University of Campinas

Department of Mechanical Engineering

Aerospace Technology Congress

Modelling and control of a long flexible guyed structure

Paulo Kurka, Paola G Ramos, Jaime Izuka, Luis Teixeira,

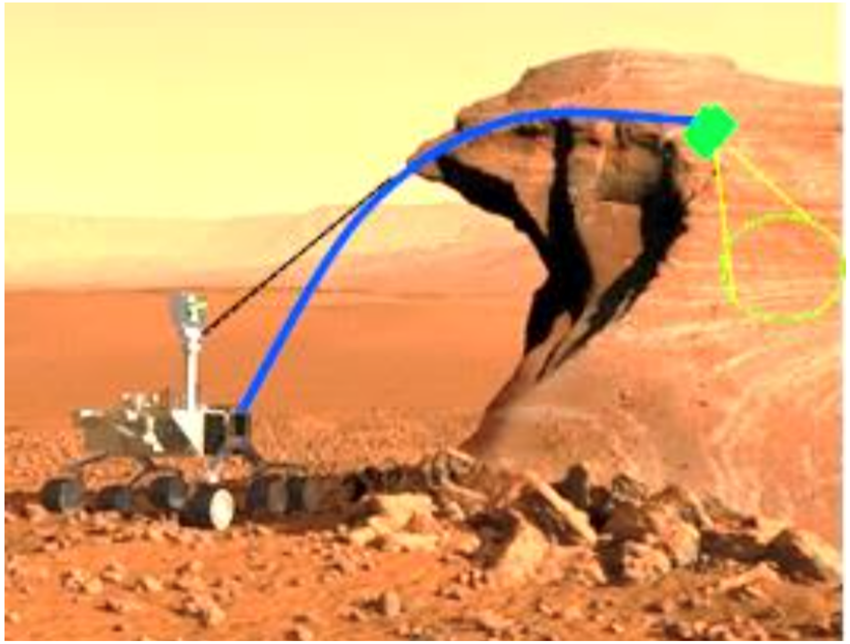
October 2016

Outline

1. Introduction
2. Analitical and numerical models of the beam
3. Design of the controller
4. Experimental setup
5. Conclusions
6. Acknowledgement

Introduction

Application of the deformed beam model



Introduction

Design challenges

Practical dynamic model of the beam

- Solution: Low order finite element adapted to the static deformation model of the beam

Introduction

Design challenges

Design of controller based on the actuation of a pulling cable and a displacement sensor.

- Solution: cable attached to a step motor, optical displacement sensor, H_∞ control based on the finite element low order model

Introduction

Design challenges

Verification of proposed strategy

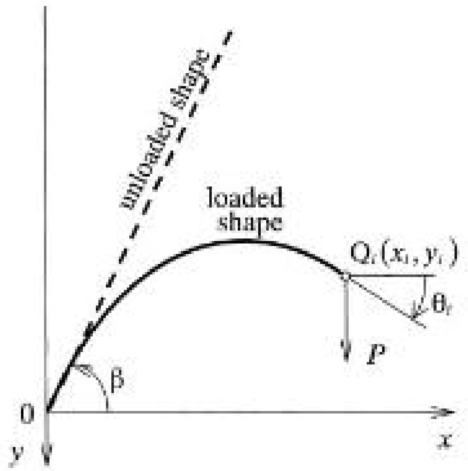
- Solution: Comparison of numerical and experimental tests.

Introduction

Models of large deformation of beams found in the litterature

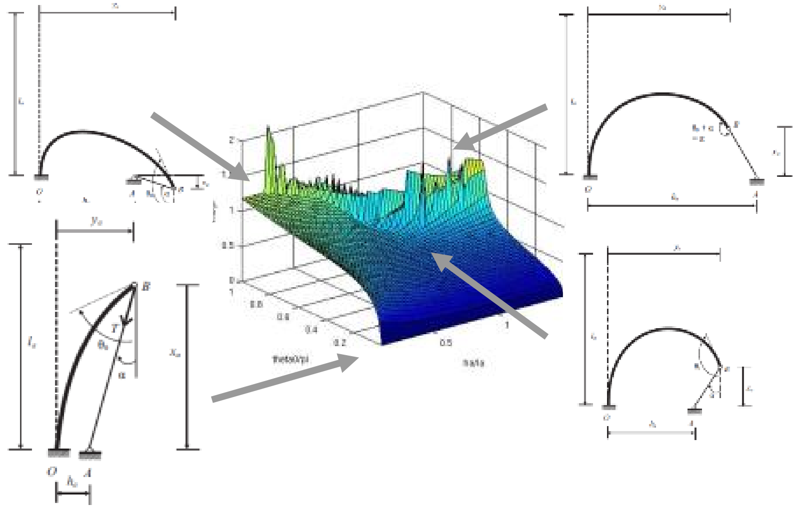
Atsumi Ohtsuki.

"Analysis of the characteristics of fishing rods based on the large deformation theory".



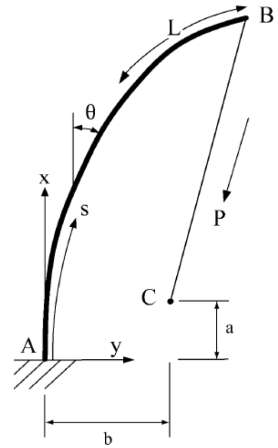
Yau, JD

Solution of large deflection for a guyed cantilever column pulled by an inclination cable.



Holland, 2006

Vibration and large deflection of cantilever elastic compressed by angled cable

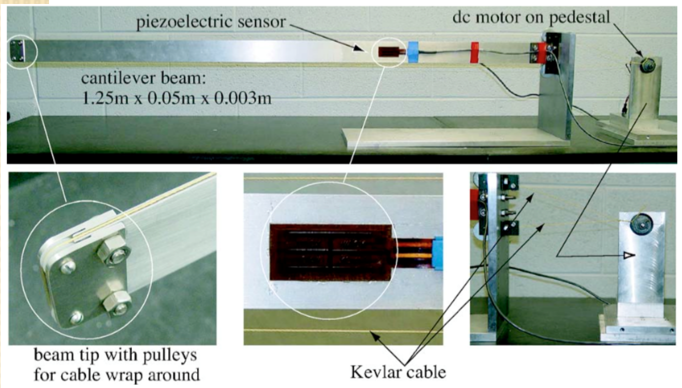


Introduction

Vibration control of long beams found in the litterature

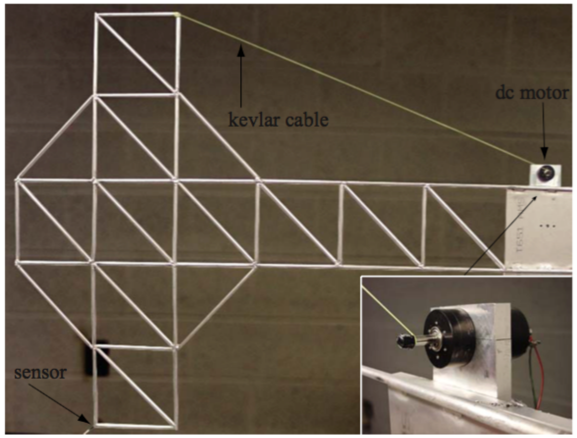
Nudehi et al, 2006

A compressive buckling-type end load is used for active vibration control of a cantilever beam, which is fitted with a cable mechanism and motor for applying the end force.



