FLEXIBLE STRUCTURE CONTROL AND VALIDATION USING FLEXCAM QUANSER SYSTEM

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Abstract. *The dynamic behavior of a flexible structure is similar to fluid moving (known as sloshing) in liquid-propellant rocket motors, subjected to external efforts. This work presents the design, implementation and results obtained from a digital control action on a flexible beam. The control design is based on compensated inverse PID technique that combines three individual controllers in parallel, tuned on flexible mode frequencies to damp any of these modes. To the beam modelling was considered the Euler-Bernoulli assumptions and a previously identification process using ARX models is discussed. The C compiler and Real-Time Workshop toolbox are used to generate the appropriate C-code. The digital control system was implemented on a computer using real-time WinCon controller, especially designed for this purposes. Tests and simulations are discribed and experimental results show a reduction on the undamped oscillations of the tip while commanding the flexible structure to a desired angular position. In this way, the complete model (position servo and flexible beam), identification process and controller are validated and can be used as reference to sloshing control designs.*

Keywords*: Control, Identification, Real-time, Flexible beam*

1. INTRODUCTION

The control of a plant and validation of the controller is an interactive process. The presence of oscillations on flexible systems can be minimized with a tuned controller and is presented in this paper. The Flexible Link FLEXCAM Quanser System is a very useful equipment to perform this interactive process, and so is briefly presented. The modeling and identification of the actuator and flexible beam are covered in Barbosa and Góes (2007), from where was obtained numerical results used in this work. The controller transfer function, $D(s)$, is implemented in the digital control system, WinCon software. The input-output data and internal variables are recorded and used to validate the controller.

2. THE FLEXCAM QUANSER SYSTEM

The Quanser System is presented in Fig. 1, used to validate control strategies to Brazilian Vehicle Satellite Launcher (VLS), placed at Hybrid Simulation Laboratory (LabSI) of Institute of Aeronautics and Space (CTA-IAE).

(a) (b)

Figure 1. (a) The FLECAM Quanser System (b) Hub, camera and flexible beam

The Figure 1 shows the Camera, Flexible Link and Light source. The Flexible Link is a uniform flexible beam mounted on the servo plant (hub). The light source is attached to the tip of the beam which is detected by a camera mounted on the rotating base in the Camera Module (FLEXCAM). The hub is used to rotary motion experiments and consists of a DC motor mounted with a gearbox. The ADC board perform the analogic to digital and digital to analogic conversion (A/D, D/A).

The software used to developing, compiling and to perform digital control consists the Simulink, Real-Time Workshop (RTW), C compiler and WinCon controller. The WinCon is a real-time program that performs the digital controller using Simulink/Matlab. The Figures as follow show the user-interface and a typical block diagrams to the system operation.

The camera output is an analog signal which is proportional to the relative deflection of the light source from the central axis. The linear displacement y (measurement of tip deflection) corresponds to a linear voltage output. The system parameters are presented in Table 1.

Table 1 – System parameters

Actuator (Hub SRV-02)		**Flexible Link**	
Parameter	**Numerical value**	**Parameter**	**Numerical value**
Motor torque constant, kt	0.00767 N.m/A	Position sensor gain	0.39 V/cm
Motor torque constant, km	0.00767 V/rd.s	Link rigid body inertia	0.0042 kg.m^2
Armature resistence	2.6 Ohm	Link mass	0.06 kg
Armature inductance	0.18 mH	Link thickness	0.8 mm
Gear ratio	14:1	Link height	0.02 m
Sensitivity	0.0284 V/deg	Link length	0.425 m
Armature inertia	3.87 e-7 kg.m^2	Link mass	0.06 kg

The camera output is an analog signal which is proportional to the relative deflection of the light source from the central axis. The gain and offset of the measurement are adjustable through two trimpots located on the camera.

3. HUB AND FLEXIBLE BEAM MODELING AND IDENTIFICATION PROCESS

The Figure 2 shows the physical system, consisting of a hub rotating around z-axis with a cantilevered flexible appendage (beam). The pinned-free boundary conditions are assumed.

