COBEM-2017-2013
MODELING AND FREQUENCY DOMAIN IDENTIFICATION OF A SATELLITE MOCKUP

André Fialho Coelho
Luiz Benicio Degli Esposte Rosa
Instituto Federal de Educação, Ciência e Tecnologia Fluminense, Department of Control and Automation Engineering, Campos dos Goytacazes, RJ, Brazil
andrefialhoc@gmail.com
engbenicio@gmail.com

Renan Santos
Instituto Tecnológico da Aeronáutica, Instituto de Aeronáutica e Espaço, Department of Aerodynamics, São José dos Campos, SP, Brazil
renanufabc@gmail.com

Abstract. Attitude control is critical to a spacecraft mission success and considering the uniqueness of the structures, a high-fidelity dynamic model is key to find the optimal, applicable design. The present work aims to obtain a model for a satellite mockup for attitude-control design purposes, with frequency response at low frequencies (less than 10 rad/s) comparable to that of the physical system. 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 components are installed on a spin table to mimic spacecraft behavior. The whole process comprehended the following steps: establishing a mathematical model for the mockup by generalization of Newton's laws to rigid bodies, and performing system identification through frequency-domain curve fitting, in order to adjust the parameters and improve the model. The final result was assessed as satisfactory and an adequate starting point for control design.

Keywords: Satellite modeling, System identification, Spin table, Reaction wheel.

1. INTRODUCTION

Since the absence of air above the Earth's atmosphere precludes the use of aerodynamic forces to adjust spacecraft orientation during flight, engineers proceeded to develop alternative systems for attitude control. Most spacecraft are equipped with reaction wheels, heavy flywheels that have their momentum changed in order to generate torque. Connected to the satellite structure, they form an action-reaction force pair, according to Newton's third law, each wheel providing torque via spinning motion variation, i.e., as the speed is changed, the vehicle moves in the opposite way. While the wheel is rotating, it contains an initial constant angular momentum vector that can be transferred from the RW to the satellite and backwards without changing the overall angular momentum (Pelivan *et al*., 2012). This conversion of angular momentum is commonly used for attitude maneuver control and to correct distortions caused by external torques, such as atmospheric drag and gravitational gradient. Momentum exchange is the preferred method of control because it offers high fidelity control and does not consume fuel (McChesney, 2012).

Spacecraft usually feature three RWs to enable rotation around each axis - pitch, yaw, and roll - and an additional fourth to serve as backup. For practical reasons, the setup used in the present work, as shown in Fig. 1, comprises a single RW that creates torque around the yaw axis, reducing the system to one degree of freedom; the attitude is 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. The aforementioned components are installed on a spin table to mimic spacecraft behavior in space.

The main objective of this work is to obtain a model whose frequency response at low frequencies (less than 10 rad/s) is comparable to that of the real system, which demanded the following steps: establishing a mathematical model for the mockup and performing system identification through frequency domain curve fitting, in order to adjust the parameters and improve the model.

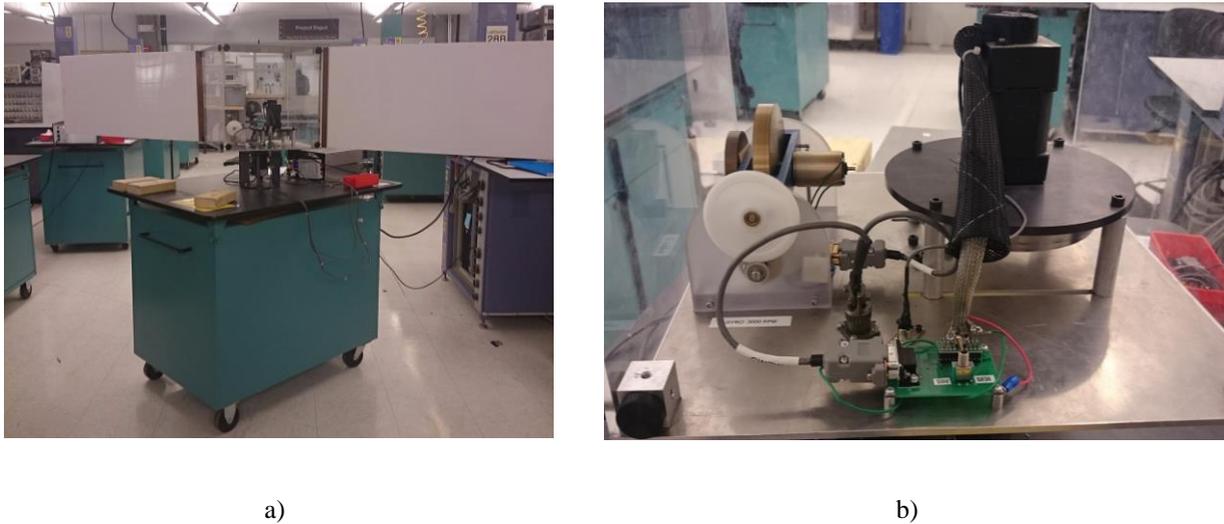a)   b)

Figure 1: Satellite mockup (a) setup and (b) spin table.