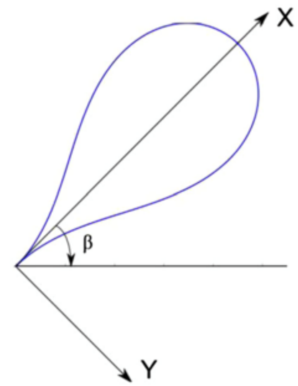
Issa J et al, 2010

To use of cable tension for active vibration control in frame structures. They utilized the first two modes of the frame, which correspond to first mode of bending in the xz plane and simple torsion about the x axis, to calculate the controller. They used a dc motor and cable to transmit the control force to the structure.



Sharma et al, 2014

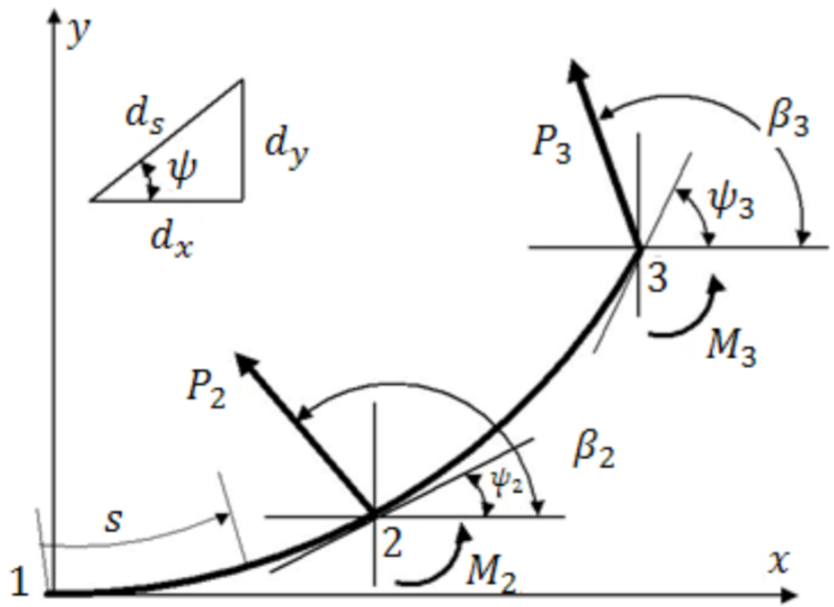
An active vibration control used for active damping in a heavy pinched loop from an H∞ algorithm and weigth functions.



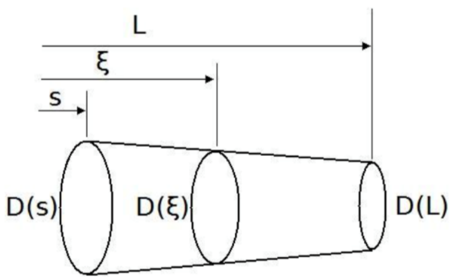
Analitical and numerical models of the beam

Analitical model of static deformation

The bending moment is proportional to the change in curvature caused by the applied loads, according to the classical Bernoulli-Euler theory for the deflection of beams.

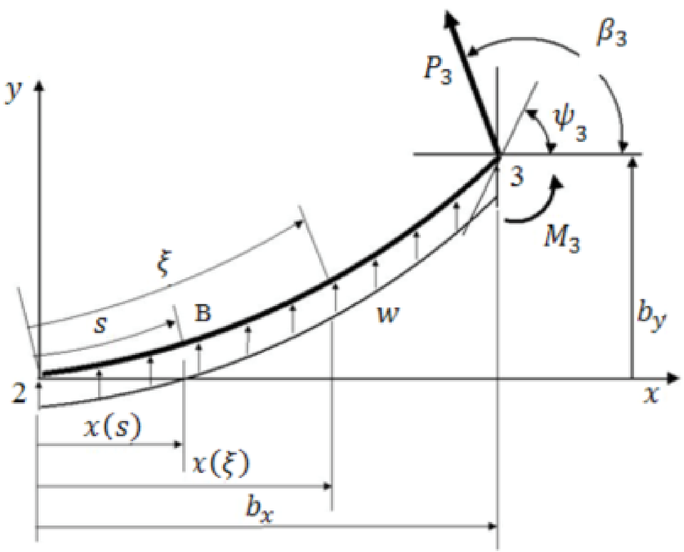


$$\frac{M}{EI} = \frac{d\psi}{ds}.$$



Analitical and numerical models of the beam

Analitical model of static deformation



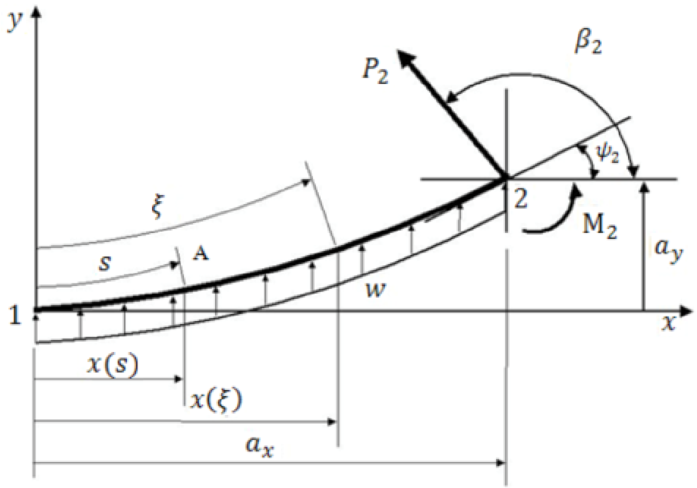
Analysis of section 2-3

Differential equation

$$\frac{d^2\psi}{du^2} - \frac{4\Delta D_2}{(1-\Delta D_2 u)}\frac{D\psi}{du} = \frac{-L_2^2 P_3 sin(\beta_3 - \psi)}{EI_2(1-\Delta D_2 u)^4} + \frac{\rho\pi g L_2^3}{12EI_2(1-\Delta D_2 u)^4}\{D_2^2 + D_2D_3 + D_3^2 - 3D_2^2 u + 3(D_2^2 - D_2D_3)u^2 - (D_2^2 - 2D_2D_3 + D_3^2)u^3\},$$