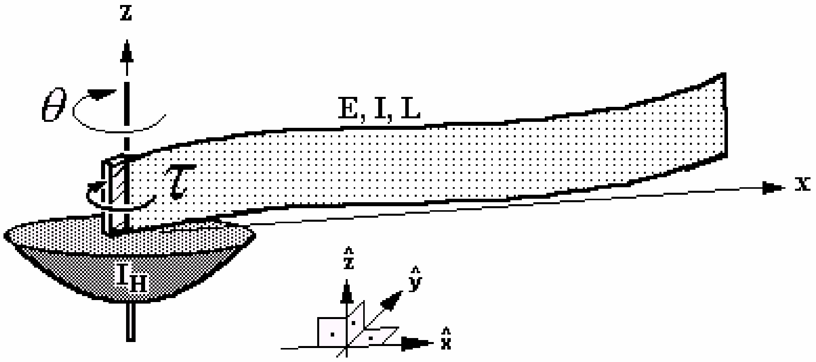

Figure 2. Uniform beam, hub and variables definitions

The equations of motion to the flexible beam are derived using the classical application of Hamilton´s Principle, considering the Euler-Bernoulli assumptions.

$$\begin{cases} EI\dfrac{\partial^4 y}{\partial x^4} + \rho\,\ddot{y} + \rho\,x\ddot{\theta} = \tau\delta'(0) \\ (I_H + I_B)\ddot{\theta} + \displaystyle\int_0^L \rho\,x\,\ddot{y}\,dx = \tau \end{cases} \qquad (1a,b)$$

The solution to flexible displacement of the beam, y, is assumed using a separation of variables, as follows.

$$y(x,t)=\sum_{i=1}^{n}\phi_i(x)\eta_i(t) \tag{2}$$

where n is the number of flexible modes included in the model, and η_i are the modal coordinates. The solution to the angular displacement is assumed as follows, considering the modal amplitudes to the beam rotational movement Θ_i according to Soares (1997).

$$\theta(t)=\sum_{i=1}^{n}\Theta_i\eta_i(t) \tag{3}$$

Substituting Equation (3) into Eq. (1b) we obtain:

$$\Theta_i=-\frac{\rho}{(I_H+I_B)}\int_0^L x\phi_i dx \tag{4}$$

The expressions of Equations (2) and (3) are inserted in the forced Eq. (1a) and then, we multiply each term by ϕ_j and integrate with respect to x from x=0 to x=L. Finally, using the orthogonality property of the modes, we obtain:

$$m_i\ddot{\eta}_i+k_i\eta_i=\tau\phi_i'(0) \tag{5}$$

with the coefficients

$$m_i=\int_0^L \rho\phi_i\phi_i dx+\int_0^L \rho x\phi_i dx \quad \text{and} \quad k_i=\int_0^L EI\frac{\partial^4\phi_i}{\partial x^4}\phi_i dx$$

The eigenfunctions and corresponding eigenvalues equations to pinned-free boundary conditions are presented as follow.

$$\phi_i(x)=A_i\left[\frac{\cosh(a_iL)}{\cos(a_iL)}\sin(a_iL)+\sinh(a_iL)\right] \quad \text{and} \quad \tan(a_iL)=\tanh(a_iL) \tag{6}$$

The numerical values of the system parameters, presented in Table 1, were inserted in the model and the results are presented below, according to Barbosa and Góes (2007).

Table 2 – Zeros, poles and frequencies associated – nonparametric methods.

Zeros	**poles**	
5 zeros (rd/s)	**6 poles (1/s)**	**frequency (Hz)**
-1.3e+10	-0.0 ± 16.0 i	0.4 Hz
-2.5 ± 11.2i	-0.0 ± 7.7 i	1.2 Hz
2.5 ± 11.2i	-0.0 ± 2.4 i	2.5 Hz

Table 3 – Frequencies of vibrations comparision

Methods	**1st mode**	**2nd mode**	**3rd mode**
Nonparametric	0.38 Hz (2.39 rd/s)	1.23 Hz (7.73 rd/s)	2.55 Hz (16.02 rd/s)
Autospectrum	-	1.1 Hz (6.91 rd/s)	2.2 Hz (13.82 rd/s)
FRF from tests	-	-	2.0 Hz (12.6 rd/s)

The frequencies associated to the first, second and third modes of vibration are now used to design a digital controller.

