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SPEED AND CURRENT CONTROL MODE STRATEGY COMPARISON IN SATELLITE ATTITUDE CONTROL WITH REACTION WHEELS

Valdemir Carrara, val@dem.inpe.br
Rafael Henrique Siqueira, rafael_controle_automacao@yahoo.com.br
Danilo Oliveira, danilo_dasors@yahoo.com.br
Instituto Nacional de Pesquisas Espaciais, INPE, Av dos Astronautas, 1758, São José dos Campos, SP, 12227-101

Abstract. *Within the motto smaller, cheaper and better, several nations can have now easy access to space, both buying or developing their own satellites. In fact, the number of small companies and even universities that make business selling space platforms weighting less than 100 kg, including payload, increases each day. If in the past small satellites mean also low power, low pointing accuracy, low price and therefore low reliability, today it is no longer valid. Some low cost satellites have 3 axis attitude control systems with high degree of pointing accuracy, like FedSat, CHIPSat and MOST. The pointing requirements for MOST (Canada's space telescope) are 25 arc-seconds in the telescope focal plane. The once expensive 3 axis attitude control system, based on gyros, star tracker and reactions wheels is now affordable for micro-satellites, giving both reliability and pointing accuracy for scientific and technological satellites. The attitude and control subsystem (ACS) acts on the reaction wheels in response to attitude errors provided by star tracker and gyros. Reactions wheels are simple brushless DC motor, coupled to a high inertia wheel. They provide torques over wide magnitude range, from micro Newton-meter up to hundreds of mili-Newton-meter. Normally they are operated in "speed control mode" in which an internal closed loop control adjusts the motor current in order to achieve a commanded angular rate. Although reaction wheels can also operate in "current mode", the non-linear bearing friction, mainly in low speed rates, causes attitude deviation whenever the wheel changes its rotation sense. By the other hand, speed control mode introduces some time lack due to the internal control loop. This work aims to model the non-linear friction of the wheel, and to compensate it in the attitude control loop based in current mode. The reaction wheel and gyro are assembled in a one-axis air-bearing table, which provides micro friction similar to those encountered in space. Furthermore, both control modes, speed and current, shall be compared. The results proved to be helpful in deciding which strategy shall be used in future micro-satellite missions.*

Keywords: *attitude control, reaction wheel, dynamic model compensation control*

1. INTRODUCTION

Requirements for satellite attitude pointing accuracy have increased over the years, pressed by technological achievements both in hardware and software for system control. From passive to active, from analog to digital, from simple to complex, the Attitude and Orbit Control System (AOCS) has evolved since Explorer I made its debut in the 50's. Although costs have also increased, today a complete, reliable, fault tolerant and high accurate attitude control can be bought at roughly tenths of a similar one some years ago. Since the AOCS is normally the most expensive subsystem (except for hi-techs payloads like special cameras, telescopes, and scientific instruments), it is expected that the number of small yet powerful satellites blows up in near future.

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 limit 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 - note that 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 (Wertz, 1978). 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 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 do not exhibit linear behavior, since the output torque is not directly proportional to the current applied to the motor (Carrara and Milani, 2007; Wertz 1978). 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 nonlinearities 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 tachometer needed to measure the angular velocity, which can show quantizing and resolution problems, as long as optical encoders are employed for this purpose. 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, which is a very usual configuration.
- 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, as shown in the simplified diagram of Fig. 1, 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 attitude performance of the improved model with the speed controller. Next sections present the experiments performed with a reaction wheel and a fiber optics gyro, both from SunSpace (Engelbrecht, 2005), 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. 2.

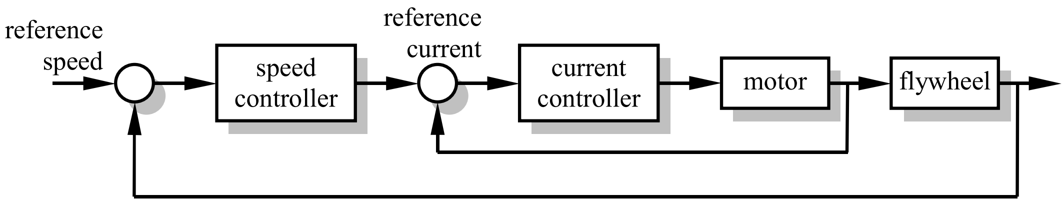

Figure 1. Reaction wheel closed loop controller.

