Sequential Estimation of Bending Stiffness and Damping Parameters of Transmission Line Conductors

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Identificación de Propiedades de Materiales por Métodos Inversos – Mar del Plata

OUTLINE

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INTRODUCTION

❑ GENERAL OVERVIEW

- Wind-induced vibrations on transmission line conductors (TLC) caused by vortex-shedding (Rawlins, 1979; Hagedorn, 1982; Meynen et al., 2005)

- Main features: frequency range 5 Hz – 60 Hz and amplitude range 0.01 *D* – 1*D* (*D* denotes de conductor diameter 15 mm – 30 mm)

- Well-known galloping vibrations of very low frequencies (below 1 Hz), caused by aerodynamic instabilities, are not addressed here

- TLC are composed of wires helically wrapped around a central core

INTRODUCTION

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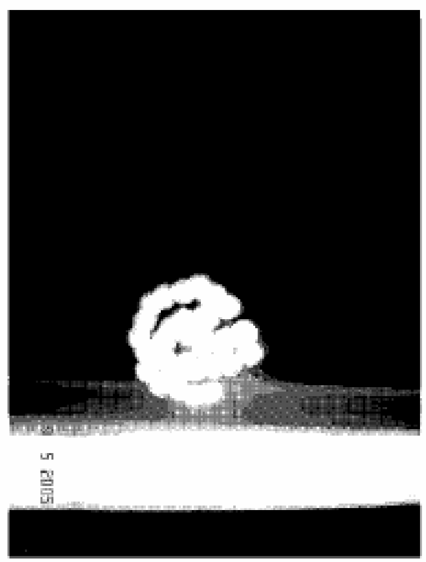
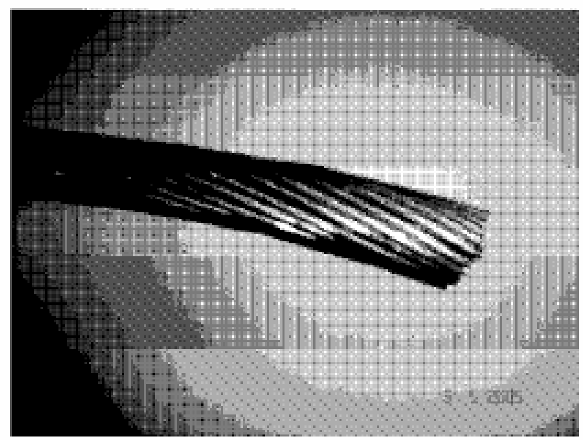
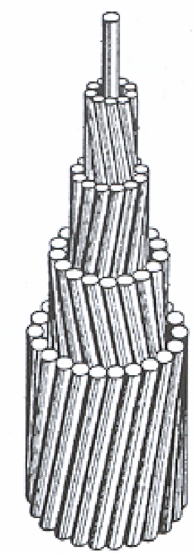
❑ GENERAL OVERVIEW (cont.)

Aluminum **C**onductor **S**teel **R**einforced (ACSR Conductors)

Layers of aluminum wires helically wrapped around a central steel core







photograph and sketch of a typical TLC

INTRODUCTION

- GENERAL OVERVIEW (cont.)
  - TLC are subjected to very high tensile loads (20 kN – 40 kN) and clamped at the suspension towers
  - Frequency spectrum almost continuous; two natural frequencies separated by approximately 0.1 Hz – 0.3 Hz
  - Vortex-shedding frequency almost always close to one of the natural frequencies of TLC
  - Field and laboratory measurements indicate that TLC have low internal damping, mainly in the frequency range 0 – 30 Hz
  - Main damping mechanisms are: (i) interstrand friction among the wires (structural damping); (ii) aerodynamic damping and (iii) material damping

INTRODUCTION

- GENERAL OVERVIEW (cont.)

  - Wind-induced vibrations on TLC occur for wind speeds in the range 1 m/s to 10 m/s
  - Reynolds number lies in the sub-critical range (10^3 to 10^4)
  - Vortex-shedding across stationary bluff bodies in this Reynolds range has a well defined frequency, expressed in terms of a nondimensional parameter called Strouhal number St
  - For smooth and circular cylinders $St = 0.2$
  - For TLC, field measurements indicate that $0.185 < St < 0.22$ (Kraus and Hagedorn, 1991; Rao, 1995)

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- GENERAL OVERVIEW (cont.)

  - Vortex-shedding across a stationary cylinder is not yet completely understood [Williamson and Govardhan (2004)]
  - Concerning wind-induced vibrations on TLC, other complicating factors come into picture
    - (i) the dynamic interaction between wind flow and TLC vibrations;
    - (ii) the turbulent nature of wind flow;
    - (iii) TLC structural vibrations due to lack of information regarding the bending stiffness and damping parameters of TLC

- MOTIVATION

  - Wind-induced vibrations are a critical problem for safety and reliability of transmission lines

  - Bending strains and stresses caused by such vibrations may cause fatigue damages of conductor wires

INTRODUCTION

- MOTIVATION (cont.)