4. CIPID Controller

The controller named '*Compensated Inverse PID*' denoted CIPID was proposed in Gani (2003). The controller is designed by taking the effect of truncated modes which might cause the spillover effects. Hence the controller is designed to attenuate vibration modes, inserting damping to the closed-loop transfer function. Thus

$$G_{CIPID}(s) = \sum_{i=1}^{2} \frac{s\left(\frac{1}{k_D}\right)_i \left(s + \frac{k_P}{k_D}\right)_i}{s^2 + \left(\frac{k_P}{k_D}\right)_i s + \left(\frac{k_I}{k_D}\right)_i} \tag{7}$$

where

k_P , k_I and k_D are respectively the parameters of the PID, tuned to damp any of the i-th mode.

ω_i is the resonant frequency for the i-th mode.

Comparing with a typical second order system, we obtain

$$\left(\frac{k_I}{k_D}\right)_i = \omega_i^2 , \tag{8}$$

$$\left(\frac{k_P}{k_D}\right)_i = 2\varsigma_i \omega_i \tag{9}$$

The angular frequencies due to the second and third modes of vibration of the flexible beam are presented below, according to Table 3. The objective is to attenuate the amplitude of these two modes of vibration.

$$\omega_1 = 6.91 rd/s \quad \text{and} \quad \omega_2 = 13.82 rd/s$$

The value of k_D is chosen to be 1. The parameter k_I is taken from Eq. (8) and k_P is adjusted by taking different value of ς_i in Eq. (9). So we obtain the results presented in Table 4.

Table 4 – Controller results

1st CIPID Controller	2nd CIPID Controller
Parameters: k_{D1}=1.00 k_{I1}=39.48 k_{P1} = 6.28	Parameters: k_{D2}=1.00 k_{I2}=191.01 k_{P2} = 2.76
Transfer Function: s^2 + 6.2832 s G2(s) = ------------------------------ s^2 + 6.2832 s + 39.4784	Transfer Function: s^2 + 2.7646 s G3(s)= ----------------------------------- s^2 + 2.7646 s + 191.0755
zeros: 0 -6.2832 Poles: -3.1416 + 5.4414i -3.1416 - 5.4414i	zeros: 0 -2.7646 Poles: -1.3823 +13.7537i -1.3823 -13.7537i

All of the zero-poles of the plant, flexible beam and hub SRV-02 are plotted on s-plane (Laplace), showed in Figure bellow.