In Carrara and Milani (2007) 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 current control mode was improved with a model compensation controller in Carrara (2010), which showed small yet significant pointing error during zero-speed crossing.The reaction wheel has a maximum capacity of 0.65 Nms, inertia of 1.5 10-3 kg m2, maximum angular velocity of 4200 rpm, maximum torque of 0.05 Nm and can be controlled by current or by speed 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 Carrara and Milani (2007). The air-bearing table has also a radio-modem to communicate the wheel and gyro with the control computer (PC) and a battery pack. The attitude control program was written in C++.

2. REACTION WHEEL MATHEMATICAL MODEL

A reaction wheel can be modeled by inertia J_w of the flywheel, a viscous friction b and a Coulomb friction c. The differential equation that describes the motion is (Carrara and Milani, 2007):

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

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 data concerning these values), one can consider that the torque is linear with the current I:

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

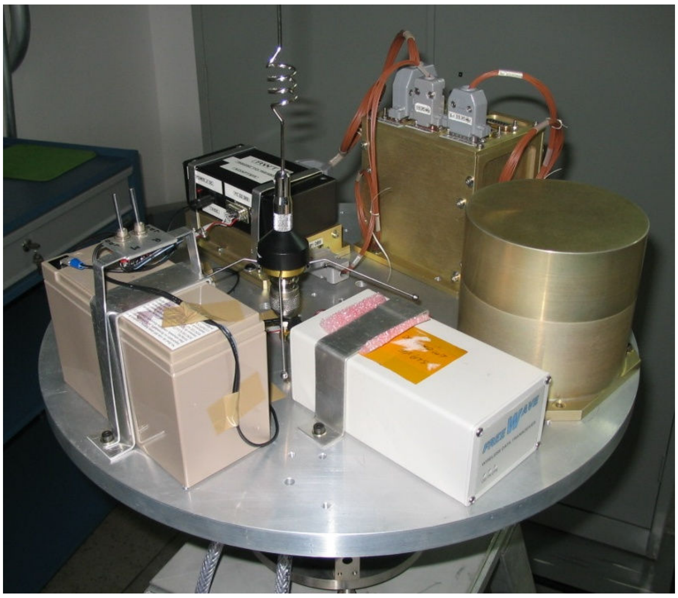

Figure 2. Reaction wheel and FOG gyro mounted on the air-bearing table.

The applied torque to the table is equal to the net torque generated by the wheel, i.e. the difference between the torque applied to the motor torque and the friction, which leads to the result derived from the law of angular momentum:

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

where J is the inertia of the air-bearing table, 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 Carrara and Milani (2007), where the wheel was accelerated up to a given rate, and then left free till complete stop, as shown in Fig. 3. The solution of differential motion equation (Eq. (1)) in this situation leads to:

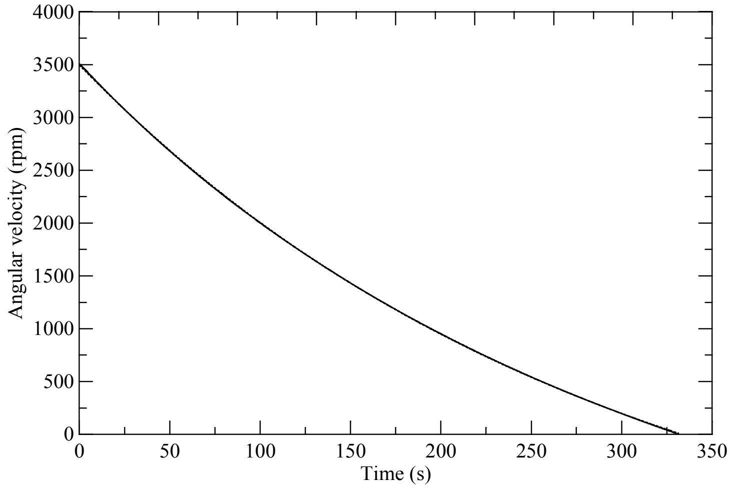

Figure 3. Angular velocity decay due to RW bearing friction.

$$\omega = \omega_o \frac{e^{-\beta t} - e^{-\beta t_f}}{1 - e^{-\beta t_f}}. \quad (4)$$

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. 3, where no visible differences can be seem. They are better evaluated in Fig. 4, which shows the difference between the model and experimental data. The maximum error is 15 rpm, or 0.5%, approximately.