Analitical and numerical models of the beam

Analitical model of static deformation



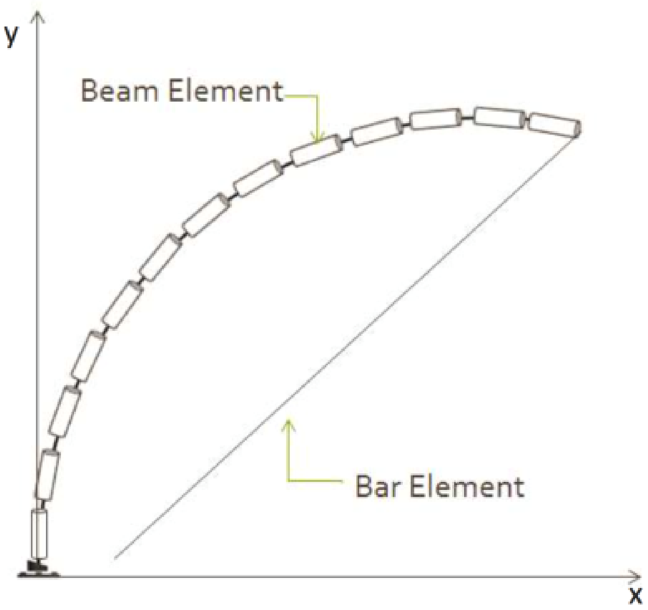
Analysis of section 1-2

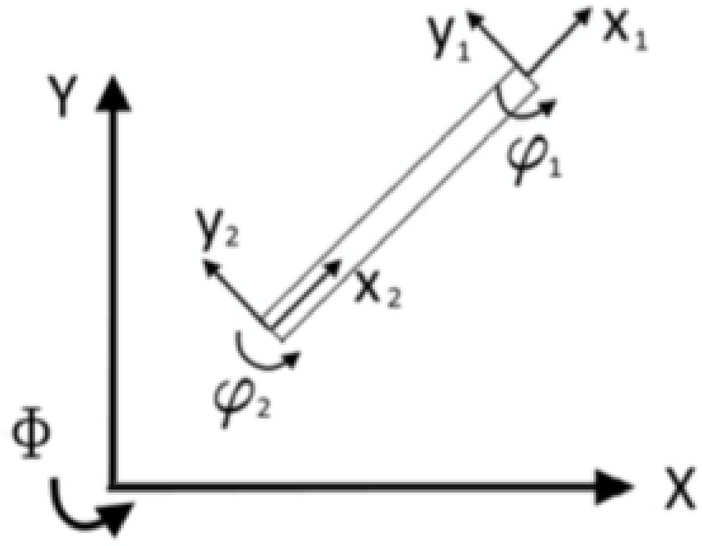
Differential equation

$$\frac{d^2\psi}{du^2}-\frac{4\Delta D_1}{(1-\Delta D_1 u)}\frac{d\psi}{du}=\frac{L_1^2}{EI_1(1-\Delta D_1\, u\,)^4}(-P_3\sin(\beta_3-\psi)+P_2\sin(\beta_2-\psi))-\frac{\rho\pi g L_1^3}{12EI_1(1-\Delta D_1\, u\,)^4}\{D_1^2+D_1D_2+D_1^2-3D_1^2u+3(D_1^2-D_1D_2)u^2-(D_1^2-2D_1D_2+D_2^2)u^3\}.$$

Analitical and numerical models of the beam

Low order adaptive finite element model



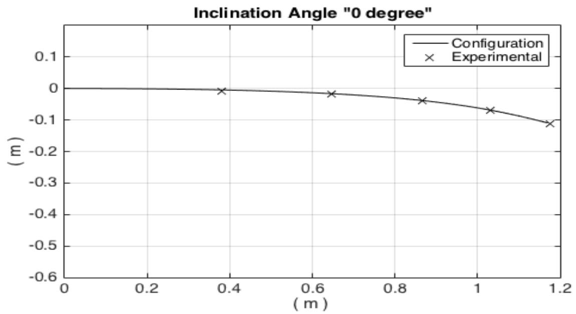


Low order model adapted to static displacement

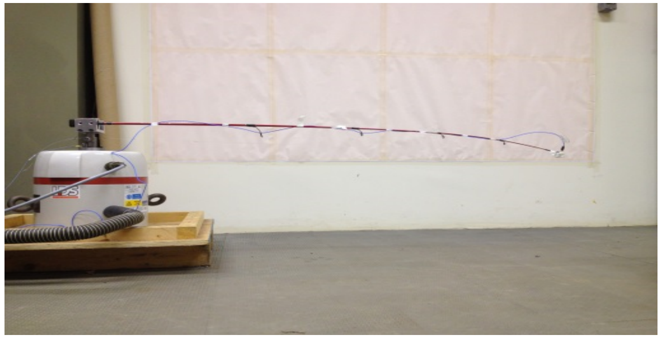
Analitical and numerical models of the beam

Experimental validation of adaptive low order model

Static deformation theoretical and experimental results.