  - Fatigue damages may lead to complete rupture of the conductor and, consequently, to the interruption on the supply of electric energy

  - Therefore, the understanding of wind-induced vibrations on TLC is a relevant issue

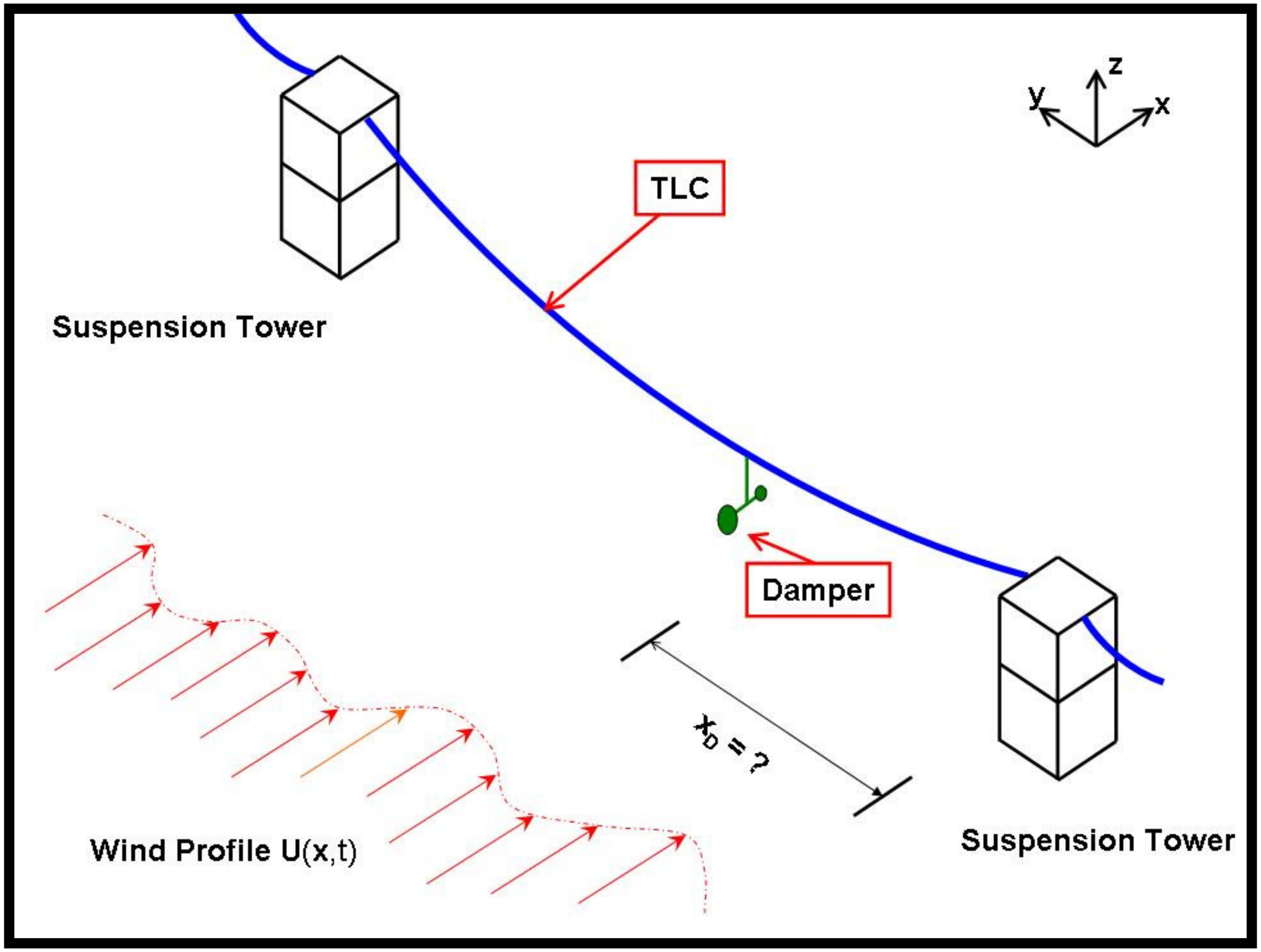
  - Accurate predictions of such vibrations depend, of course, on the knowledge of stiffness and damping properties of TLC

- OBJECTIVE

  - Estimate the bending stiffness and damping parameters of a typical TLC based on inverse analysis

INTRODUCTION

❑ALL IN ALL, WHAT IS THE SYSTEM UNDER ANALYSIS ?



INTRODUCTION

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- WHAT IS THE OBJECTIVE OF THIS PROJECT ?
  - To reduce the vibration levels of TLC.
- WHAT ARE THE TARGETS ?
  - Target 1 : Determine the bending stiffness and the damping parameters of transmission line cables.
  - Target 2: Determine a suitable mathematical model for the StockBridge Damper.

INTRODUCTION

- WHAT ARE THE TARGETS ? (Cont.)

  - Target 3 : Analyze the fluid Structure Interaction.

  - Target 4 :Determine the optimum number of StockBridge Dampers as well as their optimal positions to reduce the amplitude of vibrations of TLC when the system is excited by wind.

INTRODUCTION

- WHAT IS THIS PRESENTATION ABOUT ?

  - Target 1: Estimation of the bending stiffness and damping parameters of transmission line cables

- WHAT ARE THE MAIN ISSUES CONCERNING THIS TARGET ?

  - Which model should we use ?

  - Which damping model should we use ?

  - How do we estimate the model parameters ?

