Experimental comparison between reaction wheel attitude controller strategies

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Abstract. **Systems for satellite attitude control are usually designed based on modern control techniques, which assume that the plant, sensors and actuators have linear behavior. A reaction wheel is an actuator that produces a torque as a function of electric current applied to a brushless DC motor. Ideally the output torque should be proportional to the current, but Coulomb and static frictions in the bearing introduce non linearities in the output torque, as function of the angular velocity of the wheel, especially at low speeds, near zero. These non linearities become more relevant specially in reaction wheels that are designed to rotate in both directions, causing the controller error to increase significantly at sense of speed reversals (zero crossings). This article presents results of a control orientation of an air bearing table by means of a reaction wheel. To check the controller action during a zero crossing, a small fan was attached to the table, producing a torque whose magnitude can be altered by adjusting the direction of the airflow. The control loop uses a fiber optic gyroscope (FOG) as angular velocity sensor. A PID digital controller drives the wheel based on the angular position of the table with respect to a given reference. In order to have a controller with a linear output torque, a mathematical model of torque was developed as function of the input current and wheel speed, from which it was constructed an algorithm of the inverse function, so that the non linearities were partially compensated (dynamic compensation). The results indicated that dynamic compensation can effectively reduce the maximum pointing error during zero crossing, while keeping constant other parameters such as response and settlement time.**

Keywords **– Attitude control, reaction wheel, dynamic compensation.**.

1. INTRODUCTION

3-axis attitude control systems has been largely employed in space missions, due to the high reliability of current sensors and actuators, including computer, together with the decrease of equipment pricing and reusing of embedded control coding. A 3-axis AOCS is normally based on a set of reaction wheels, magnetic torque coils, gyroscopes and a star tracker or star sensor. This arrangement provides torque in wide range, and is powered by renewable energy generated by solar panels. A reaction wheel (RW) consists of a high inertia flywheel powered by a brushless DC motor. By adjusting the motor electric current the flywheel can speed up or slow down, and, by reaction, an opposite torque is applied to the satellite. Reaction wheels are designed to work within a limited range of angular momentum or speed, and therefore require an external action in order to eliminate the momentum when the speed reaches its maximum magnitude. This process is known as wheel de-saturation or momentum dumping. Despite the versatility of this type of control - with only three wheels, aligned with Cartesian axes, one can control and stabilize the satellite attitude - the reaction wheel is itself a complex device. Major problems in RW design are the bearing alignment, motor selection, bearing lubrication, internal degasification, motor control electronics and flywheel balancing [1]. RW specification requires deeply knowledge of its characteristics and performance. There are few companies that design and delivery RW for space applications, from very small (0.1 Nms) to large ones (20 Nms or higher). Due to its inherent high technology, there are few academic articles that describe RW design and control. Although the wheel output torque is related to the motor current, it is uncommon to command a commercial RW by means of only its current. In fact they are driven by analog voltage (reference to torque or current) or to serial interface, which exhibit torque, current or speed control. Whatever be the RW command, it requires an internal electronics for current control in closed loop. Velocity or speed control uses digital tachometer and a PID control. Torque command is converted to current by means of the flywheel inertia and wheel acceleration. Nevertheless the control complexity, it is known that these devices present nonlinear behavior, since the output torque is not directly proportional to the current applied to the motor [1], [2]. The non-linearity is caused mainly by the friction torque, which presents spikes in low angular velocity. The friction torque can be modeled by means of a viscous torque proportional to the wheel speed, a constant or Coulomb torque, and a stiction or static friction torque. A continuous Stribeck friction sometimes replaces the static friction. The motor current control is affected by those non-linearities and the reaction wheel presents the so-called zero-speed problem, which increases the attitude pointing error. While conventional attitude control techniques can still be employed, the controller performance is affected by the response of the wheel to a greater or lesser degree. Unfortunately the non-linearities present in the wheel derail or at least make it difficult to tune the controller to a particular performance requirement. To overcome this problem, almost all embedded attitude controllers uses the "speed-control", rather than the conventional "current control". From the attitude control point of view, the reaction torque is equal to the product of the flywheel's inertia by the angular acceleration, and that means that it is practical to directly control the torque from the speed. The price to pay for adopting this strategy is an increase in the operation complexity, a delayed response of the wheel (due to the internal speed controller), and the errors associated from deriving the acceleration of the flywheel from some sort of speed measurement device, like a tachometer, for instance. Even the current control mode may have several adverse effects, also shared by the speed control, such as:

