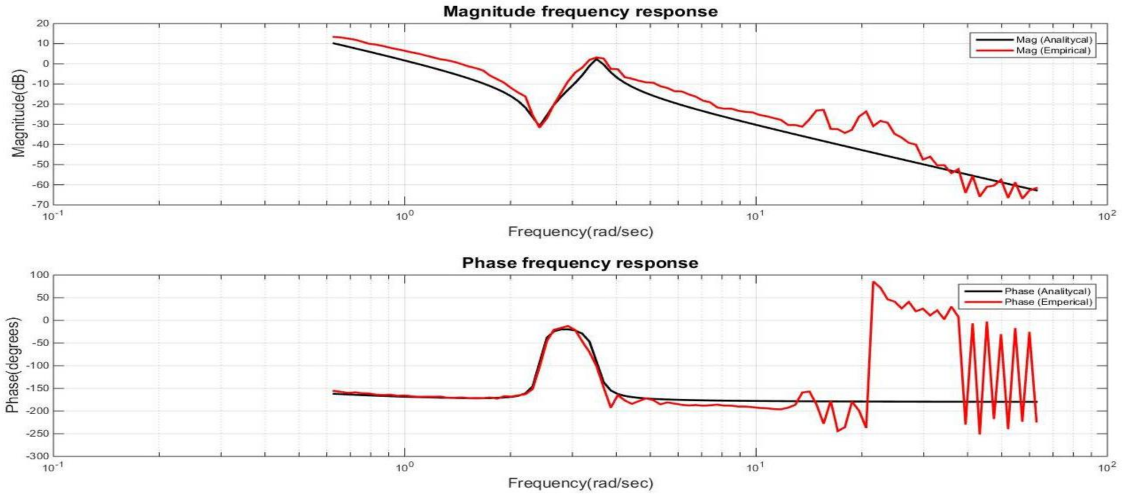
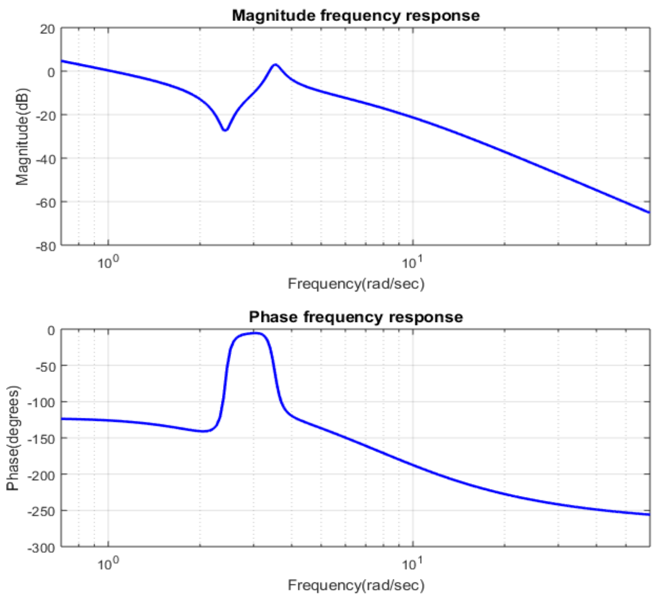
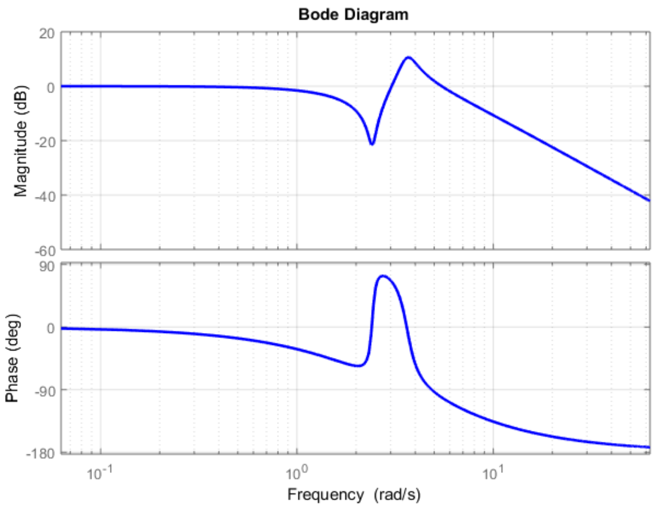


