A PRACTICAL SYSTEM FOR EXPERIMENTS IN ATTITUDE CONTROL

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Abstract. *On-off thrusters are used for attitude control in some aerospace applications. These thrusters lead to discontinuous control actions and are frequently subject to switching constraints. This contribution discusses the development of a practical system intended as a laboratory prototype for the study of the effect of switching restrictions on attitude control dynamics in rockets and satellites. Its usefulness in the study of complex behavior such as chaotic and quasi-periodic motion is emphasized. This system has dynamics similar to that found in upper satellite launching vehicle stages, e.g. in Brazilian VLS. The prototype is software controlled and consists of a rotating platform, attitude sensor and actuators (thrusters). The software allows implementation of different switching restrictions to mimic real rocket/satellite actuators. The prototype is controlled through two PC's in host-target configuration running Matlab/xPCTarget. xPCTarget uses the host PC with Real Time Workshop and a C/C++ compiler to create executable code. Executable code is downloaded from the host to the target PC, which controls the plant and communicates data to the host on the fly, for monitoring purposes. On-off pneumatic valves are used as actuators and an encoder is used as positioning sensor. The actuators are activated by a relay output interface board. In a baseline experiment, the non-linearities of the system were treated through the describing function approach.*

Keywords*: Attitude control, Non-linearity, Describing function*

1. INTRODUCTION

Throughout the last decades, attitude control systems with switching actuators have been used in satellite and launching systems (Mendel, 1970; Leite Filho, 1998; Oliveira and Kienitz, 2000). Typically these actuators are subject to switching constraints. A limit cycle is the normal steady state operation mode of such attitude control systems. Analysis and controller design for these systems have been presented by Oliveira and Kienitz (2000), using a describing function approach. In this reference it was shown that non-conventional analysis/design problems arise when such actuators are subject to switching-time restrictions. A certain condition ensures that limit cycles exist. When this condition does not hold, system movements do not correspond to a limit-cycle.

This contribution discusses the development of a practical system intended as a laboratory prototype as well as the analysis and the controller design for such system that allows implementation of different switching restrictions to mimic real rocket/satellite actuators. The switching-time restrictions adopted in this paper have different values than those used in Oliveira and Kienitz (2000), due to practical limitations of the system. The prototype also allows implementation of different nonlinearities. For example, herein the system's behavior with hysteresis is also studied. Differently from Oliveira and Kienitz (2000), where all predicted results were checked by simulation, here the results were implemented in the system.

The system is software controlled and consists of a rotating platform, attitude sensor and actuators. The control has been implemented through two PC's in host-target configuration running Matlab / xPCTarget. xPCTarget uses a host PC running Real Time Workshop and a C/C++ compiler to create executable code. Executable code is downloaded from the host to the target PC, which controls the plant and communicates data to the host on the fly, for monitoring purposes.

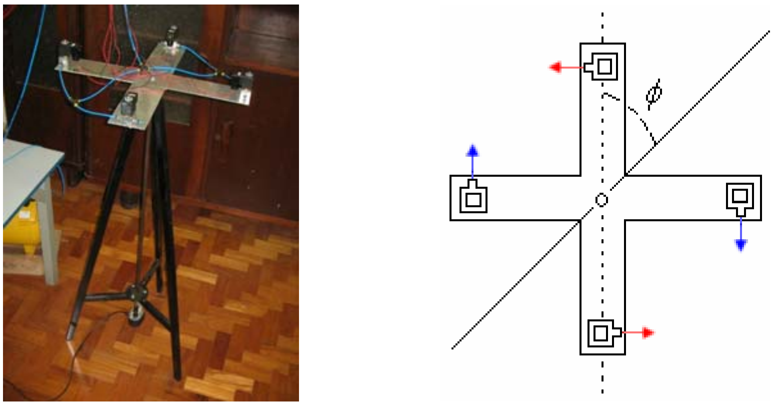
This contribution is structured as follows: the system description and the model are given in section 2; the section 3 deals with control system analysis and design; conclusions are presented in section 4; section 5 is devoted to acknowledgements and references are found in section 6.