BRIEF LITERATURE REVIEW

- The majority of theoretical models proposed to predict wind-induced vibrations idealizes TLC structure as a continuous (Claren and Diana, 1969; Dhotarad et al., 1978; Hagedorn et al., 1987; Diana et al., 2000; Vecchiarelli et al., 2000; Barbieri et al., 2004; Meynen et al., 2005)

- The simplest models idealize TLC as homogeneous taut strings without bending stiffness; more complex ones idealize TLC as homogeneous elastic beams with structural damping being represented as of hysteretic kind

- Authors rarely report the values adopted for the bending stiffness and damping parameters; there is a current lack in the literature about mechanical properties of typical TLC

- Most of data available refers to the power dissipated by TLC during standard self-damping tests on a laboratory span. Discrepancy among measurements performed by different authors may reach 100%!

- Authors rarely compare their theoretical predictions against experimental measurements (Claren and Diana, 1969; Diana et al., 2000; Barbieri et al., 2004)

BRIEF LITERATURE REVIEW

- Few works have attempted to account for the helicoidal structure of TLC and all damping mechanisms, most authors adopts a constant value for the bending stiffness

- Recommendation is to choose such the bending stiffness as a constant value between the minimum and maximum values [CIGRÉ (1989)]
  - minimum value (EI_{min}) is obtained by considering TLC as a bundle of individual wires free to move relative to each other
  - maximum value (EI_{max}) is obtained by considering TLC a bundle of individual wires unable to move relative to each other due to contact pressure

- Nevertheless, Papailiou (1997) presented a more sophisticated model which accounts for helicoidal geometry of the wires, interlayer friction and slipping during bending (non-linear model)

- Such a model leads to a bending stiffness which changes with amplitude and mechanical load applied to TLC

- Papailiou (1997) compared his theoretical predictions against experimental measurements performed on laboratory and the agreement was satisfactory

BRIEF LITERATURE REVIEW

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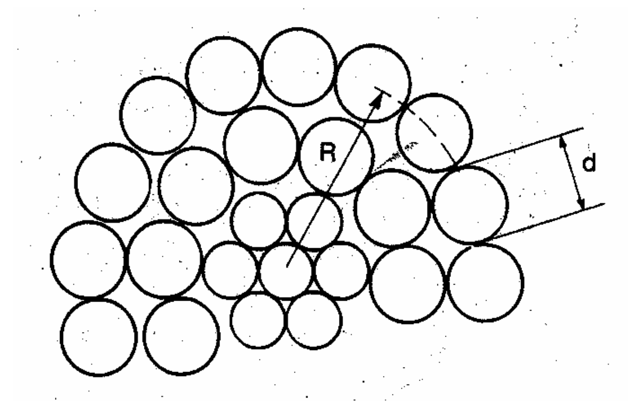
MINIMUM AND MAXIMUM VALUES OF THE BENDING STIFFNESS [CIGRÉ (1989)]

$$EI_{min} = \frac{\pi}{64}\left(E_s\, d_s^4\, N_s + E_a\, d_a^4\, N_a\right)$$

$$EI_{max} = E_s \sum_{i=1}^{n_s} I_{max,i} + E_a \sum_{j=1}^{n_a} I_{max,j}$$

$$I_{max,i} = \frac{N_i\, \pi\, d^2}{8}\left(\frac{d^2}{8} + R_i^2\right)$$

E_s	Young's modulus of elasticity for steel
E_a	Young's modulus of elasticity for steel
d_s	Steel wire diameter
d_a	Aluminum wire diameter
N_s	Number of steel wires
N_a	Number of aluminum wires
n_s	Number of layers of steel wires
n_a	Number of layers of aluminum wires
N_i	Number of wires in the i^{th} layer
R_i	Radius of i^{th} layer



ACSR conductor Grosbeak

26 aluminum wires d_a = 3.973 mm
7 steel wires d_s = 3.089 mm
EI_{min} = 28.4 N.m^2
EI_{max} = 1027 N.m^2

What value of *EI* should we use?

MATHEMATICAL FORMULATION OF THE PHYSICAL PROBLEM

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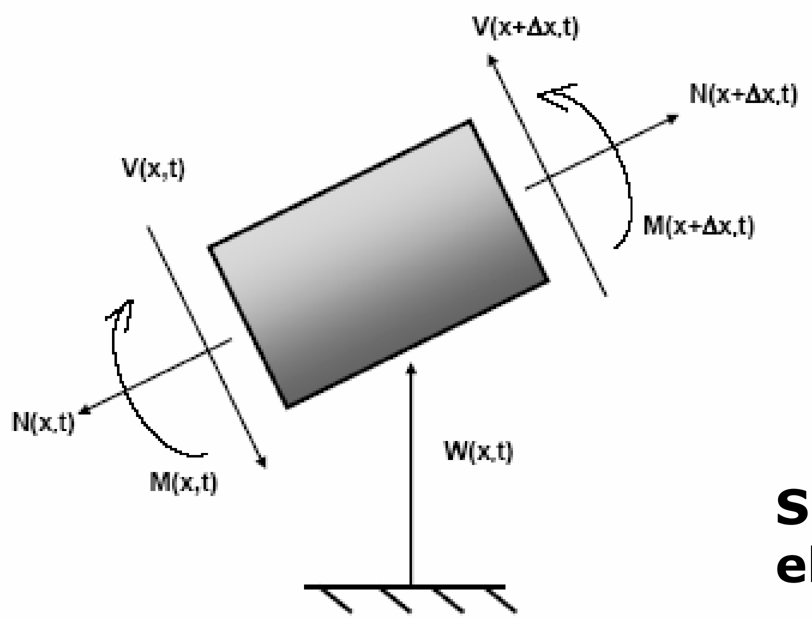
- HYPOTHESIS
  - TLC modelled as an Euler-Bernoulli beam with constant bending stiffness and subjected to a constant axial load
  - Small displacements
  - Aerodynamic damping of viscous type
  - Material damping modelled from constitutive equation