Figure 4: Curve fitting

A Bode plot containing open-loop analytical and empirical frequency response can be seen in Fig. 4. The state feedback controller was designed for the following closed-loop pole locations: p_1=-0.3480 + 3.6276j; p_2= -0.3480 - 3.6276j; p_3=-3.6442; p_4=-3.7171.The resulting open-loop and closed-loop frequency responses are presented in Fig. 5, respectively. The gain and phase margins of the designed control system are 19.4 dB and 54 degrees, and its bandwidth is 1.35 rad/s. A full state observer was designed for the closed-loop pole locations were p_1=-2.08; p_2= -2.1; p_3= -2.2; p_4=-2.25. In order to test observer performance the state-space model with arbitrary initial conditions was used to simulate the physical system. The deviation between analytical and simulated real model outputs is shown in Fig. 6. The error settling time between the two systems was 2.86 seconds. The controller/observer system was then implemented to the hardware. Response of analytical system, analytical system with initial conditions and physical system to a 0.1 rad step is shown in Fig. 7. It can be seen that the response of the mockup did not obey the settling time requirement, however its response followed the reference closely, which was considered satisfactory.



a)



b)

Figure 5: Compensated frequency responses with (a) open-loop and (b)closed-loop.

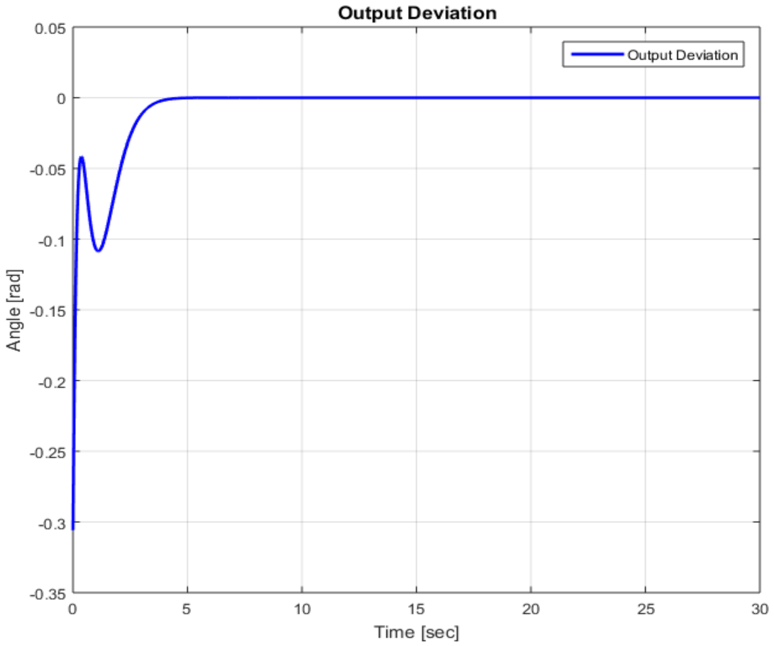


Figure 6: Output deviation.

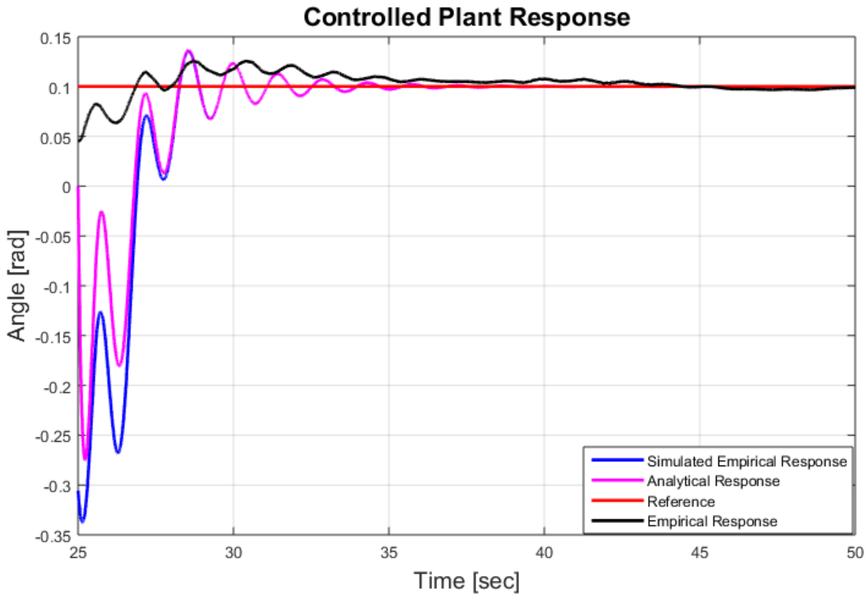


Figure 7: Step response.

4. CONCLUSIONS

This work presented the successful application of the classical and modern approaches to control a spacecraft mockup, obtaining satisfactory results as stability and performance criteria were met.

5. ACKNOWLEDGEMENTS

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