- Communication delay caused by digital processing and serial communication line.
- Noise in the analog control line (typically a reference voltage to current or to speed control).
- Non-linearity, noise and scale factor of some electronic components used in the analog circuits for current control loop.

The current on the RW motors can be controlled by Pulse Width Modulation (PWM) or by voltage control, and a chopper circuitry can be used to increase both torque and maximum speed. In other words, the current actually applied to the motor varies with the angular position of the shaft, which means that the reference current can be related, at most, with the average current. Because the speed control loop must rely on the current control loop, a current controlled RW can be preferable under certain circumstances. In this case an accurate mathematical model (if possible) of a current controlled reaction wheel can be a significant step toward having an improvement in the attitude control performance. Thus the objectives of this work are: to establish a mathematical model for the friction in a RW and to compare the current control mode with a model dynamic compensator controller. Next sections present the experiments performed with a reaction wheel and a fiber optics gyro, both from SunSpace [3], coupled to a single axis air-bearing table at the Simulation Laboratory of INPE (National Institute for Space Research – São José dos Campos, SP, Brazil), shown in Fig. 1.

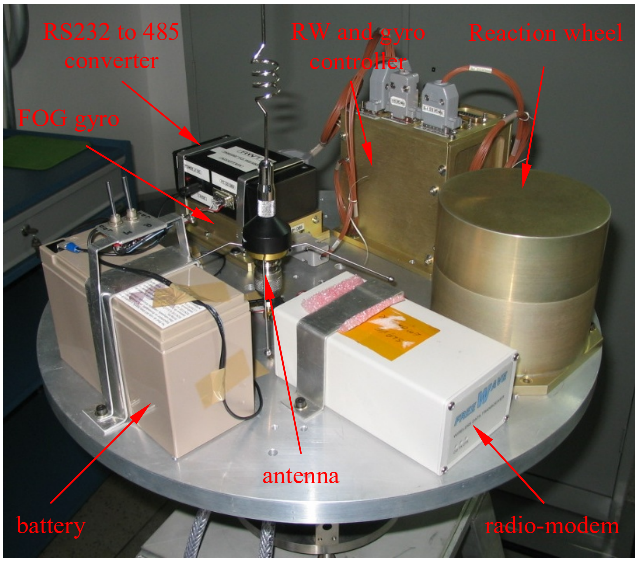

Figure 1. Reaction wheel and FOG gyro mounted on the air-bearing table.

2. REACTION WHEEL MATHEMATICAL MODEL

In [2] an experiment with the above-mentioned RW was performed using current control mode to stabilize and to point the air-bearing table. Even considering that no gyro filtering was done, the steady state pointing error remained below 0.02 degrees. The reaction wheel has a maximum capacity of 0.65 Nms, inertia of 1.5 10^{-3} kg m^2, maximum angular velocity of 4200 rpm, maximum torque of 0.05 Nm and can be controlled in current or speed modes through a serial RS485 interface. The single axis fiber optic gyroscope presents a bias less than 3 degrees per hour and was calibrated previously in [2]. The air-bearing table has a battery pack and a radio-modem to communicate the wheel and gyro electronics to the control computer (PC). The attitude control program was written in C++.