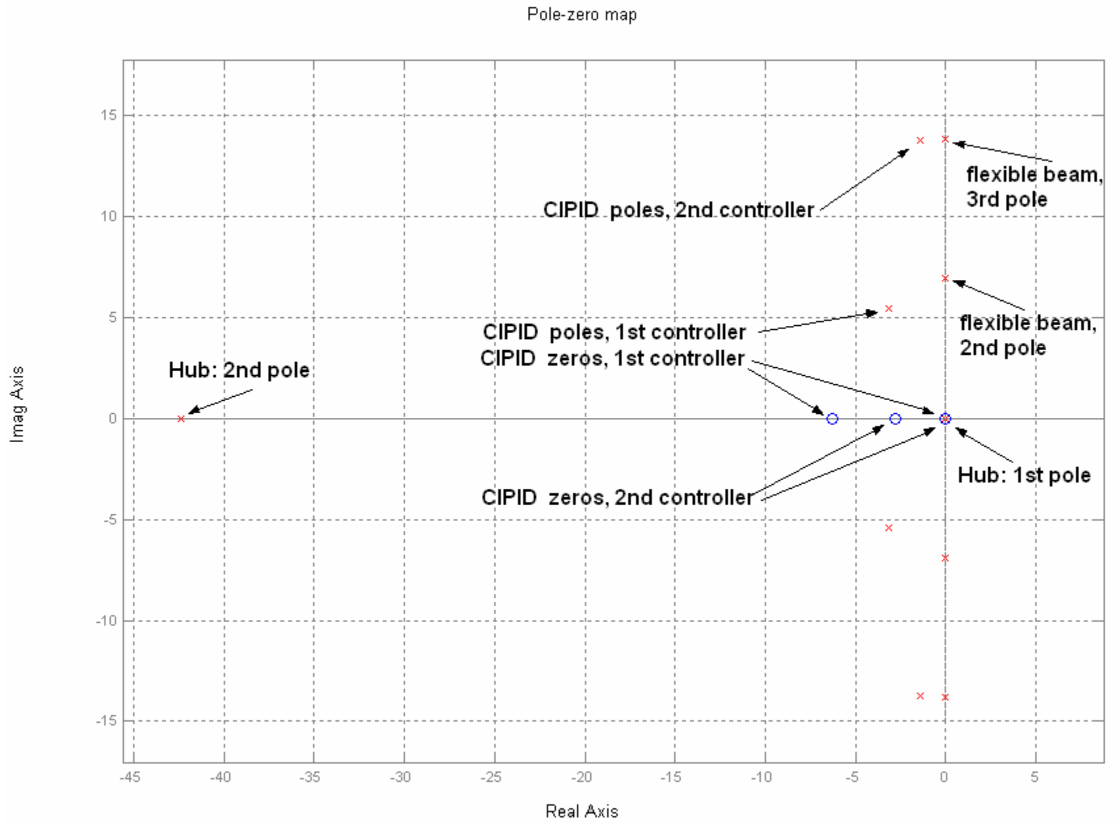

Figure 3. Open-loop zero-poles of plant and controller.

The pole due to A/D and D/A converters does not appear in s-plane of Fig. 3 because is located at s=-2/T=-400 rd/s and certainly its effects on dynamic system is irrelevant. The transfer function $G_{CIPID}(s)$ was implemented in the WinCon digital controller, as shown in Fig. 4.