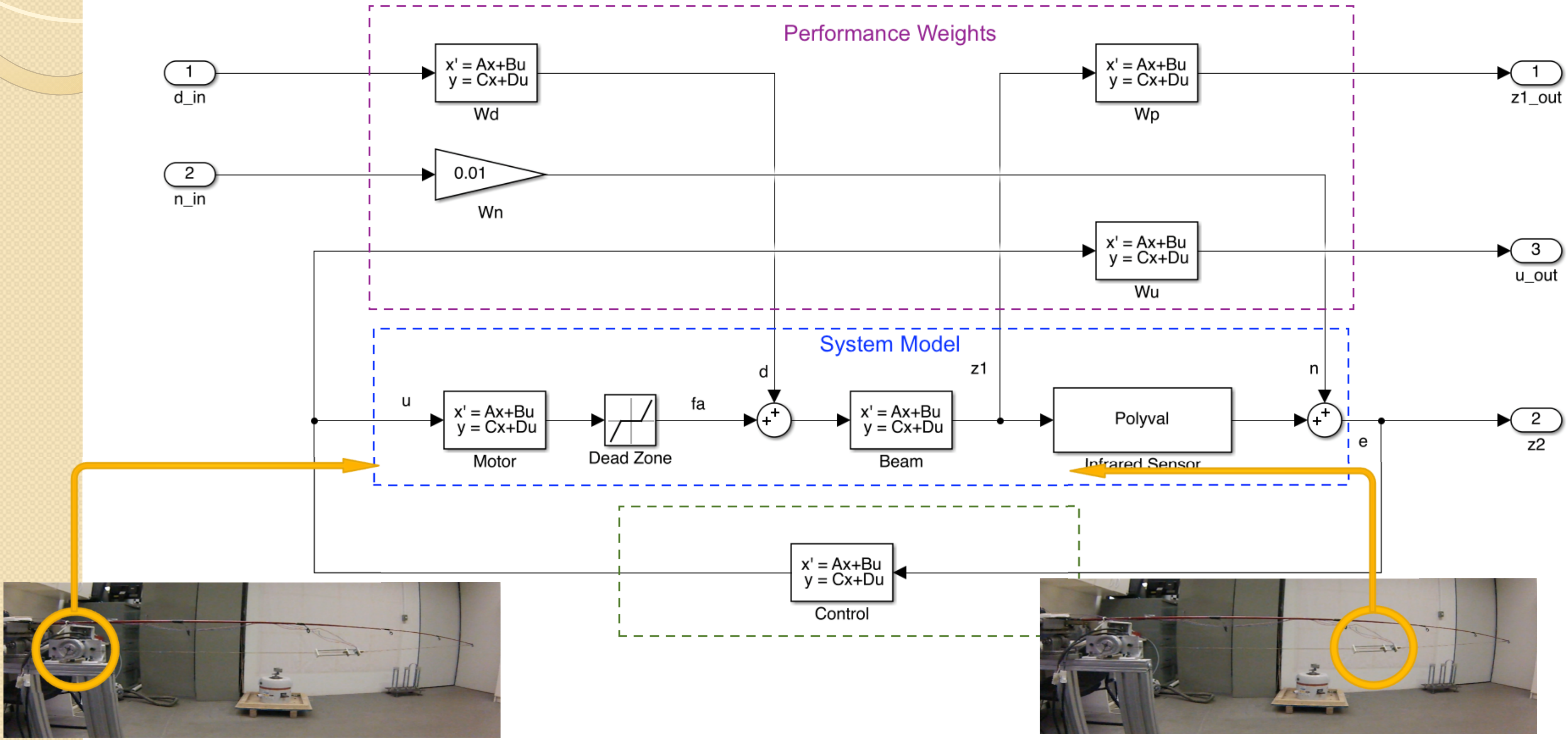


Experimental test setup

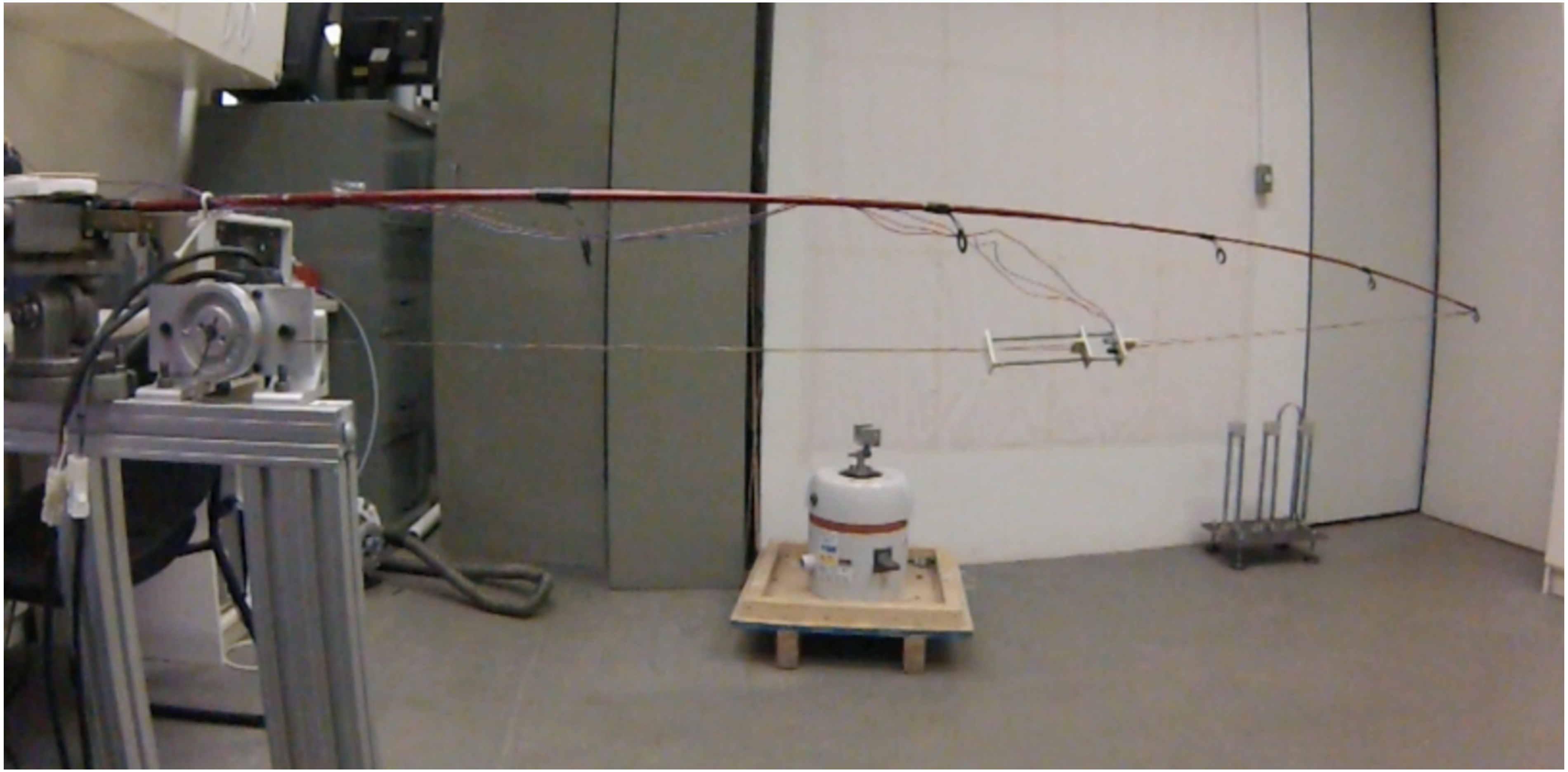


Natural frequencies (Hz)	1	2	3	4	5
Numerically calculated from the finite element model.	2.9	13.7	30.1	58.0	96.8
Obtained from impulse input test.	3.6	12.0	26.6	53.0	90.5
Obtained from shaker frequency sweep test.	-	10.5	26	55	95