A reaction wheel can be modeled by the inertia J_w of the flywheel, a viscous friction b and a Coulomb friction c. The differential equation that describes the motion is [2]:

$$T_w = J_w \dot{\omega}_w + b\,\omega_w + c\,\mathrm{sgn}(\omega_w) \qquad (1)$$

where ω_w is the angular velocity of the wheel and T_w is the motor torque. Neglecting nonlinear effects present in the conversion from current to torque (there is no information from the RW manufacturer concerning these values), one can consider that the torque is proportional to the current I:

$$T_w = k_m\, I\,. \tag{2}$$

The applied torque to the table is equal to the net torque generated by the wheel, or, in other words, the difference between the torque applied to the motor and the friction, which leads to the result derived from the angular momentum law, neglecting any disturbance torque on the air-bearing table:

$$(J - J_w)\,\dot{\omega} = -J_w\,\dot{\omega}_w\,, \tag{3}$$

where J is the air-bearing inertia, including the flywheel, and ω is the angular velocity of the table. The gyroscope measures ω, while ω_w is obtained by the wheel's electronics and transmitted by telemetry. To estimate the viscous friction coefficient b, it was performed the same procedure reported in [2], where the wheel was accelerated up to a given rate, and then left free till complete stop, as shown in Fig. 2. The solution of differential motion equation (Eq. (1)) in this situation leads to:

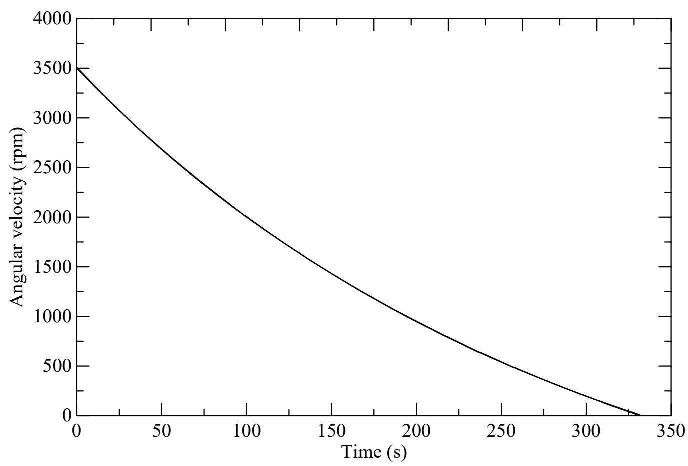

Figure 2. Angular velocity decay due to RW bearing friction.

$$\omega = \omega_o\,\frac{e^{-\beta t} - e^{-\beta t_f}}{1 - e^{-\beta t_f}}\,. \tag{4}$$

where $\beta = b\,/\,J_w$, ω_o is the initial decay rate and t_f is the decay time. Through least square error fitting b results equal to 5.16 10^{-6} Nms, c = 0.8795 10^{-3} Nm, ω_o = 3495 rpm and t_f = 333.3 s, if one considers that J_w = 1.5 to 10^{-3} kg m^2 according to the manufacturer. The theoretical and measured curves were superimposed in Fig. 2, where no visible differences can be seem. They are better evaluated in Fig. 3, which shows the difference between the model and experimental data. The maximum error is 15 rpm, or 0.5%, approximately.

Another parameter of interest to the model is the motor constant, k_m. It can be estimated by measuring the steady state of the angular velocity for a given commanded current. The result is shown in the solid curve of Fig. 4, while the dashed one shows the model obtained from the steady state solution of the equation of motion:

$$k_m\, I = b\,\omega_w + c\,\mathrm{sgn}(\omega_w)\,, \tag{5}$$

adjusted after minimizing the mean square error. Since b and c are now known, one can calculate k_m with any of them, which provide, respectively 0.0277 and 0.0251 Nm/A. The difference is due probably to uncertainty in the knowledge of inertia, in addition to measurement errors. The maximum model error occurs when the wheel starts moving from rest, as shown in Fig. 5, that presents the difference between the measured data and the mathematical model. The region around zero-speed where the wheel does not respond to the commanded current (between -38 to 38 mA), is a dead zone that must be taken into account in the model because it causes a sudden change in the dynamic behavior of the wheel. In fact, this non-linear behavior can be compensated by means of an integral, besides proportional, attitude control, but the large settling time may compromise the controller performance.