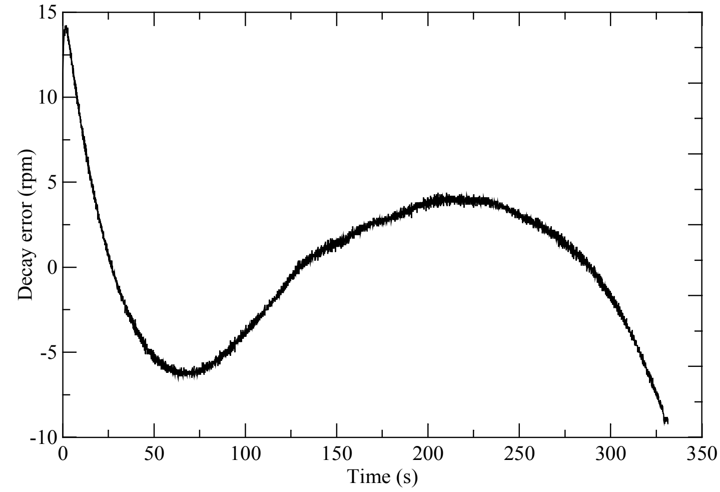

Figure 4. Mathematical model error of the viscous and Coulomb friction torques.

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. 5, while the dashed one shows the model obtained from the steady state solution of the equation of motion:

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

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. 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.

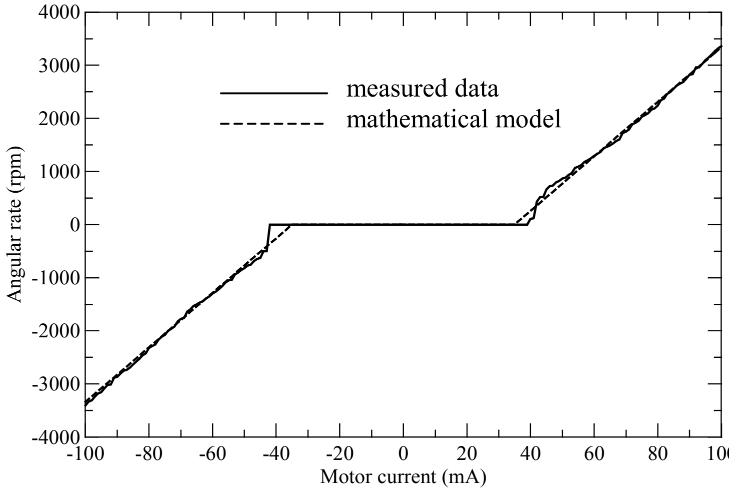

Figure 5. Mathematical model and measured data of RW speed in steady state.

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 is supplied directly by the gyro output, after bias and local latitude compensation Carrara and Milani (2007). The angular position error is 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 speed of the wheel was set at 500 rpm. As can be seen in Fig. 7, the angular velocity crosses the zero-speed twice, the first one in 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, seem in Fig. 8.

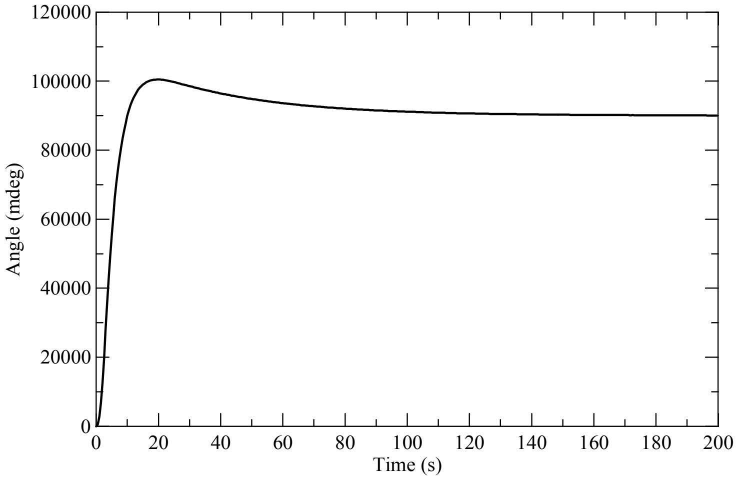

Figure 6. Step response of the air-bearing attitude controller.