Sketch of a differential element of the TLC

MATHEMATICAL FORMULATION OF THE PHYSICAL PROBLEM

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- EQUILIBRIUM EQUATIONS

$$H(x,t)+\frac{\partial}{\partial x}\left(T\frac{\partial w}{\partial x}\right)-\frac{\partial^2 M}{\partial x^2}-\alpha\frac{\partial w}{\partial t}=\mu\,\frac{\partial^2 w}{\partial t^2}$$

$$M(x,t)=\int_A -y\,\sigma(x,t)\,dA$$

- CONSTITUTIVE EQUATION ?

  - Linear or nonlinear ?

  - Candidate models ?

MATHEMATICAL FORMULATION OF THE PHYSICAL PROBLEM

- CONSTITUTIVE EQUATION – LINEAR ?
  - STICK-SLIP BETWEEN THE STRANDS (PAPAILIOU, 1997)
  - FOR TLC THE AXIAL TENSION IS EXTREMELY HIGH
  - EXPERIMENTS AIMED AT ASSESSING WHETHER TLC POSSES LINEAR BEHAVIOUR WERE PERFORMED.
  - BASED ON EXPERIMENTAL DATA WE DECIDED TO ADOPT A LINEAR MODEL FOR THE TLC USED (HORIZONTAL, HIGH AXIAL TENSION AND LOW SAG)

MATHEMATICAL FORMULATION OF THE PHYSICAL PROBLEM

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❑CONSTITUTIVE EQUATION

- ❑ Generalized damping model (time domain)

$$\sigma(x,t) = E\,\varepsilon(x,t) + \int_0^t K(x,\tau - t)\frac{\partial \varepsilon}{\partial \tau}\,d\tau.$$

- ❑ Kelvin-Voigt model (time domain)

$$\sigma = E\varepsilon + \xi\,\frac{\partial \varepsilon}{\partial t}$$

- ❑ Hysteretic damping model (frequency domain)

$$\hat{\sigma}(x,\, j\omega) = \left(EI + j\overline{\eta}I\right)\hat{\varepsilon}(x,\, j\omega)$$

MATHEMATICAL FORMULATION OF THE PHYSICAL PROBLEM

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- KELVIN-VOIGT MODEL
  - Constitutive equation defined in time domain what enables one to obtain the governing partial differential equations also in time domain.
  - Governing equation

$$EI\frac{\partial^4 w}{\partial x^4} - T\frac{\partial^2 w}{\partial x^2} + \xi I\frac{\partial}{\partial t}\left(\frac{\partial^4 w}{\partial x^4}\right) + \alpha\frac{\partial w}{\partial t} + \mu\frac{\partial^2 w}{\partial t^2} = H(x,t)$$

  - \+ Boundary conditions

MATHEMATICAL FORMULATION OF THE PHYSICAL PROBLEM

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❑HYSTERETIC DAMPING MODEL

- ❑ Constitutive equation defined in frequency domain. Coresponds to the dissipation model mostly adopted for the analysis of TLC.

- ❑ Characterized by a constant loss factor.

- ❑ Non-causal. Therefore, we cannot obtain the governing equations in time domain.

MATHEMATICAL FORMULATION OF THE PHYSICAL PROBLEM

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- DIRECT PROBLEM

  - Comprises the solution of the above equations subjected to appropriate boundary and initial conditions, assuming that parameters EI, ξI, $\bar{\eta I}$ and a, and the excitation H(x,t) are known

  - Two techniques were used to solve the direct problem:

    (i) the finite-element method FEM (Hughes, 2000; Reddy, 1993) and (ii) the generalized integral transform GITT (Cotta, 1993; Özişik, 1993)

MATHEMATICAL FORMULATION OF THE PHYSICAL PROBLEM

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- DIRECT PROBLEM BY FEM : KELVIN-VOIGT DAMPING MODEL
  - Weak Form

$$\int_{x_e}^{x_{e+1}} \left(-T \frac{\partial w}{\partial x} \frac{\partial u}{\partial x} - EI \frac{\partial^2 w}{\partial x^2} \frac{\partial^2 u}{\partial x^2} - \xi I \frac{\partial^3 w}{\partial x^2 \partial t} \frac{\partial^2 u}{\partial x^2} - \alpha \frac{\partial w}{\partial t} u - \mu \frac{\partial^2 w}{\partial t^2} u + H u \right) dx = 0$$

  - Galerkin Discretization

$$w(x,t) = \mathbf{N}(x) \mathbf{w}_h(t)$$

  - System of Ordinary Differential Equations

$$\mathbf{M}^e \ddot{\mathbf{w}}_h + \mathbf{D}^e \dot{\mathbf{w}}_h + \mathbf{K}^e \mathbf{w}_h = \mathbf{f}^e$$