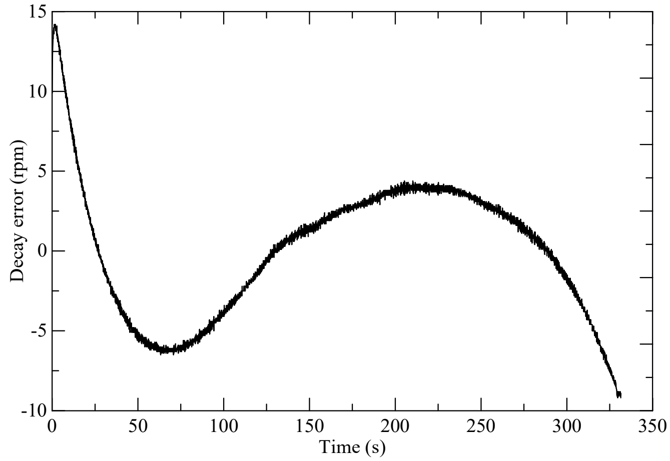

Figure 3. Mathematical model error of the viscous and Coulomb friction torques.

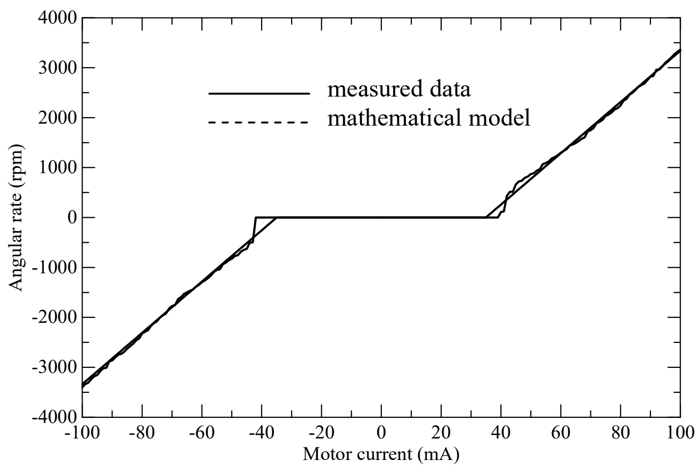

Figure 4. Mathematical model and measured data of RW speed in steady state.

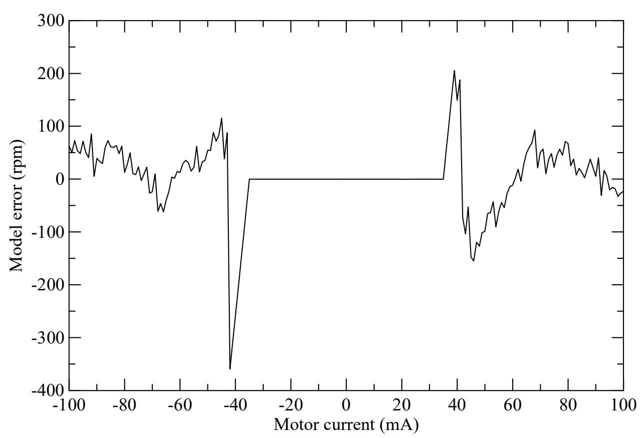

Figure 5. Model error of the RW speed in steady state.

3. AIR-BEARING TABLE ATTITUDE CONTROL

A digital PID controller was implemented in the stationary PC computer to control the angular position of the air-bearing table. The controller gains were adjusted manually, and chosen in such a way as to reduce the settling time and to avoid high overshoots. The rate error for derivative gain was supplied directly by the gyro output, after bias and local latitude compensation [2]. The angular position error was calculated by the difference between the reference attitude and the integrated (summed) angular rate. A second integration provides the integrated error signal. It shall be mentioned, however, that there isn't in the control loop any sensor providing directly position information.