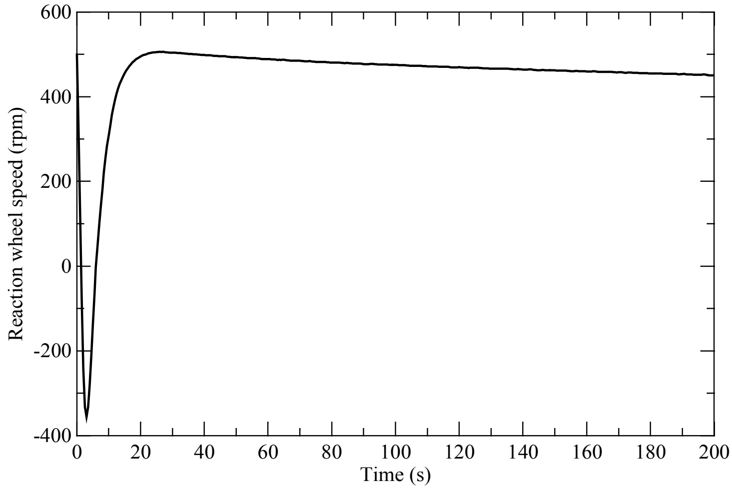

Figure 7. RW speed for a step response of the attitude controller.

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 crossover occurs during the control action. 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 crossover 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 not accomplish 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.

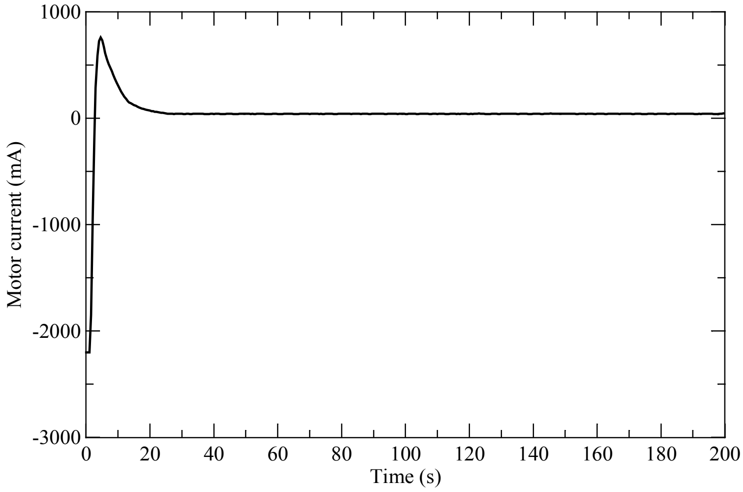

Figure 8. Control signal for a step response.

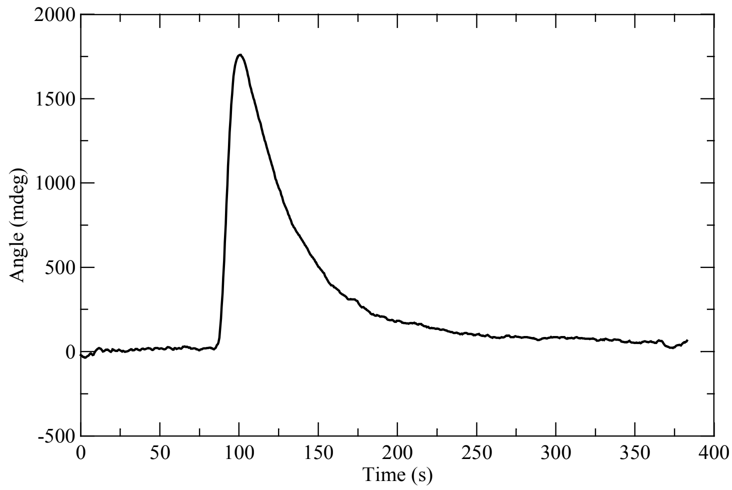

Figure 9. Attitude error during zero-speed crossing and with external disturbance (cooler fan).