MATHEMATICAL FORMULATION OF THE PHYSICAL PROBLEM

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❑DIRECT PROBLEM BY FEM : KELVIN-VOIGT DAMPING MODEL

- Mass, Stiffness and Damping Matrices

$$\mathbf{M}^e = \int_{x_e}^{x_{e+1}} \mu\, \mathbf{N}^T \mathbf{N}\, dx$$

$$\mathbf{K}^e = \int_{x_e}^{x_{e+1}} \left(EI \frac{\partial^2 \mathbf{N}}{\partial x^2}^T \frac{\partial^2 \mathbf{N}}{\partial x^2} + T \frac{\partial \mathbf{N}}{\partial x}^T \frac{\partial \mathbf{N}}{\partial x} \right) dx$$

$$\mathbf{D}^e = \frac{\alpha}{\mu}\mathbf{M}^e + \int_{x_e}^{x_{e+1}} \xi I \frac{\partial^2 \mathbf{N}}{\partial x^2}^T \frac{\partial^2 \mathbf{N}}{\partial x^2}\, dx = \frac{\alpha}{\mu}\mathbf{M}^e + \frac{\xi}{E}\mathbf{K}^e - \frac{\xi T}{E} \int_{x_e}^{x_{e+1}} \frac{\partial \mathbf{N}}{\partial x}^T \frac{\partial \mathbf{N}}{\partial x}\, dx.$$

MATHEMATICAL FORMULATION OF THE PHYSICAL PROBLEM

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- DIRECT PROBLEM BY FEM : HYSTERETIC DAMPING MODEL

  - The relationship between the excitation and the response of the system can be written only in the frequency domain

$$\left[(j\omega)^2 \mathbf{M} + (j\omega)\mathbf{D}_\alpha + \left\{ \mathbf{K} + j.\mathbf{D}_{\bar{\eta}} \right\} \right] \mathbf{w}(j\omega) = \mathbf{F}(j\omega)$$

  - Elemental matrices

$$\mathbf{D}_\alpha^e = \frac{\alpha}{\mu}\mathbf{M}^e$$

$$\mathbf{D}_{\bar{\eta}}^e = \int_{x_e}^{x_{e+1}} \bar{\eta} I \frac{\partial^2 \mathbf{N}^T}{\partial x^2} \frac{\partial^2 \mathbf{N}}{\partial x^2} dx$$

MATHEMATICAL FORMULATION OF THE PHYSICAL PROBLEM

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- DIRECT PROBLEM: HYBRID SOLUTION BY GITT – KELVIN-VOIGT
  - Auxiliary Eigenvalue Problem + homogeneous B.C.'s

$$EI\frac{d^4\Psi_m}{dx^4} - T\frac{d^2\Psi_m}{dx^2} - \mu\,\lambda_m^2\Psi_m = 0$$

  - Inverse-Transform Pair

$$\begin{cases} \bar{w}_m(t) = \int_0^L \Psi_m(\lambda_m,x)\,w(x,t)\,dx & \text{(transform)} \\ w(x,t) = \sum_{m=1}^{\infty}\frac{\Psi_m(\lambda_m,x)}{N(\lambda_m)}\bar{w}_m(t) & \text{(inverse)} \end{cases}$$

  - Transformation of Original Problem - System of Coupled Ordinary Differential Equations

$$\zeta_m \equiv \frac{\alpha}{2\mu\lambda_m},\ \zeta_m^* \equiv \zeta_m + \frac{1}{2}\frac{\xi I}{EI}\lambda_m$$

$$\frac{d^2\bar{w}_m}{dt^2} + 2\zeta_m^*\lambda_m\frac{d\bar{w}_m}{dt} + \frac{\xi I}{EI}\frac{T}{\mu}\sum_{n=1}^{\infty}\Lambda_{mn}\frac{d\bar{w}_n}{dt} + \lambda_m^2\bar{w}_m = \frac{H_0}{\mu}\Psi_m(\lambda_m,x_s)\,e^{i\Omega t}$$

$$\Lambda_{mn} \equiv \frac{1}{N(\lambda_n)}\int_0^L \Psi_n(\lambda_n,x)\frac{d^2\Psi_m}{dx^2}\,dx = -\frac{1}{N(\lambda_n)}\int_0^L \frac{d\Psi_n}{dx}\frac{d\Psi_m}{dx}\,dx.$$

MATHEMATICAL FORMULATION OF THE PHYSICAL PROBLEM

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❑ INVERSE PROBLEM

- The unknown parameters are the bending stiffness EI, the viscous damping coefficient α, and the constitutive damping parameters

  ηI and ξI.

- Additional information used to estimate these two parameters are the complex frequency response functions 'measured' at prescribed locations x_p, $p = 1, 2, ..., N_s$, and circular frequencies W_q, $q = 1, 2, ..., N_f$ (N_s and N_f denote, respectively, the number of sensors and frequency data)

MATHEMATICAL FORMULATION OF THE PHYSICAL PROBLEM

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❑INVERSE PROBLEM

- Solution of inverse problem comprises the minimization of a suitable error function S(**p**), viz.

$$S(\mathbf{p}) = f(\mathbf{p}, \mathbf{H}^{Exp}, \mathbf{H}^{Est}(\mathbf{p}))$$

- What is a suitable choice for S(p) ?

- What are the characteristics of our experimental data and what is our interest ?

MATHEMATICAL FORMULATION OF THE PHYSICAL PROBLEM

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❑INVERSE PROBLEM - FIRST STAGE

- Use the experimental data concerning the lowest frequency bands

- Estimate EI and one of the damping parameters by the the classical *Levenberg-Marquardt* iterative procedure [Beck and Arnold, 1977; Özişik and Orlande (2000)].