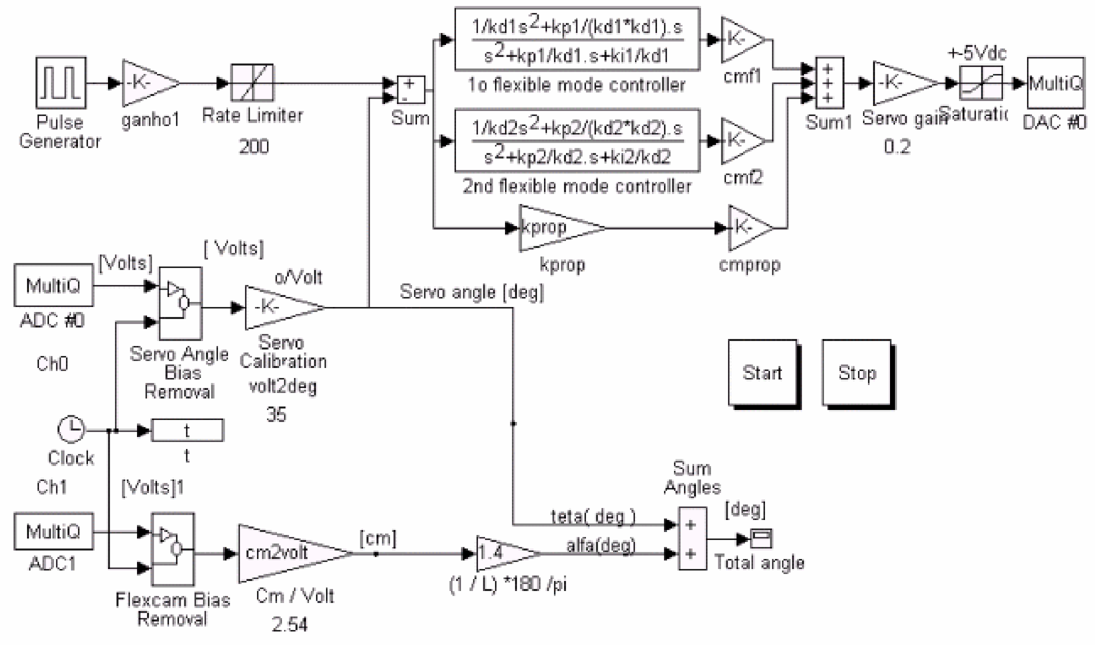

Figure 4. CIPID controller implemented in WinCon

5. RESULTS COMPARISION

The Figures below show the results obtained from action of controller CIPID and a simple Proportional controller. The Fig. 5 shows clearly the minimization of amplitudes of oscillations during its movement to a desired angular position (10 degrees). In the Fig. 6, it can be observed a short rise time using CIPID controller compared to the rise time from proportional action. The overshot also is better using CIPID, as can be verified in the step response.