2. SYSTEM DESCRIPTION AND MODEL

2.1. SYSTEM DESCRIPTION

The mechanical system consists of a rotating platform connected to an axis mounted to a base as indicated in Fig. 1 (a). In the coupling points between axis and base good quality bearings are used that allow for minimum friction. On-off pneumatic valves fixed on the platform are used as actuator (thrusters). These thrusters are turned on pair wise, resulting in binaries as indicated in Fig. 1 (b), which produces moments acting on the platform clockwise or counter clockwise.

The air for valves is supplied by a pneumatic subsystem. It consists of a compressor and a pressure regulator that hold a prescribed pressure on the pneumatic valves. The attitude ϕ is the controlled variable. The encoder connected to the axis is used as positioning sensor. The encoder produces 1024 pulses per turn, i.e. its resolution is 0.0061 rad.



(a) (b)

Figure 1. Prototype considered in this work

The prototype is software controlled by Matlab/Simulink and the xPCTarget environment, which uses a target PC, in addition to the host PC, for running real-time applications. The host and target computers are connected directly through a cross-over Ethernet cable and use the TCP/IP protocol for communication. xPCTarget uses a host PC running Matlab's Real Time Workshop and a C/C++ compiler to create executable code. Executable code is downloaded from the host to the target PC, which controls the plant and communicates data to the host on the fly, for monitoring purpose. The target PC communicates with the plant by a relay output interface board and a digital input board. The encoder signal is acquired by a general purpose digital input board and the actuators are activated by a relay output interface board.

The relay of the output interface board is not ideal; it has switching-time restrictions. The prototype has second order dynamics, therefore the system in closed loop presents a limit cycle of small amplitude, about 0.0244 rad. Due to the very small amplitude of the limit cycle, the quantization error has significant impact. The describing function of quantization for amplitudes close to the order of magnitude of encoder resolution is not unity and is discussed by Gelb and Vander Velde (1968). The non-linearity's effect is quite complex for small amplitudes. However in this paper this problem will not be considered because the plant will be operated with the addition of artificial (software imposed) prevailing nonlinearities such as hysteresis or switching-time restrictions, which make the effect of the encoder almost irrelevant.

The Figure 2 shows the block diagram of the controlled system. *C(s)* is the transfer function of controller and *G(s)* is the transfer function of prototype.

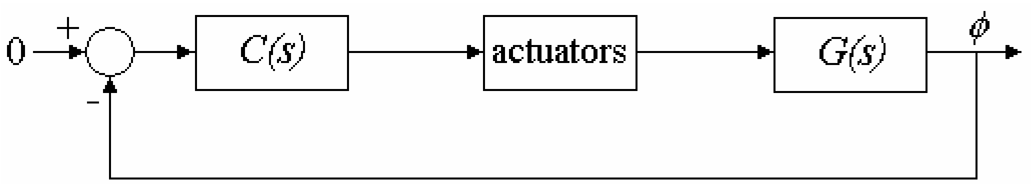


Figure 2. Block diagram of the controlled system

2.2. MODEL

The differential equation that describes system motion is:

$$\tau = J \cdot \frac{d^2\phi}{dt^2} + \beta \cdot \frac{d\phi}{dt} \tag{1}$$

Where τ is the torque, J is the inertial momentum, β is the viscous friction coefficient and ϕ is the angular position (attitude). The parameters of the differential equation were found by closed loop identification (without controller), using the describing function approach. A hysteresis type non-linearity with width 0.1 and height 1, was created via software at the system's input. The goal of this action is to force the system to operate in limit-cycle. The limit-cycle obtained at the non-linearity's input is shown in Fig. 3.