The proportional, derivative and integral gains were, respectively, k_p = 0.04 A/deg, k_d = 0.2 A s/deg and k_i = 0.001 A/deg s. The commanded current to RW was set equal to the PID control signal, $I = u$. The control response is shown in Fig. 6 for a step of 90 degrees, featuring an overshoot of about 10 degrees, or 10%, approximately. The settling time is about 100 s for an error less than 1 degree and 250 s to stabilize with an error of about 0.2 degree. The initial wheel speed was set at 500 rpm. As can be seen in Fig. 7, the angular velocity crosses the zero-speed twice, the first one at 1 s (with maximum current of −2.2 A) and the second at 6.5 s. However, since the transient error is still large, there is no significant reduction of the control performance at this time. During steady state the integral gain keeps the current around 0.04 A, as can be seem in Fig. 8.

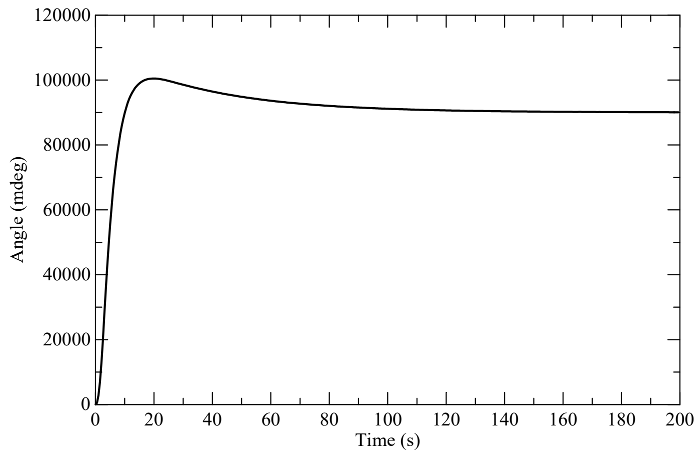

Figure 6. Step response of the air-bearing attitude controller.

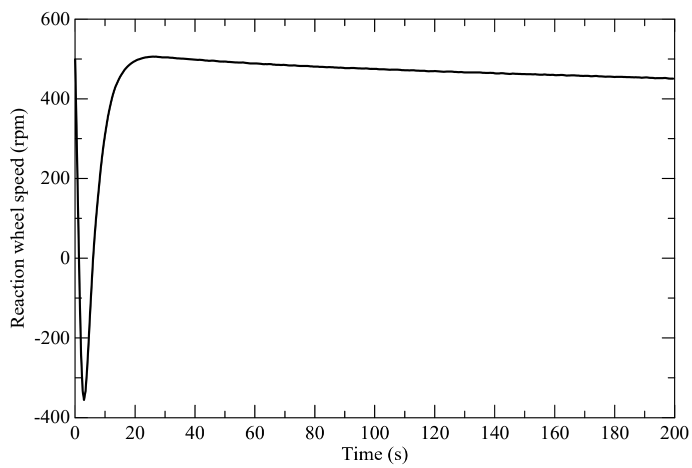

Figure 7. RW speed for a step response of the attitude controller.

To demonstrate the effect of the dead zone at zero-speed in the controller performance, a cooler fan was attached to the air-bearing table and oriented in such a way as to introduce a small and constant torque. The initial velocity of the wheel was adjusted so that a zero-speed crossing occurs while the control is in steady-state. Figure 9 shows the attitude error with a null reference signal, while Fig. 10 and 11 show the angular velocity and motor current, respectively. In Fig. 10 it is observed that the fan applies an almost constant torque, which results a straight line. It can be noted that the zero-speed crossing occurs at 87 s, and lasts about 2.5 s, whereupon the current is inverted. The attitude error reaches almost 2 degrees after zero-speed crossing, followed by an error of 0.2 degree in steady state. From controller viewpoint, this means that the pointing requirement is no longer accomplished during zero-speed crossing. The torque generated by the fan can also be estimated based on the angular momentum variation resulting 5.6 10^{-4} Nm.