Design of the Controller

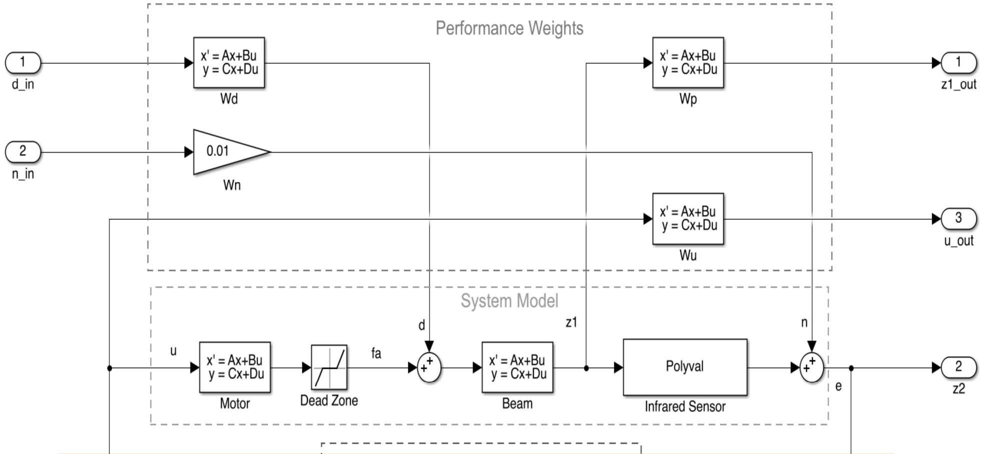


Design of the Controller



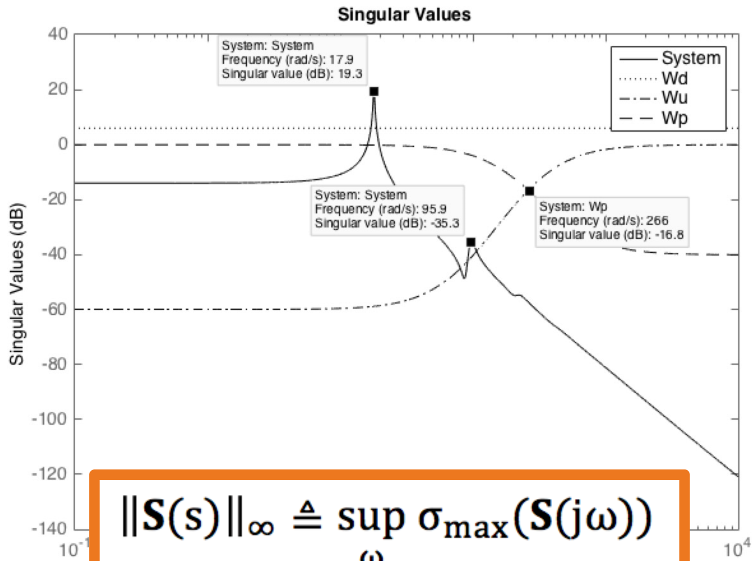
Design of the Controller

Mathematic model of the general system



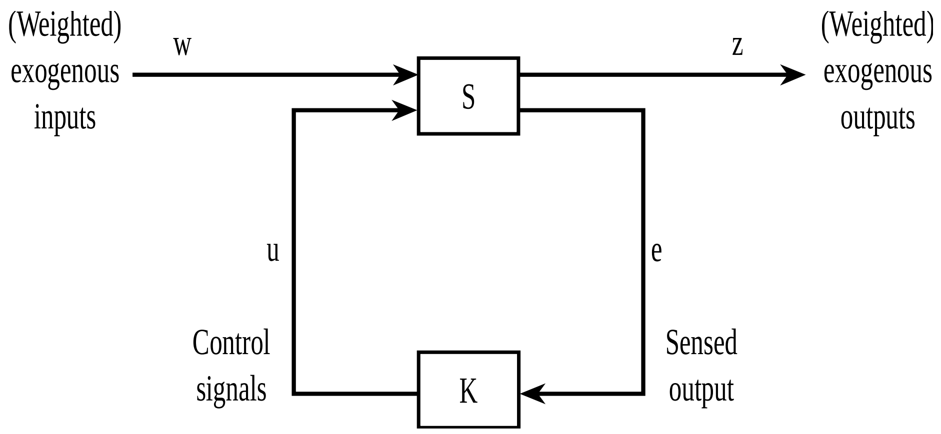
$$
\begin{aligned}
\dot{v}(t) &= Av(t) + B_w w(t) + B_u u(t),\\
z(t) &= C_1 v(t) + D_{1w} w(t) + D_{1u} u(t),\\
e(t) &= C_2 v(t) + D_{2w} w(t) + D_{2u} u(t).
\end{aligned}
$$

Infinite norm is an estimation of the eigenvalue of the system with largest modal contribution



$$\|S(s)\|_\infty \triangleq \sup_{\omega} \sigma_{max}(S(j\omega))$$

Design of the Controller



$$\begin{bmatrix} \boldsymbol{z} \\ \mathbf{e} \end{bmatrix} = \mathbf{S} \begin{bmatrix} \boldsymbol{w} \\ \mathbf{u} \end{bmatrix} = \begin{bmatrix} \mathbf{S_{zw}} & \mathbf{S_{zu}} \\ \mathbf{S_{ew}} & \mathbf{S_{eu}} \end{bmatrix} \begin{bmatrix} \boldsymbol{w} \\ \mathbf{u} \end{bmatrix}.$$

$$\mathbf{u} = \mathbf{K}\mathbf{e}.$$

$$\mathbf{z} = \mathbf{T_{zw}}\boldsymbol{w}.$$

$$\mathbf{u} = \mathbf{K}(\mathbf{I} - \mathbf{S_{eu}}\mathbf{K})^{-1}\mathbf{S_{ew}}\boldsymbol{w}.$$

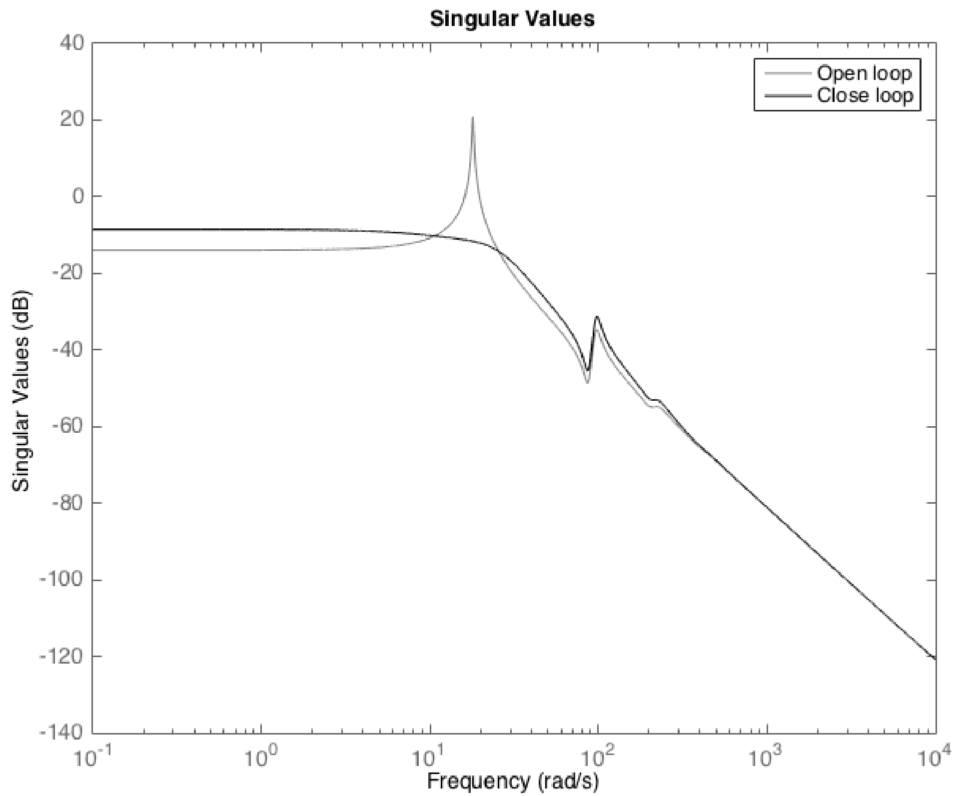
$$\mathbf{T_{zw}} = \mathbf{S_{zw}} + \mathbf{S_{zu}}\mathbf{K}(\mathbf{I} - \mathbf{S_{eu}}\mathbf{K})^{-1}\mathbf{S_{ew}}$$