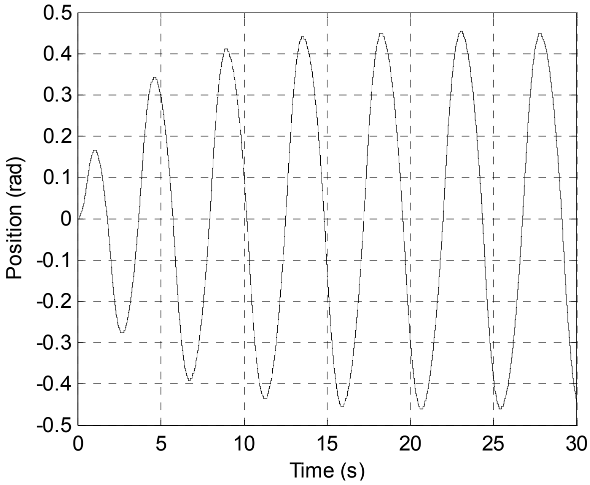


Figure 3. Limit-cycle obtained at the non-linearity's input
with hysteresis type non-linearity

This limit-cycle has amplitude 0.45 rad and frequency 1.34 rad/s. The limit-cycle existence condition is:

$$\frac{-1}{N(A)} = G(j \cdot \omega) \quad (2)$$

Where $N(A)$ is the describing function of the non-linearity (hysteresis) and $G(j \cdot \omega)$ is the frequency response of the system. The negative reciprocal of the describing function (Ogata, 1997) is:

$$\frac{-1}{N(A)} = -\frac{\pi \cdot A}{4 \cdot M} \cdot \cos\left(\arcsin\left(\frac{h}{A}\right)\right) - j \cdot \frac{\pi \cdot h}{4 \cdot M} \quad (3)$$

Where A is the amplitude at the non-linearity's input, h = 0.1 is the width of the hysteresis and $M = 1$ is its amplitude. ϕ is the system output and the torque τ is the system input, resulting in the following transfer function:

$$G(s) = \frac{\Phi(s)}{T(s)} = \frac{1/J}{s \cdot (s + \beta/J)} \quad (4)$$

From Equation (2) the transfer function of system is:

$$G(s) = \frac{0.66}{s \cdot (s + 0.3)} \quad (5)$$

A sine signal, with frequency 2 rad/s and amplitude 0.5 rad, was applied in the model input and prototype input for validation purpose. The prototype model should be valid for all types of non-linearity, therefore the validation is without the hysteresis. The remaining nonlinearities are the non-ideal relay of the output interface board and encoder quantization. Figure 4 shows the system and model responses.

The model present reasonable behavior in the transient and it has satisfactory behavior in steady state. The system has some sources of uncertainties, such as the residual mechanical damping created by as wires and pipes that supply electric energy and compressed air to pneumatic valves. These uncertainties affect the results more intensely in the transient.

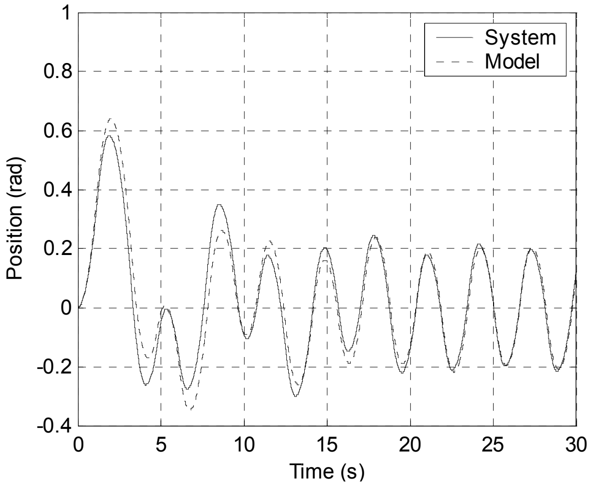


Figure 4. System and model responses to a sine input of frequency 2 rad/s and amplitude of 0.5 rad

3. CONTROL SYSTEM ANALYSIS AND DESIGN

3.1. HYSTERESIS TYPE NONLINEARITY

The hysteresis implemented here is equal that used in the subsection 2.2. The behavior of the closed loop system without controller was shown in the Fig. 3. Now a controller is designed to reduce limit-cycle amplitude to 0.25 rad and to increase the frequency to 2.0 rad/s. A magnitude × phase plot of $G(j \cdot \omega)$ is shown in the Fig. 5. The phase values of the negative reciprocal of describing function at amplitude 0.25 rad and of $G(j \cdot \omega)$ at frequency of 2 rad/s are marked on the plot.