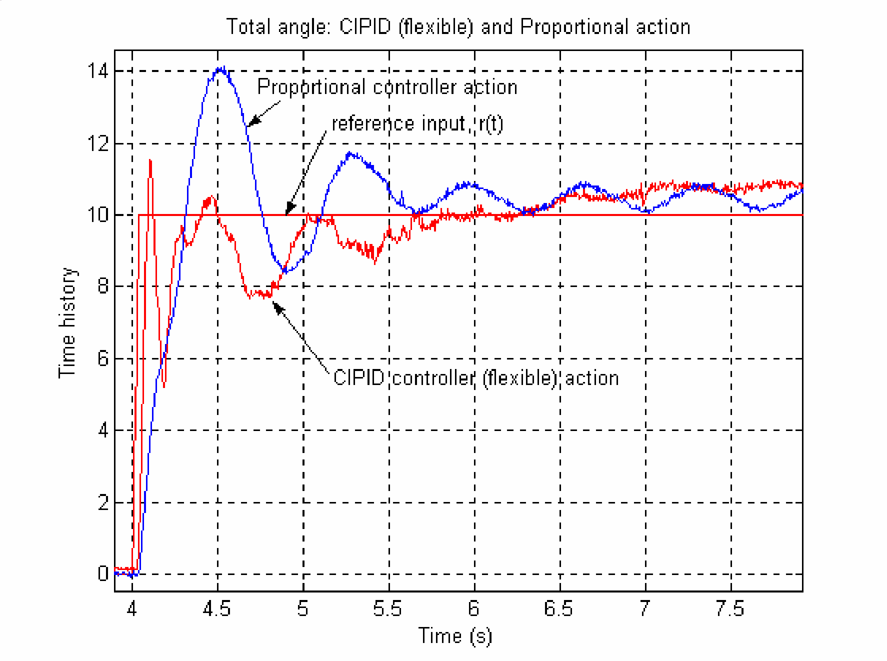

Figure 5. Total angle: CIPID (flexible) and Proportional action

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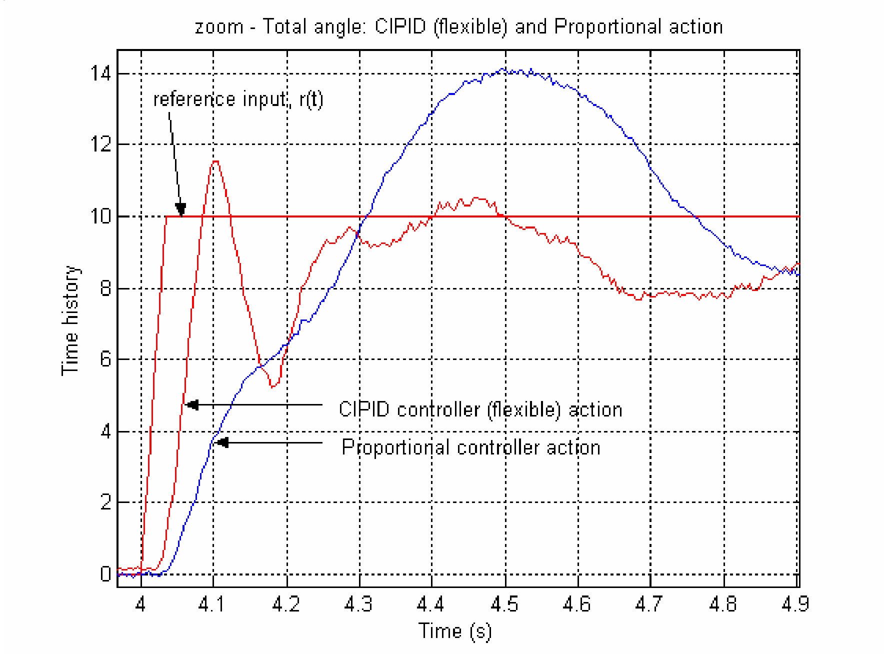

Figure 6. Zoom - Total angle: CIPID (flexible) and Proportional action

The Figure 7 shows the contribution of each controller, from second and third mode controller. The Fig. 8 presents a zoom of Fig. 7 to show the contribution of each controller that forces acceleration on the angular velocity of the hub.