Design of the Controller

The controller has the form

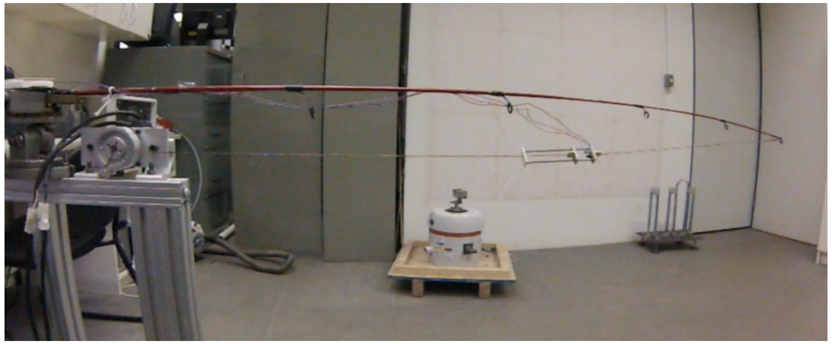
$$\dot{\boldsymbol{x}}_{\boldsymbol{K}} = \mathbf{A}_{\mathbf{K}}\boldsymbol{x}_{\boldsymbol{K}} + \boldsymbol{B}_{\mathbf{K}}\mathrm{e},$$

$$\mathrm{u} = \boldsymbol{C}_{\boldsymbol{K}}\boldsymbol{x}_{\boldsymbol{K}}.$$



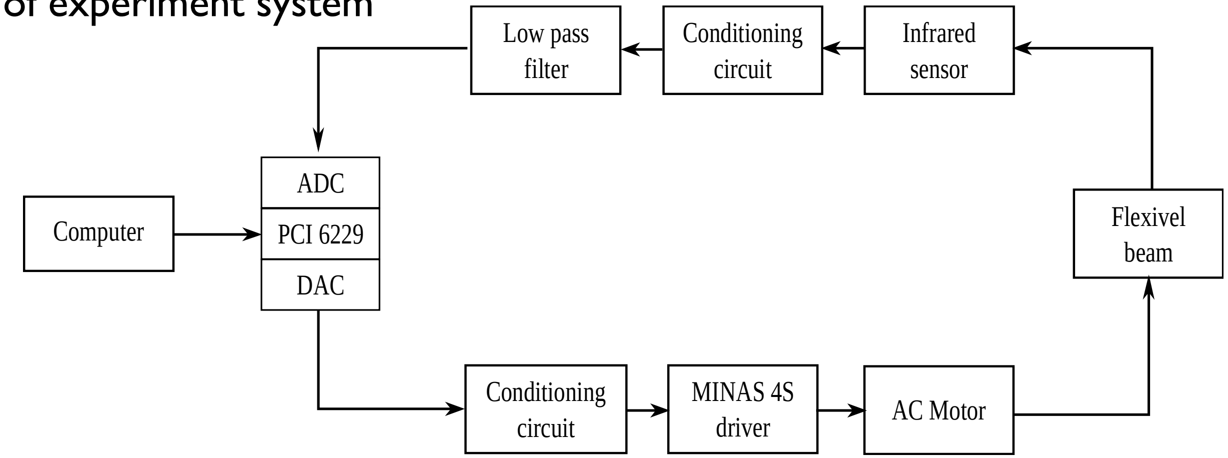
Experimental Setup

Fishing rod length	• 1.185 (m)
Cross section diameter 1	• 0.0088 (m)
Cross section diameter 2	• 0.002 (m)
Modulus of elasticity	• 42 (GPa)
Density	• 2.000(Kg/m^3)



Experimental setup for the vibration control of a flexible beam using infrared sensor

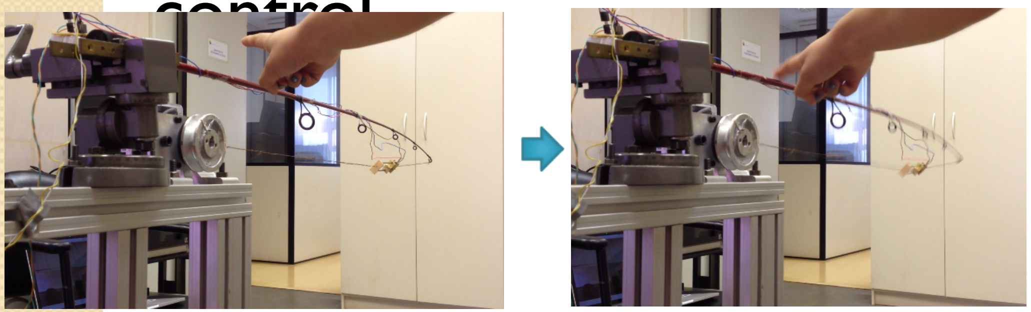
Flow chart of experiment system



Experimental Setup

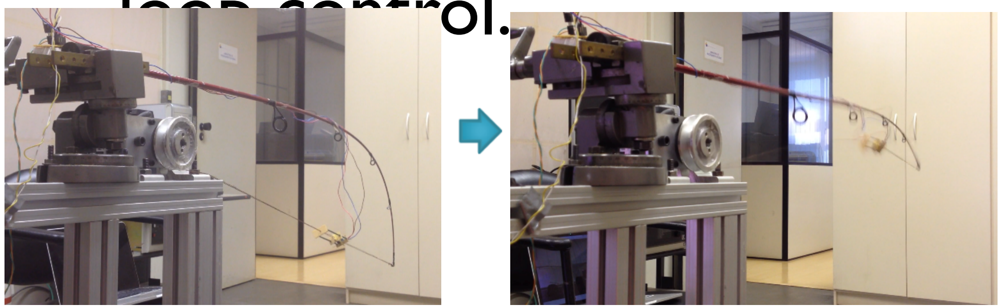
Experiment 1

- Static deformation of beam
- Impulsive disturbance force open and closed loop control.