The phase of the negative reciprocal of describing function is -156.42º (vertical dashed line) at amplitude 0.25 rad and the phase of system at 2 rad/s is -171.47º (vertical solid line). Thus a controller was designed to provide a phase contribution of 15º at 2 rad/s. Thus the transfer function of a suitable first order controller is:

$$C(s) = \frac{1.7013 \cdot s + 2.6085}{s + 2.6085}$$

Figure 6 shows the controlled system response.

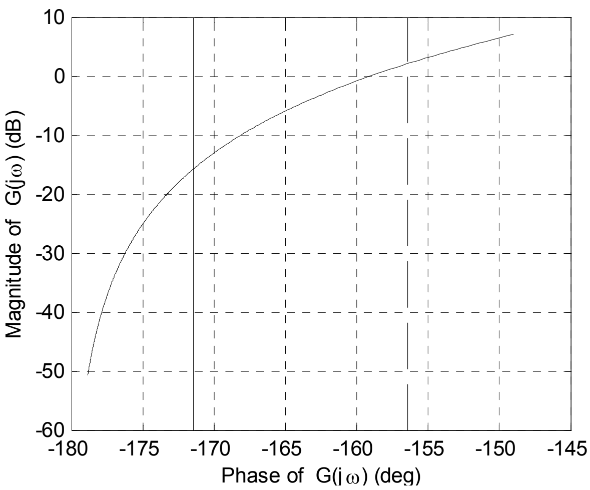


Figure 5. Magnitude × phase of $G(j \cdot \omega)$

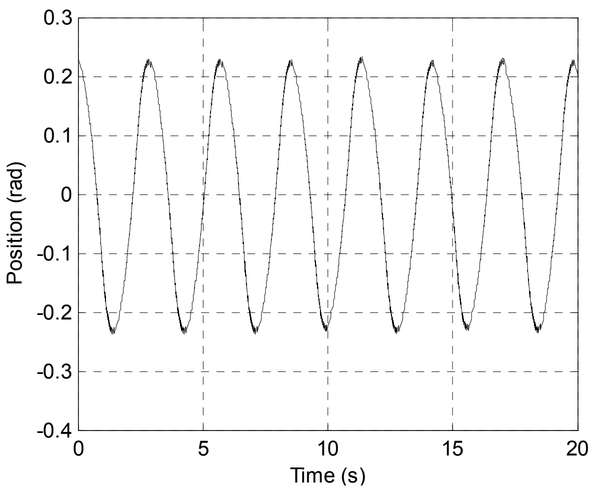


Figure 6. Controlled system response

The desired limit cycle amplitude and limit cycle frequency are 0.25 rad and 2 rad/s, respectively. In the practical implementation the measured limit cycle amplitude was 0.22 rad and the limit cycle frequency was 2.2 rad/s. Since the describing function approach is approximate and the model has uncertainties, these practical results with approximately 12 % error were considered satisfactory.