MATHEMATICAL FORMULATION OF THE PHYSICAL PROBLEM

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- INVERSE PROBLEM - FIRST STAGE

  - Error function

$$S(\mathrm{p}) = \left[\mathbf{H}^{exp}(\mathrm{p}) - \mathbf{H}^{est}(\mathrm{p})\right]^T \left[\mathbf{H}^{exp}(\mathrm{p}) - \mathbf{H}^{est}(\mathrm{p})\right]$$

  - Iterative procedure

$$\Delta \mathrm{p}^k = [\mathrm{J}^{k^T}\,\mathrm{J}^k + \lambda^k \Lambda^k]^{-1}\mathrm{J}^k[\mathrm{H}^{exp} - \mathrm{H}^{est}(\mathrm{p}^k)]$$

$$\Delta \mathrm{p}^k = \mathrm{p}^{k+1} - \mathrm{p}^k$$

MATHEMATICAL FORMULATION OF THE PHYSICAL PROBLEM

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- INVERSE PROBLEM - SECOND STAGE

- Use the experimental data containing informmation of the higher frequency bands

- Use the estimated parameters obtained in the first stage as *a priori* information for the estimation of the unknown parameters.

- Error function

$$S_{MAP}(\mathrm{p}) = [\mathrm{H}^{exp} - \mathrm{H}^{est}(\mathrm{p})]^T \, \mathrm{W} \, [\mathrm{H}^{exp} - \mathrm{H}^{est}(\mathrm{p})] \\ + [\mathrm{p}_\mu - \mathrm{p}]^T \, \mathrm{V}^{-1} \, [\mathrm{p}_\mu - \mathrm{p}]$$

MATHEMATICAL FORMULATION OF THE PHYSICAL PROBLEM

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- INVERSE PROBLEM - SECOND STAGE

  - Error function

$$S_{MAP}(\mathrm{p}) = [\mathbf{H}^{exp} - \mathbf{H}^{est}(\mathrm{p})]^T \mathbf{W} [\mathbf{H}^{exp} - \mathbf{H}^{est}(\mathrm{p})] + [\mathrm{p}_\mu - \mathrm{p}]^T \mathbf{V}^{-1} [\mathrm{p}_\mu - \mathrm{p}]$$

  - Iterative procedure

$$\Delta \mathrm{p}^k = [\mathbf{J}^{k^T} \mathbf{W} \mathbf{J}^k + \mathbf{V}^{-1}]^{-1} \{\mathbf{J}^k \mathbf{W} [\mathbf{H}^{exp}(\mathrm{p}) - \mathbf{H}^{est}(\mathrm{p}^k)] + \mathbf{V}^{-1}(\mathrm{p}_\mu - \mathrm{p}^k)\}$$

MATHEMATICAL FORMULATION OF THE PHYSICAL PROBLEM

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- INVERSE PROBLEM - SECOND STAGE

  - In the present work the iterative procedure for the second stage was implemented in a convenient form for computational purposes, which avoids matrix inversions. For this we have employed the sequential estimation technique [Beck and Arnold, 1977, Orlande, 2002 , Beck, 2003].

MATHEMATICAL FORMULATION OF THE PHYSICAL PROBLEM

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❑INVERSE PROBLEM - SECOND STAGE -ALGORITHM

- Step1:Initialize the iterative procedure by setting the iteration index k to 0 and $\mathbf{p}^{(0)} = \mathbf{p}_{\mu}$.
- Compute the estimate for the vector of unknown parameters sequentially, by using

$$\mathrm{A} = \mathrm{V}_n \mathrm{J}_{n+1}^T$$

$$\Delta = \mathrm{J}_{n+1}\mathrm{A} + W_{n+1}^{-1}$$

$$\Gamma = \Delta^{-1}\mathrm{A}$$

$$E_{n+1} = H_{n+1}^{exp} - H_{n+1}^{est}(\mathrm{p}^k)$$

$$\mathrm{p}_{n+1}^{k+1} = \mathrm{p}_n^{k+1} + \Gamma[E_{n+1} - \mathrm{J}_{n+1}(\mathrm{p}_n^{k+1} - \mathrm{p}_k)]$$

$$\mathrm{V}_{n+1} = \mathrm{V}_n - \Gamma\,\mathrm{J}_{n+1}\,\mathrm{V}_n$$

$$\mathrm{V}_0 = \mathrm{V},\ \mathrm{p}_0^k = \mathrm{p}_\mu,\ W_{n+1} = \sigma_{n+1}^{-2}$$

$$\mathrm{J}_n = \left.\frac{\partial H_n^{est}}{\partial \mathrm{p}}\right|_{\mathrm{p}=\mathrm{p}^k}$$