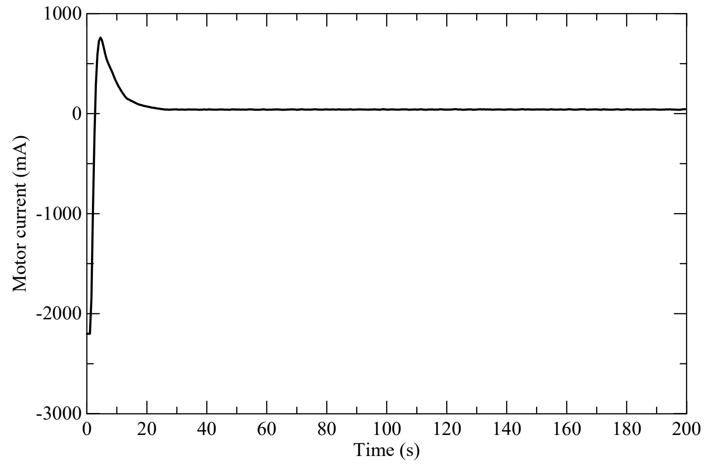

Figure 8. Control signal for a step response.

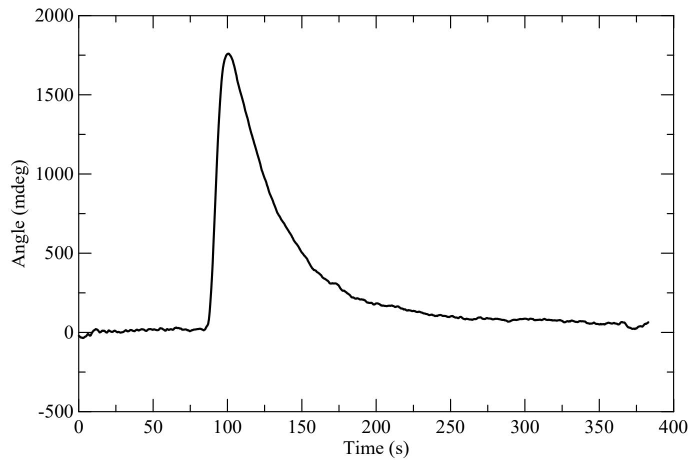

Figure 9. Attitude error during zero-speed crossing and with external disturbance (cooler fan).

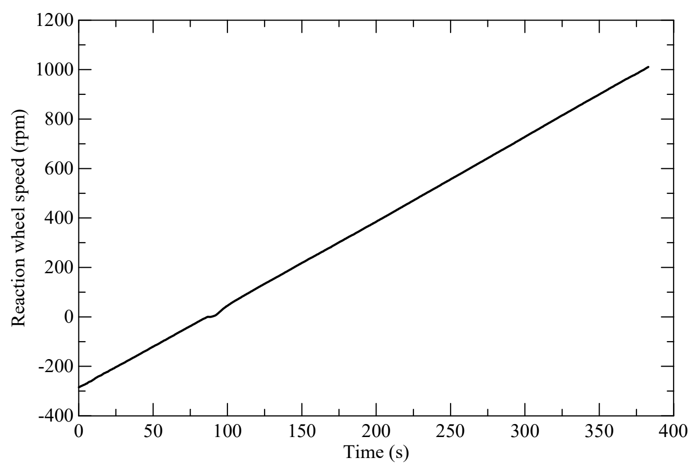

Figure 10. RW angular velocity under constant external disturbance (cooler fan).