3.1. SWITCHING-TIME RESTRICTIONS

The practical system described in this paper is useful for experimentation with switched actuators subject to switching-time restrictions. Large sets of switching-time restrictions can be implemented by software using the xPCTarget environment and will allow for practical assessment of the impact of such restrictions. The switching-time restrictions adopted in this paper to illustrate the plant's capabilities have different values than those used in Oliveira and Kienitz (2000) due dynamical limitations of the system (mainly encoder precision and quantization nonlinearity). The switching-time restrictions implemented for illustration purpose are the following:

-duration of pulses (t_{on_min}): ≥ 1.4s

-rest between successive pulses of the same valve: ≥ 0.1s

-rest between switching-off of one valve pair and switching-on of the other pair (t_{off_min}): ≥ 0.4s

A describing function for this switching actuator type was derived by Oliveira and Kienitz (2000). As explained in that reference, this describing function can be decomposed into a (pure) time-delay-type phase shift and real valued function of limit-cycle frequency and amplitude. The maximum possible limit cycle frequency ω for the system with the aforementioned restrictions is given by:

$$\omega = \frac{\pi}{(t_{on\_\min} + t_{off\_\min})} \tag{6}$$

Behavior of closed loop system without C(s) can be studied using the describing function derived by Oliveira and Kienitz (2000). Provided they satisfy condition above, as shown in the aforementioned reference, limit cycles for this describing function are obtained from:

$$\frac{-1}{|N(A,\omega)|} = G(j\cdot\omega)\cdot e^{-j\cdot\frac{\omega\cdot t_{off\_\min}}{2}} = G_1(j\cdot\omega) \tag{7}$$

Where $|N(A,\omega)|$ is given by:

$$|N(A,\omega)| = \frac{4\cdot b}{\pi\cdot A}\cdot\sqrt{1-\sin^2(\omega\cdot\frac{t_{off\_\min}}{2})} \text{ and } b = 1$$

Plots of $G_1(j\cdot\omega)$ are found in Figs. 7 and 8.

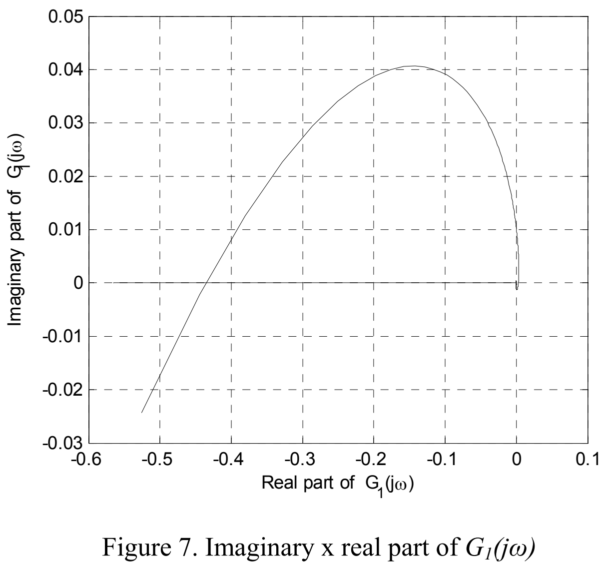


Figure 7. Imaginary x real part of $G_1(j\omega)$

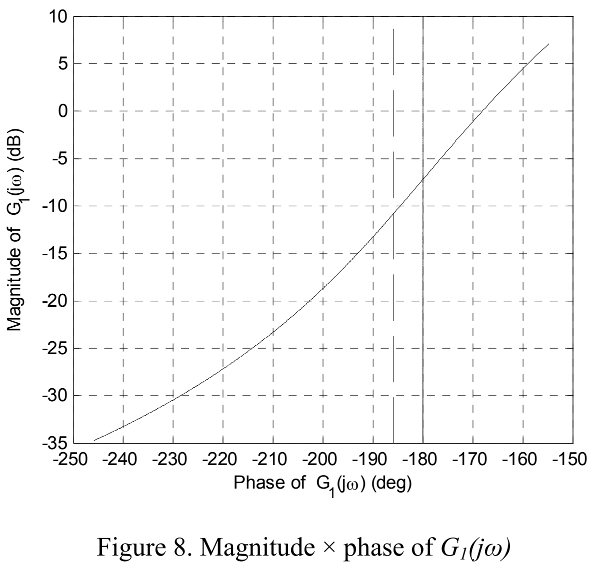


Figure 8. Magnitude × phase of $G_1(j\omega)$

In Figure 7 the plot of $G_I(j\cdot\omega)$ crosses the phase of -180º at frequency 1.21 rad/s, which corresponds to the limit cycle frequency. Estimated amplitude is obtained from the intersection point of $G_I(j\cdot\omega)$ with the real axis. Intersection occurs at -0.4351.