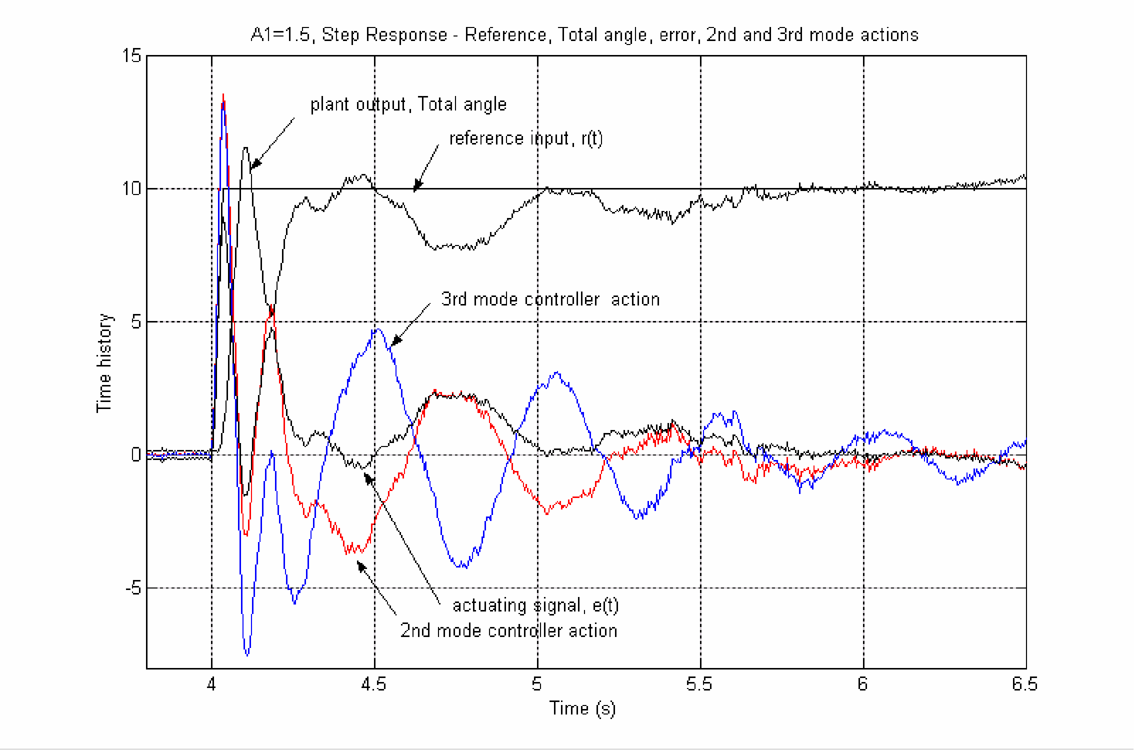

Figure 7. Step response: CIPID controller

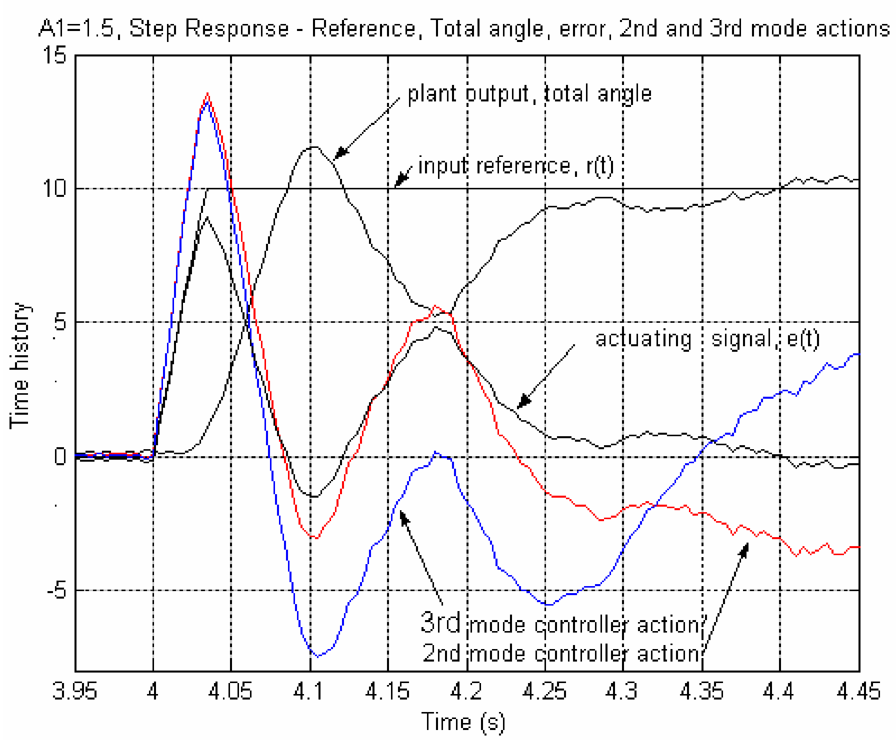

Figure 8. Zoom - Step response: CIPID controller

6. RECOMMENDATIONS

During the use of FLEXCAM is recommended the camera be aligned in directions that do not have source lights, because this can mask the signals. Frequently is recommended the calibration to the FLEXCAM to obtain the actual camera gain. Verify the cables on the back side of the FLEXCAM, they must be free in such way that does not hold the rotating movement of the hub.

The sample period shall be chosen as fast as the dominant poles (4 to 20 times due to sampling frequency) to be controlled or to identification process.

The best tuning of CIPID controller depends on precision of frequency determined. So, the use of precision equipment (dynamic analyzer) is recommended.

The choice of location to the source light must be done with care, because it can superimpose two modes of vibration. In Miu (1991) "*If the location of the sensor is exactly at the node,* a_r *will be identically zero and the resulting transfer zero will superimpose on the second system pole. This pole-zero cancellation has the simple physical meaning that the second mode has become unobservable*".

7. CONCLUSIONS

The main conclusion in this work is that the designed controller damped the second and third vibrations modes of the flexible beam, during its movement to a desired angular position. In this sense, it can be recommended to be applied in controllers to liquid propellant rocket motors, subjected to external forces.

This work presented the design control and controller validation, via practical results, showing the minimization of amplitudes of oscillation, typically encountered in vibrations of flexible structures.

The FLEXCAM Quanser System was fundamental to the modeling, identification, control implementation and validation process of the controller, as can seen trough this text. The flexibility of using Simulink/Matlab on this test bed is very interesting to study and design digital control systems.

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