The dead zone can be modeled by a saturation function that counteracts the applied torque whenever the RW angular velocity is equal to zero, thus resulting for the dynamic equation:

$$\begin{cases} I\, k_m = J_w\, \dot{\omega}_w + b\, \omega_w + c\, \mathrm{sgn}(\omega_w), \text{ if } \omega_w \neq 0 \\ I\, k_m - c\, \mathrm{sat}(I\, k_m / c) = J_w\, \dot{\omega}_w, \text{ if } \omega_w = 0 \end{cases}, \quad (6)$$

where sat(x) is defined by:

$$\text{sat}(x) = \begin{cases} x, & \text{if } -1 < x < 1 \\ -1, & \text{if } x \le -1 \\ 1, & \text{if } x \ge 1 \end{cases} . \tag{7}$$

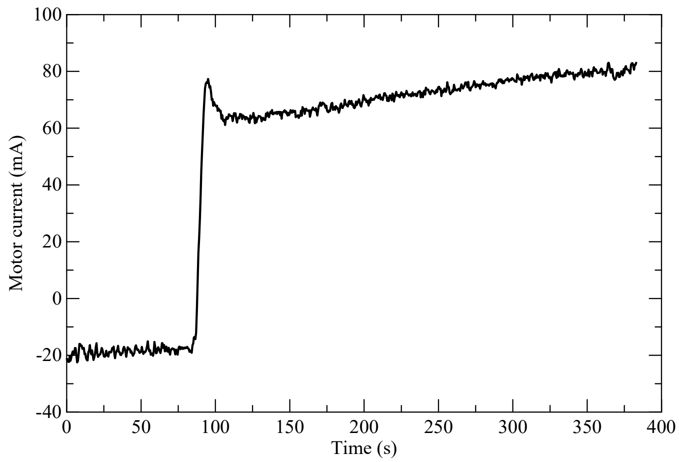

Figure 11. Control signal (motor current) to the RW under external disturbance.

3. DYNAMIC MODEL COMPENSATOR CONTROL

The idea of using a nonlinear controller to handle the zero-speed problem is a natural consequence of the fact that the previously proposed mathematical model represents the behavior of the wheel reasonably well. It is, therefore, straightforward to use the model as a nonlinear compensator for the controller, and to make the wheel action directly proportional to the PID signal [4]. Since the table responds only to an acceleration of the wheel, the control command shall be in the form:

$$I = \frac{J_w \dot{\omega}_w}{k_m}, \tag{8}$$

but for that happens, the current I shall be computed by:

$$I = u + \frac{b}{k_m}\omega_w + \frac{c}{k_m}\text{sgn}(\omega_w), \tag{9}$$

where u is the PID control signal. For a null wheel angular velocity the compensator takes the form:

$$I = u + c\,\text{sgn}(u) / k_m . \tag{10}$$

Figure 12 shows a simplified block diagram of the dynamic model compensator (DMC) control. The new controller was tested under the same condition as the previous one, but incorporates the dynamic compensation. As can be seen in Figs. 13 to 15 (analogous to Figs. 9 to 11) the error was decreased by a factor of 10, reached a maximum deviation of only 0.2 degree and it took about 100 s to reduce the error back to 0.02 degree in steady state. Fig. 14 shows that the fan disturbance torque is constant, with zero-speed crossing at 45 s, approximately. The control signal is shown in black in Fig. 15 and separated in its two components: the dynamic compensator (in red) and the PID signal (blue curve). It is clear in this graph that the PID control is approximately constant, as it would be expected due to the disturbing torque of the fan. The PID controller gains were kept identical to those used previously, although they could be adjusted in order to achieve a better performance, since the dynamics is now almost linear due to the model compensator.

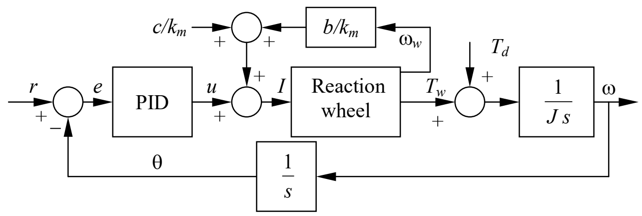

Figure 12. PID controller with RW dynamic model compensation.