An entire spacecraft mission often depends on the performance of the attitude control system (ACS), and for both scientific and commercial satellites, the accuracy requirements for the ACS can be in the order of arcseconds (Hagen, 2006). Therefore, modeling and identification are critical to the design of a controller that meets the system requirements

2. EXPERIMENTAL PROCEDURE

The process of obtaining a linear model for the spacecraft mockup was divided into three steps: acquiring data from physical system; developing a mathematical model based on Newton's laws; and performing frequency-domain system identification based on experimental data.

The first stage was performed by acquiring data from the gyroscope, whereas sine waves of various frequencies were applied by the RW (Bode's Experiment). The modeling part was accomplished by considering the solar arrays as a lumped mass, lumped spring equivalent. The system could thus be described by a rigid body representation, as shown in Fig. 2.

a)

b)   c)
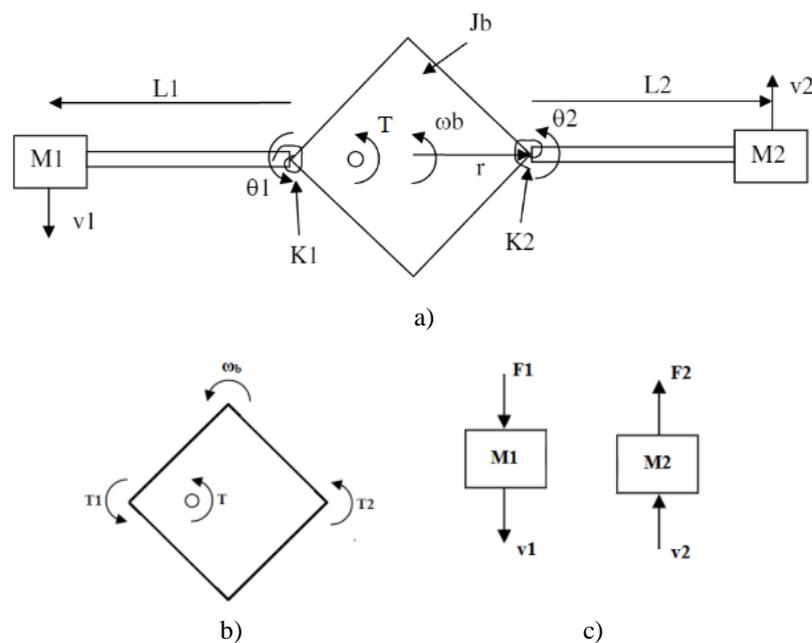
Figure 2: Physical representation of the mockup. (a) rigid body representation; (b) satellite free body diagram; (c) solar array masses free body diagram.

A description of model parameters, as well as definitions and values of constants are given in tables 1 and 2.

Table 1 – Model constants

Symbol	Definition	Value
$M = M_1 = M_2$	solar array masses	0.995 kg
$L = L_1 = L_2$	lengths of the arrays	1 m
J_b	body moment of inertia	0.35 kg-m2
r	radius of the body	0.315 m
$K = K_1 = K_2$	array stiffnesses	4.4791 N-m/rad

Table 2 – Model variables

Symbol	Definition
v_1 and v_2	linear velocities on tip of arrays
θ_1 and θ_2	array displacements
ω_b	body angular velocity
Tb	net torque on body
T	torque generated by actuator
T_1 and T_2	torques through K1 and K2
ω_1 and ω_2	angular velocities across K1 and K2
F_1 and F_2	net forces on M1 and M2

Subsequently, after analyzing the forces and moments acting in the system, as well as the energy storage components, an initial state-space representation was derived and the values of the parameters were uploaded. Next, adjustments of pole and zero locations of the analytical model using MATLAB allowed that the open-loop frequency response shape, with reaction wheel torque as input and body rotation as output, would match the empirical data acquired. Alongside, space minimization and pole-zero cancellation were performed in order to get a simpler model. The process of fitting curves was carried out experimentally, through the computation and analysis of multiple Bode plots in MATLAB, and the choice of which poles and zeros yielded the most resembling curve was done qualitatively. The fitting procedure generated a new state-space representation, with different states that more closely matched the data from the mockup.

3. RESULTS AND DISCUSSION

The initial state space derived from Newton's laws representation was the following.

$$[\dot{x}] = A[x] + B[u]$$
$$[y] = C[x] + D[u]$$

(1)

$$A = \begin{bmatrix} 0 & 0 & 0 & \frac{1}{J_b} & \frac{1}{J_b} & 0 \\ 0 & 0 & 0 & \frac{-1}{LM} & 0 & 0 \\ 0 & 0 & 0 & \frac{-1}{LM} & 0 & 0 \\ -K\frac{(r+L)}{L} & \frac{K}{L} & 0 & 0 & 0 & 0 \\ -K\frac{(r+L)}{L} & 0 & \frac{K}{L} & 0 & 0 & 0 \\ 1 & 0 & 0 & 0 & 0 & 0 \end{bmatrix}, B = \begin{bmatrix} \frac{1}{J_b} & 0 & 0 & 0 & 0 & 0 \end{bmatrix}^T$$