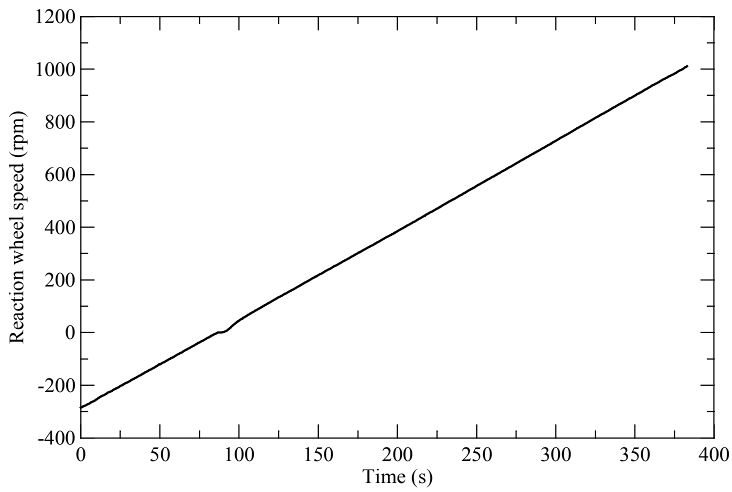

Figure 10. RW angular velocity under constant external disturbance (cooler fan).

The dead zone can be modeled by a saturation function when the angular velocity is equal to zero, thus resulting for the dynamic equation:

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

where sat(x) is defined by:

$$\mathrm{sat}(x) = \begin{cases} x,\ \text{if}\ -1 < x < 1 \\ -1,\ \text{if}\, x \leq -1 \\ 1,\ \text{if}\, x \geq 1 \end{cases}. \tag{7}$$

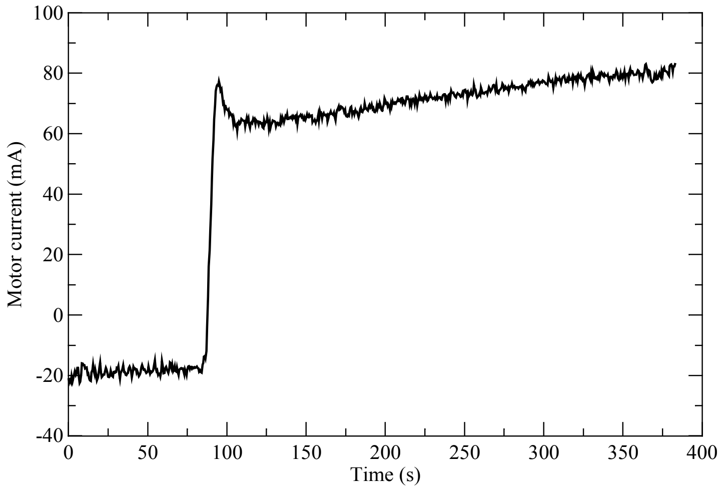

Figure 11. Control signal (motor current) to the RW under external disturbance.

The above equations were programmed in Matlab/Simulink in order to check it correctness. The block diagram of the wheel is presented in Fig. 12, whereas the simulated PID control during zero-speed crossing is depicted in Fig. 13. An external torque of the same magnitude of the fan ($5.6\ 10^{-4}$ Nm) was also introduced in simulation. In spite of small differences in the initial conditions between experiment and simulation, the resemblance among Figs. 9 and 13 is remarkable.