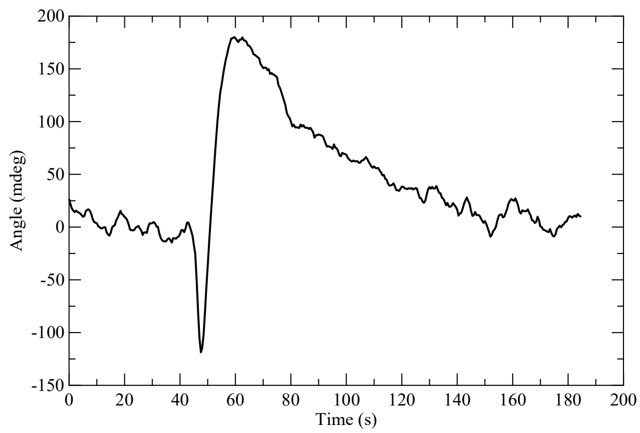

Figure 13. Attitude error of the dynamic model compensator with external disturbance.

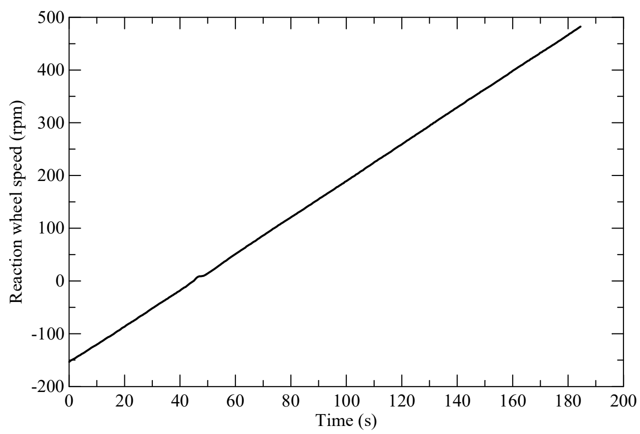

Figure 14. Reaction wheel speed with dynamic model compensator attitude control.

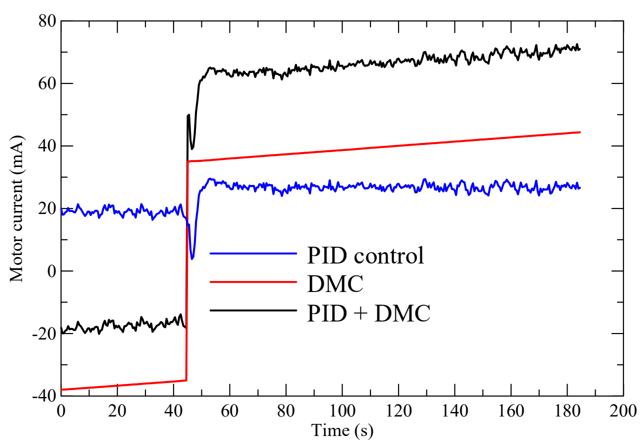

Figure 15. Total control, PID and the dynamic model compensator (DMC) signals during zero-speed crossing.

4. CONCLUSIONS

This paper presented a mathematical and computational model for a reaction wheel (RW) of SunSpace [3]. The nonlinear model and the viscous and Coulomb friction parameters were obtained for this wheel by means of curve fitting. The reaction wheel and a FOG gyro were mounted in a one-axis air-bearing table, and a PID attitude controller was implemented in a PC, which send RW commands and receive the gyro telemetry through a wireless communication device. It was found that the controller error increases considerably (from 0.02 to 1.8 degrees) when the wheel changes its direction of spin (zero-speed crossing). A nonlinear dynamic model compensator (DMC) for the RW control was then implemented in order to make the wheel behavior linear. The controller showed improved performance in this new condition and reached the maximum error of only 0.2 degree at zero-speed crossing. Finally, it is suggested as a continuation for this work the following tasks:

- To improve the mathematical model of the wheel by inclusion of static and Stribeck frictions.
- To model the reaction wheel including the dynamic compensator.
- To compare the dynamic model compensator to a speed mode attitude controller.
- To compare the integrated attitude error to an angular measurement system (optical encoder)

5. ACKNOWLEDGEMENTS

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6. REFERENCES

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