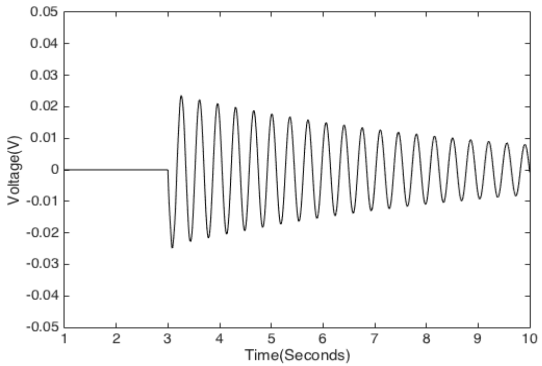
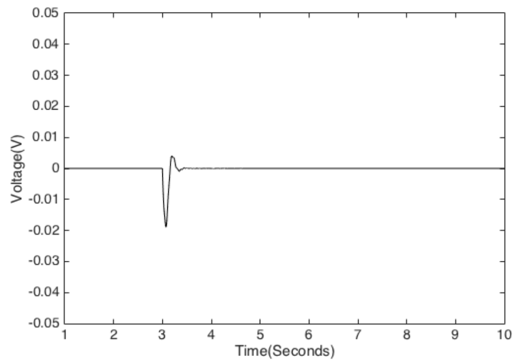
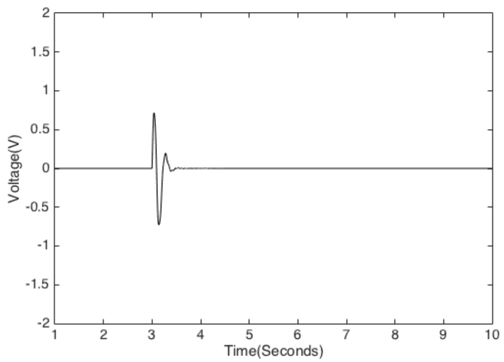
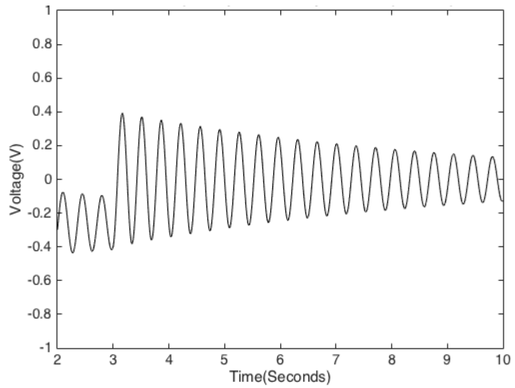
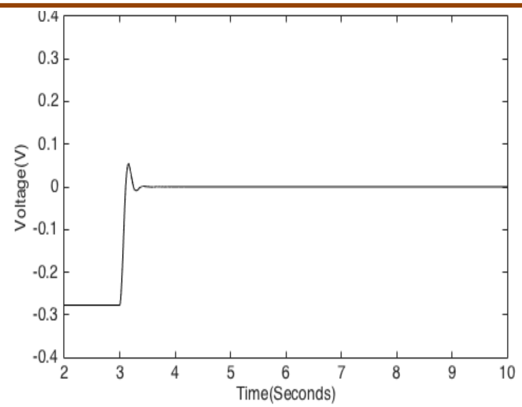
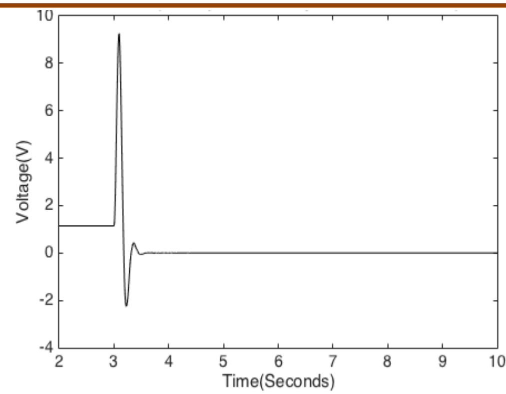


Experiment 2

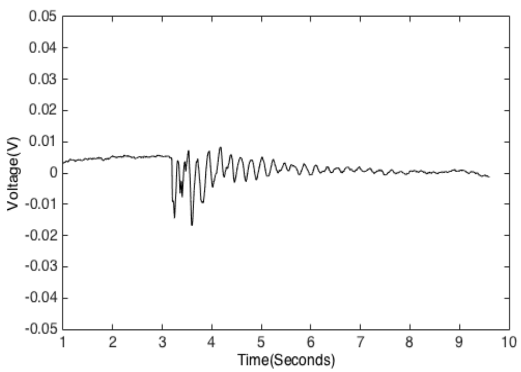
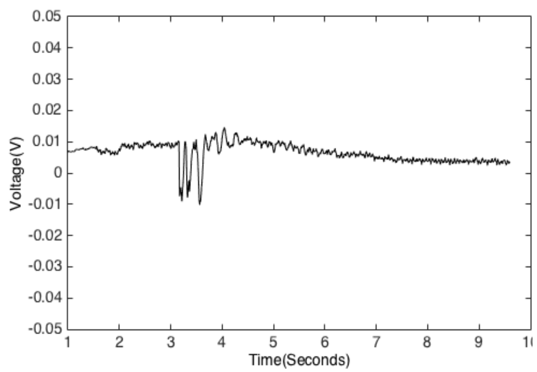
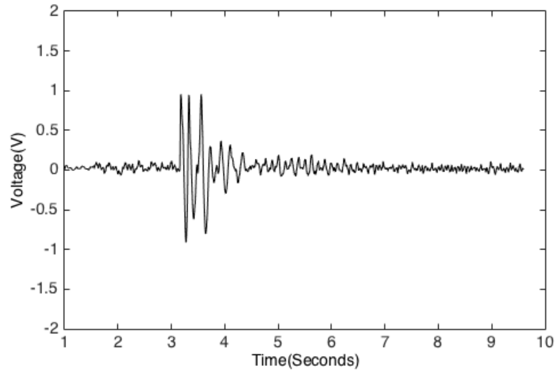
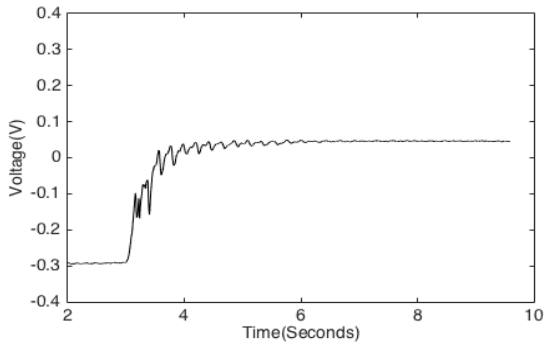
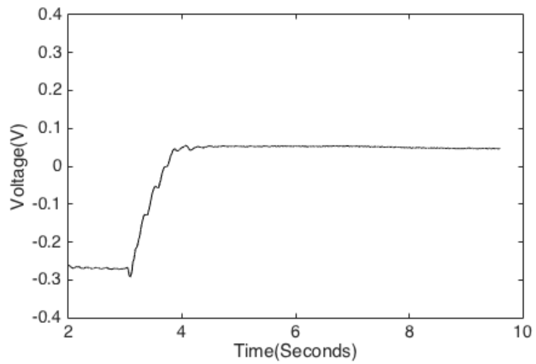
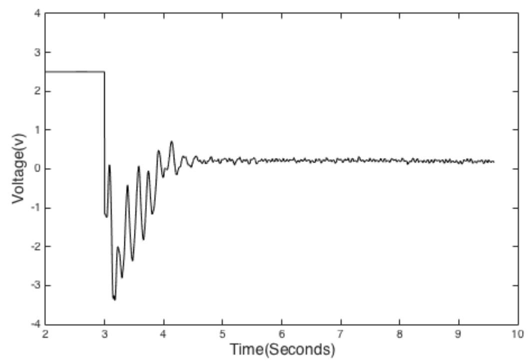
- Static deformation of beam
- Step deformation and relaxation open and closed loop control.