RESULTS AND CONCLUSIONS

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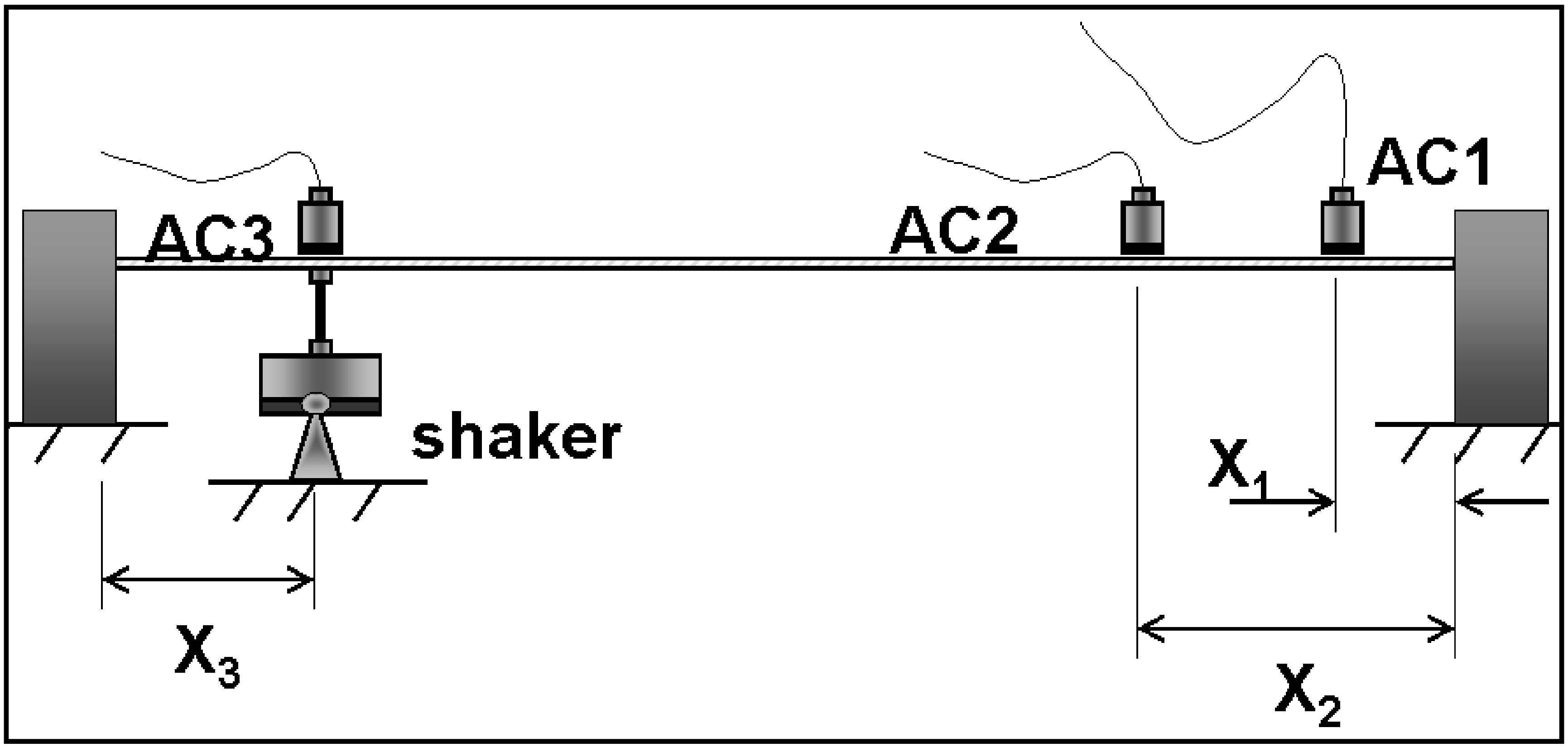
- EXPERIMENTAL SET-UP (Sketch)