$$C = [0 \quad 0 \quad 0 \quad 0 \quad 0 \quad 1], D = [0]$$

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

$$[y] = \theta_b, [u] = T$$

After the properly incorporating the values of each constant, the representation below emerged:

$$A = \begin{bmatrix} 0 & 0 & 0 & 2.86 & 2.86 & 0 \\ 0 & 0 & 0 & -1.01 & 0 & 0 \\ 0 & 0 & 0 & -1.01 & 0 & 0 \\ -5.89 & 4.48 & 0 & 0 & 0 & 0 \\ -5.89 & 0 & 4.48 & 0 & 0 & 0 \\ 1 & 0 & 0 & 0 & 0 & 0 \end{bmatrix}, B = [2.86 \quad 0 \quad 0 \quad 0 \quad 0 \quad 0]^T$$

$$C = [0 \quad 0 \quad 0 \quad 0 \quad 0 \quad 1], D = [0]$$

The comparison between the open-loop frequency response of the initial state-space model and the resulting one is shown in Fig. 3. The goal of this work was uniquely to find a model that matches frequency response of the real system at low frequencies, for control design purposes. Then, pole-zero cancellation and location changes were numerically performed in MATLAB with no regard for the physical meaning of the states. However, the input and output were kept the same, which is sufficient to develop a control law that is likely to achieve the same stability and performance when implemented in hardware.
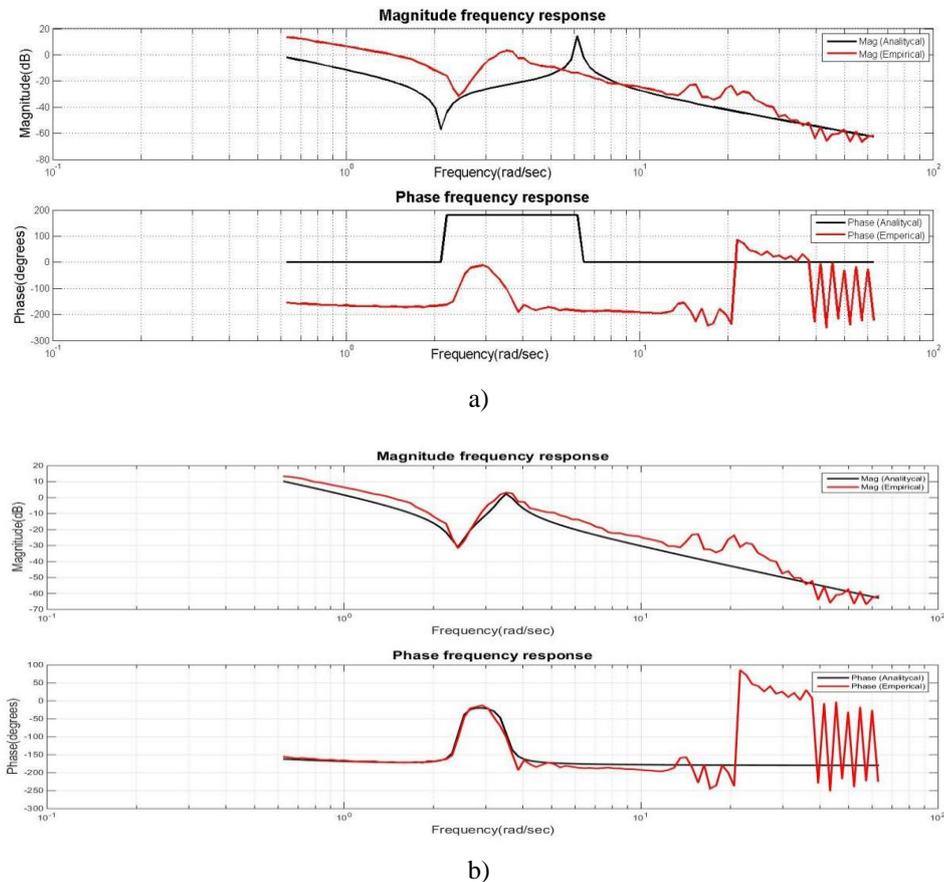

a)

b)

Figure 3: Frequency response a) before fitting and b) after fitting.

4. CONCLUSIONS

The modeling and identification procedure resulted in a linear model, whose frequency response at frequencies lower than 10 rad/s was sufficiently similar to the physical behavior, which allows for the successful applicability of control design.

5. ACKNOWLEDGEMENTS

6. REFERENCES

Hagen, D., 2006. *Spacecraft attitude control: modelling and controller design considering actuator dynamics*, (Master's thesis, Narvik University College, Narvik, Norway), p. 1.

McChesney, C.G., 2012. *Design of attitude control actuators for a simulated spacecraft*, 1st ed., Wright-Patterson Air Force Base, Ohio. p.1.

Pelivan, I., Heidecker, A., Theil, 2012. S. High performance satellite dynamics and control simulation for multi-purpose application, *Journal of Aerospace Engineering, Sciences and Applications*, IV(3) p.119–130.

7. RESPONSIBILITY NOTICE

The authors are the only responsible for the printed material included in this paper.