$$\frac{-1}{|N(A,\omega)|} = -0.4351 \Rightarrow A = 0.5378$$

The Figure 9 shows the limit cycle obtained with practical implementation of switching-time restrictions.

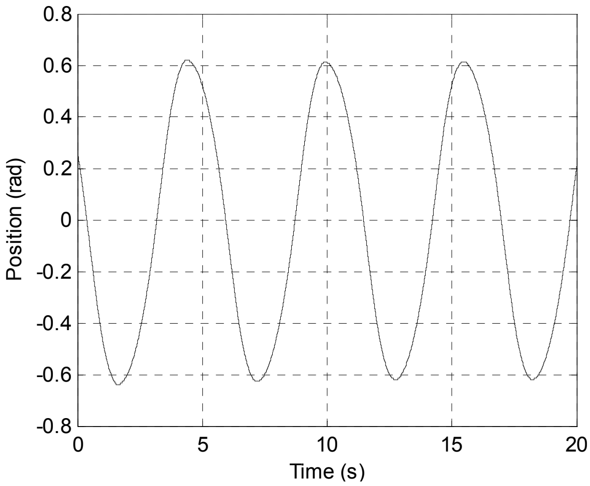


Figure 9. Limit cycle measured with practical implementation of switching-time restrictions

Figure 9 shows that the limit cycle amplitude is 0.61 rad with 13.42% of error with respect to the calculated value and the limit cycle frequency is 1.15 rad/s with 4.67% of error. These results were found to be within the usual error margins observed for the describing function method.

Because an increase in limit cycle frequency yields a decrease in limit cycle amplitude, the amplitude can be reduce introducing a lead compensator into loop. This can be concluded from Fig. 8. There at frequency 1.5 rad/s the phase of $G_I(j\cdot\omega)$, is 185.88º (vertical dashed line). Thus the lead controller should give a phase contribution of 5.88º at 1.5 rad/s to make this the limit cycle frequency. Thus the transfer function of a suitable first order controller is:

$$C(s) = \frac{1.2282\cdot s + 1.6624}{s + 1.6624}$$

The controlled system has estimated limit cycle amplitude of 0.3878 rad and frequency of 1.5 rad/s. The practical results are shown in the Fig. 10. The measured limit cycle amplitude was 0.3150 rad (18.77% error) at frequency 1.68 rad/s (12.04% error). In the scope of the describing function approach this also was considered satisfactory.

Using Equation (6) one concludes that the maximum possible limit cycle frequency ω for the system is given by:

$$\omega = \frac{\pi}{(1.4 + 0.4)} \Rightarrow \omega = 1.7453\, rad/s$$

To illustrate what happens if this restriction is not adequately considered at design time, a controller is now designed with the goal of setting a limit cycle frequency of 1.9 rad/s, which clearly violates the theoretical limit above.

Figure 11 shows that the phase of $G_I(j\cdot\omega)$ is -192.80º (vertical dashed line) in the frequency 1.9 rad/s. This frequency violates the maximum possible limit cycle frequency. A lead controller was designed to supply a phase contribution of 12.80º at frequency of 1.9 rad/s. The transfer function of a suitable first order controller is:

$$C(s) = \frac{1.5691\cdot s + 2.38}{s + 2.38}$$

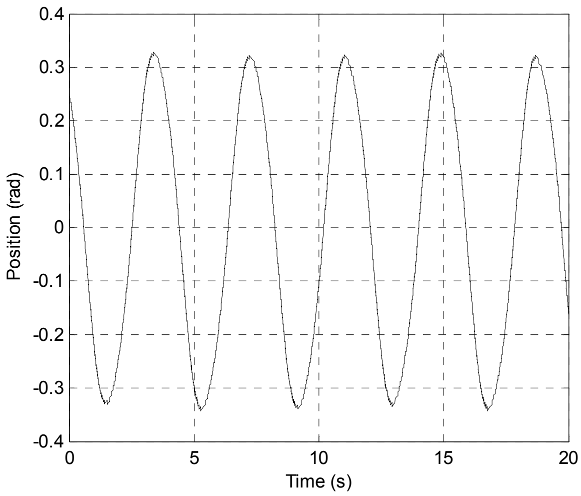


Figure 10. Controlled system response

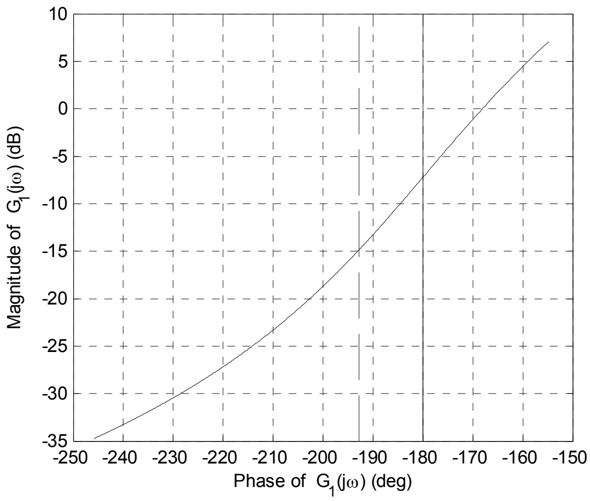


Figure 11. Magnitude × phase of $G_1(j\omega)$

Figure 12 shows the response obtained with this controller. The observed response is a non-periodical persistent motion, which is consistent with our theoretical prediction. This type of persistent motion was studied in detail by Mesquita et al. (2007).

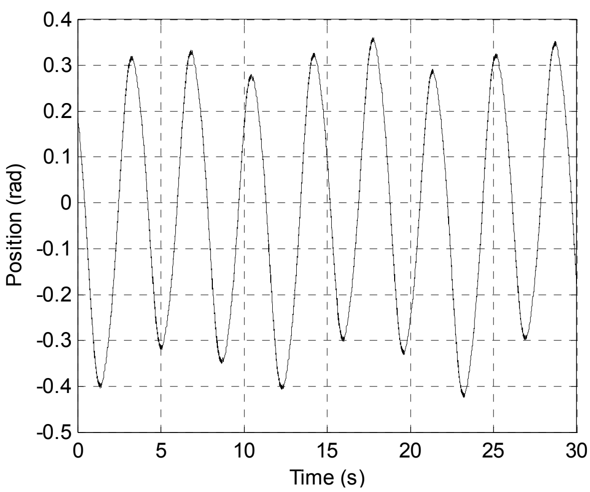


Figure 12. Non-periodical persistent motion

4. CONCLUSIONS

This paper discussed the development of a practical system intended as a laboratory prototype. Its usefulness was illustrated for the study of the effect of various types of non-linearities such as hysteresis and switching-time restrictions on attitude control dynamics. Nonlinear phenomena such as periodic as well as non periodic motions could be predicted using the describing function approach and observed in practical experiments. The implementation of different types of nonlinearities illustrates the flexibility of the system and how it can be used to study nonlinear phenomena.
Future research using this plant will concentrate on:

- the practical investigation of robust limit cycle controller design methods, such as that described by Oliveira (2003);
- the practical investigation of quasi-periodic and chaotic motion;
- instrumentation issues of attitude control systems;
- novel control strategies for switching-restricted systems, such as predictive control;
- the use of the describing function approach in system identification.

5. ACKNOWLEDGEMENTS

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