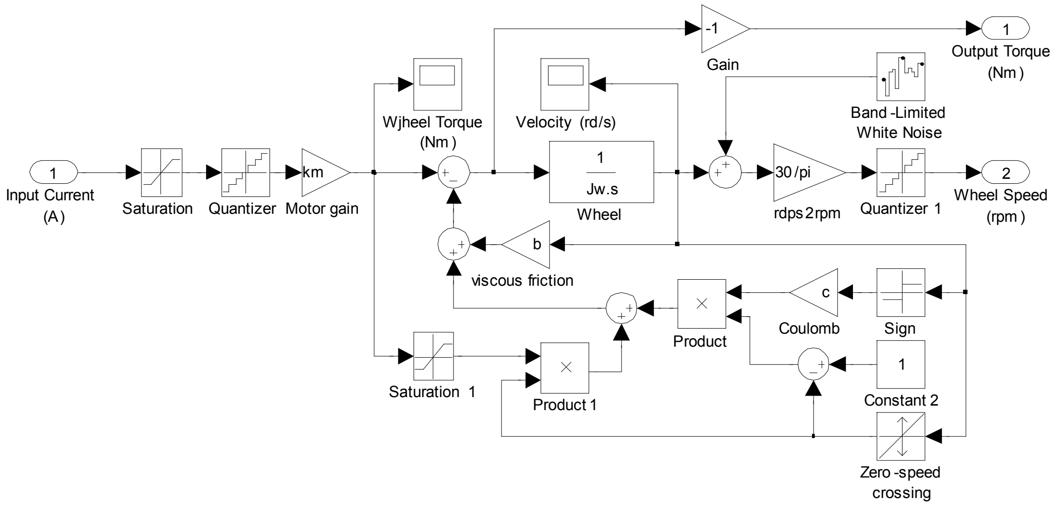

Figure 12. Block diagram of the reaction wheel, including viscous and Coulomb frictions.

3.1. 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 (Canudas De Wit and Lischinsky, 1997). Since the table responds only to an acceleration of the wheel, the control command shall be in the form:

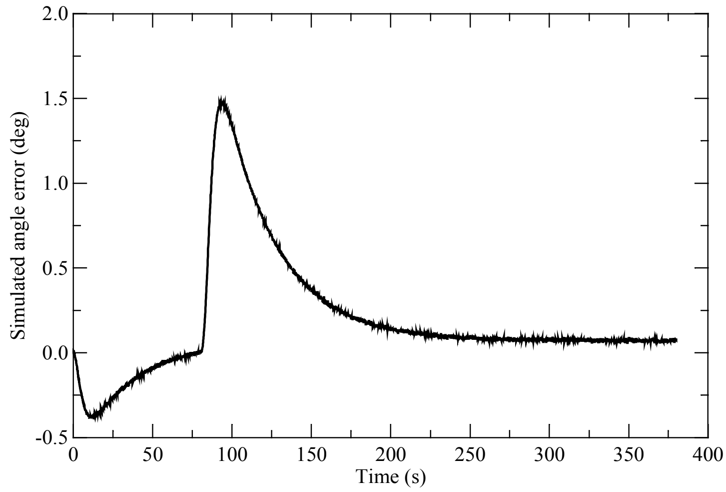

Figure 13. Simulation of the reaction wheel with external torque during zero-speed crossing.

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

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

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

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

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

Figure 14 shows a simplified block diagram of the dynamic model compensator (DMC) control. The new controller was tested under the same condition as the previous test, but incorporating the dynamic compensation. As can be seen in Fig. 15 and 16 (analogous to Fig. 9 and 11) the error was decreased by a factor of 10, reached a maximum deviation of only 0.2 degree and it takes now about 100 s to reduce the error back to 0.02 degree in steady state. The control signal is shown in black in Fig. 16, 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.

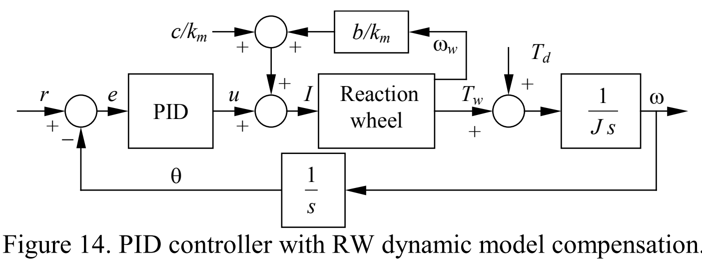

Figure 14. PID controller with RW dynamic model compensation.

3.2. Speed control

For attitude control using the RW speed control a relation between the wheel angular velocity and the applied torque shall be established. From the angular momentum law (Eq. 6) it yields

$$\omega_{cw} = \int \frac{k_m}{J_w} u \, dt, \tag{11}$$

where u is the PID control signal and ω_{cw} is the reference wheel speed (see Fig. 1). The integration was replaced by a simple sum at each dt interval (equal to 0.1 s in the attitude control loop). The speed control and the dynamic model compensator control are compared in Fig. 17, for attitude control of the air-bearing table with disturbance torque introduced by the cooler fan. The zero-speed cross occurs at 161 s for DMC and 156 s for speed control (SC). It is easy to conclude that the speed control presents a better performance when compared with the current control and even with the DMC control, at least concerning the attitude error. However, it should be expected some kind of response delay in the speed control due to the double internal control loop depicted in Fig 1.