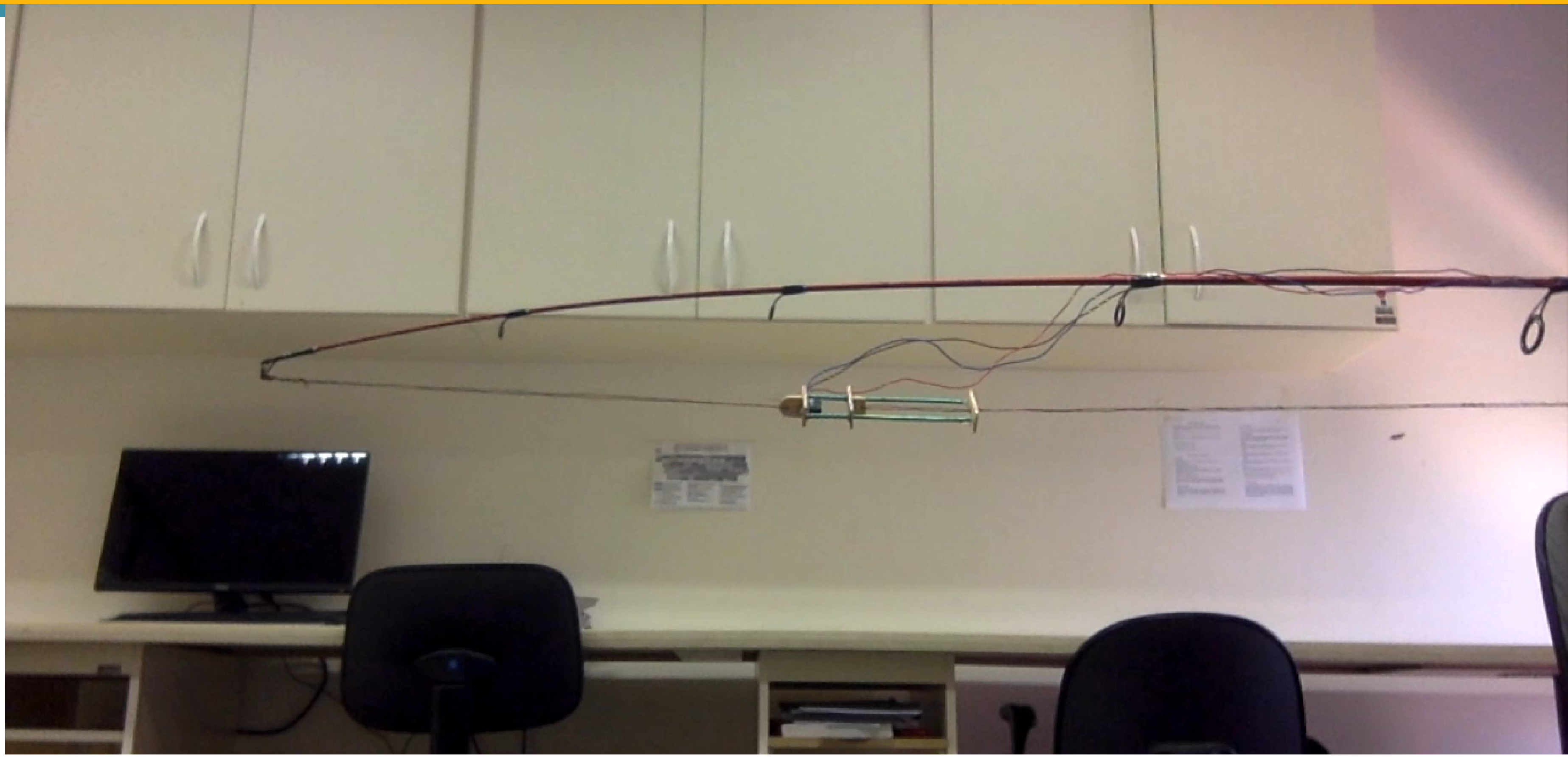
Simulation Results

	Sensor output signal in open loop	Sensor output signal in closed loop	Motor input signal in closed loop
Experiment 1			
Experiment 2			

Experimental Results

	Sensor output signal in open loop	Sensor output signal in closed loop	Motor input signal in closed loop
Impulse input			
Step input			

Video



Discussion of Results

- Good agreement between analytical and experimental results.
- The control strategy produces the desired results of attenuation of vibration.
- The single cable configuration does not allow the control of vibration in the transversal plane of the beam.
- The displacement sensor used interfered in the experimental results.

Conclusions

- The work considered the construction of an analytical model of a long, light weighted and flexible beam with variable cross section, pulled by a cable attached to its tip and base.
- An efficient numerical model of the deformed beam allows to calculate the parameters of a control, based on its natural modes and frequencies of vibration.
- The proposed control strategy was successfully used to attenuate the vibrations of the beam in both simulation and experimental tests.

Acknowledgements

CNPq
Conselho Nacional de Desenvolvimento
Científico e Tecnológico

The authors wish to thank Conselho Nacional de Desenvolvimento Científico (CNPq), Brazilian Research Support Foundations, for sponsoring this work.

TACK FÖR DIN UPPMÄRKSAMHET!

THANK YOU FOR YOUR ATTENTION!