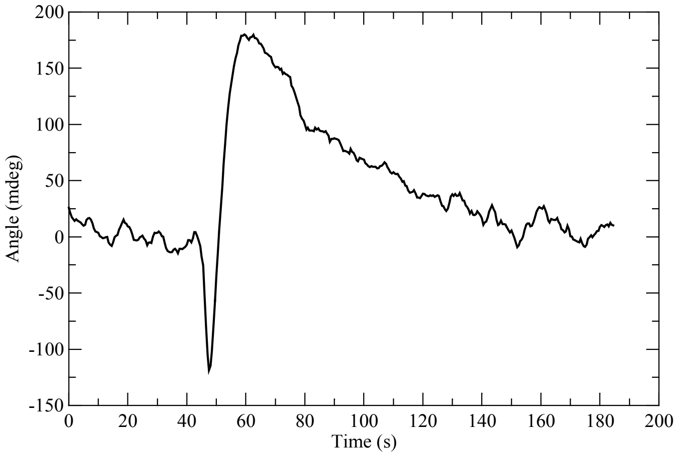

Figure 15. Attitude error of the dynamic model compensator with external disturbance.

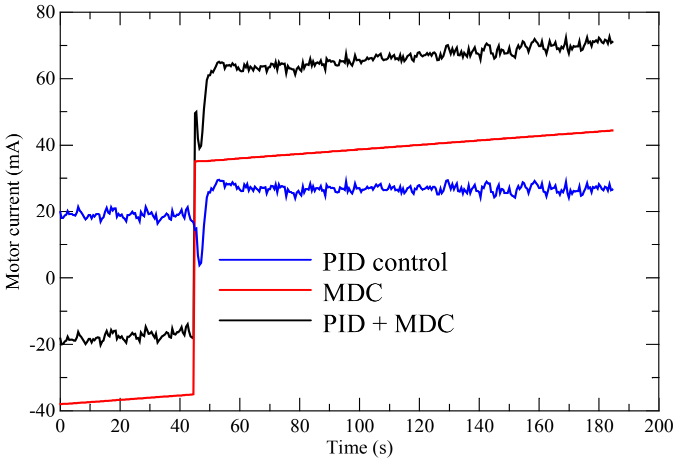

Figure 16. Total control, PID and the dynamic model compensator (DMC) signals during zero-speed crossing.

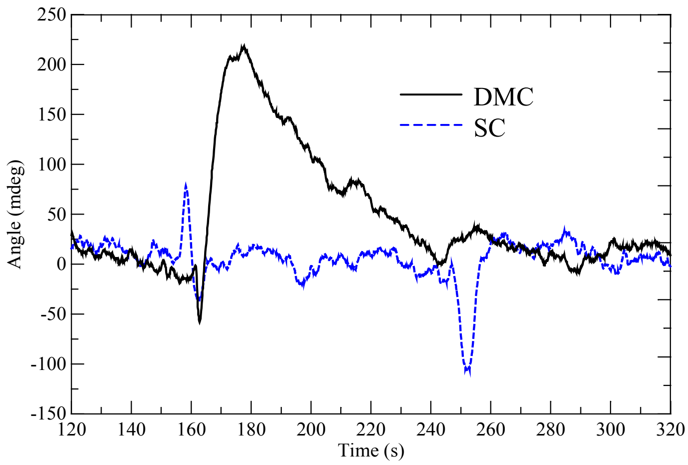

Figure 17. Attitude error for RW speed control (SC) and dynamic model compensator (DMC) with disturbance torque.

4. CONCLUSIONS

This paper presented a mathematical and computational model for a reaction wheel (RW) of SunSpace (Engelbrecht, 2005). It was obtained the nonlinear friction model parameters for the Coulomb and viscous friction by 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. The DMC controller was compared with the speed control (SC), a usual technique employed in several satellites equipped with RW systems (Wertz, 1978). Although the SC has clearly shown a reduction in the attitude error during zero-speed operation, some considerations shall be take into account during selection of the attitude control strategy, like reliability, delay and error pruning between different control techniques. Finally, it is suggested as a continuation for this work, to improve the mathematical model of the wheel by inclusion of static and Stribeck frictions.

5. ACKNOWLEDGEMENTS

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