RESULTS AND CONCLUSIONS

- EXPERIMENTAL SET-UP – CEPEL's LABORATORY SPAN

RESULTS AND CONCLUSIONS

- EXPERIMENTAL SET-UP – SHAKER

RESULTS AND CONCLUSIONS

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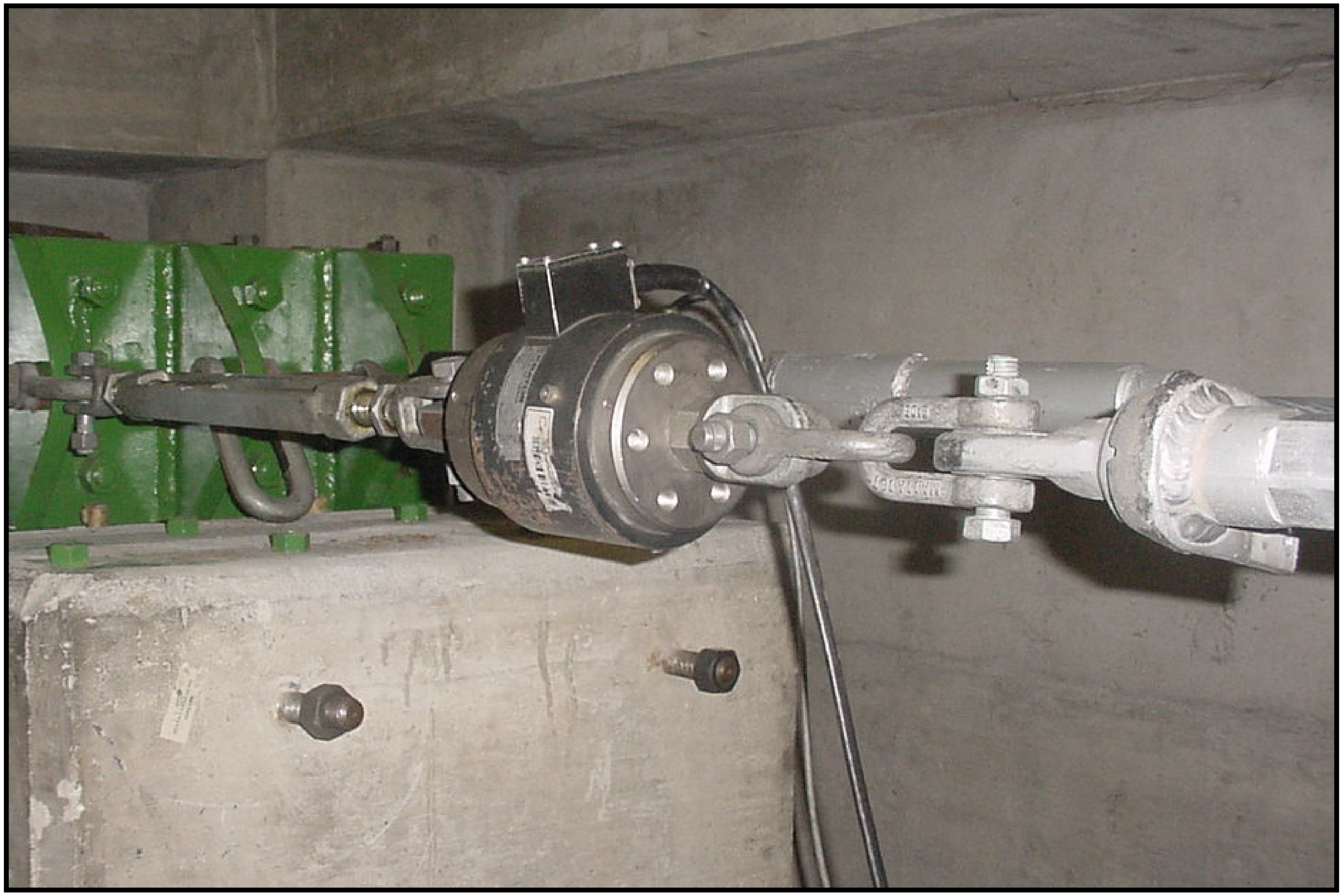
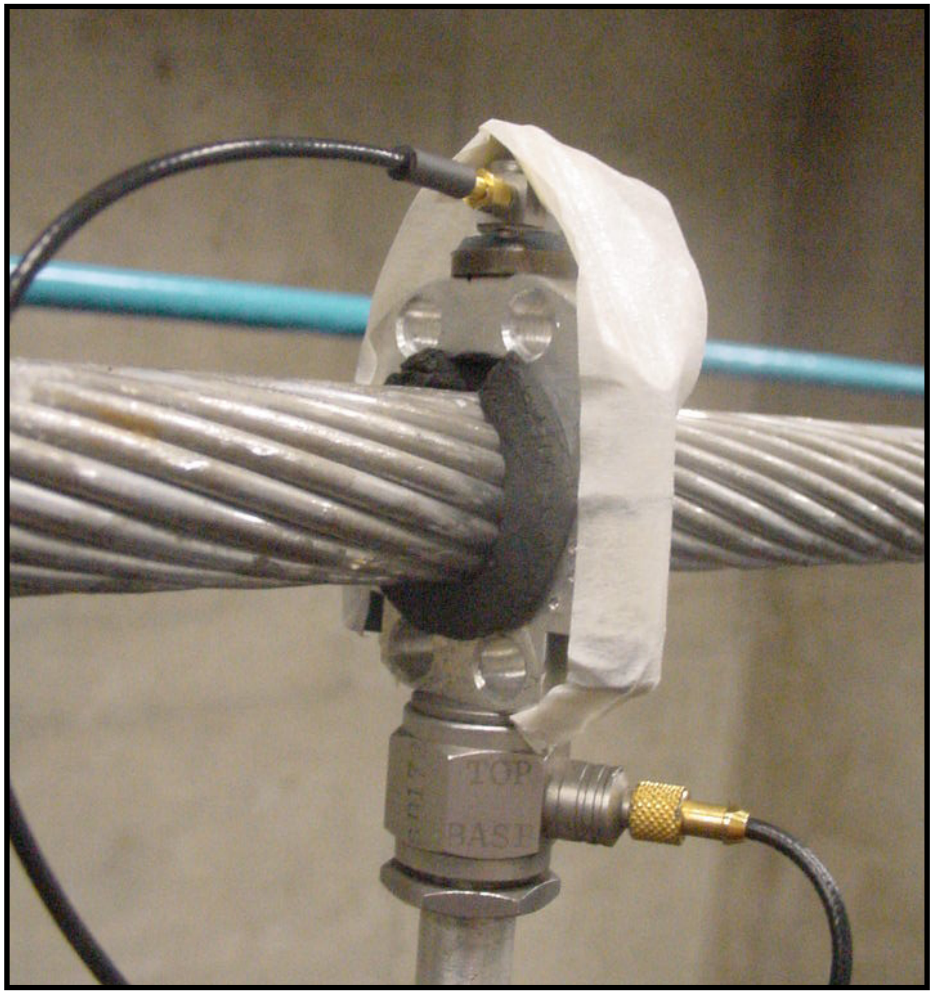
- EXPERIMENTAL SET-UP – LOAD CELL



RESULTS AND CONCLUSIONS

- EXPERIMENTAL SET-UP – ACCELEROMETER AND LOAD CELL



RESULTS AND CONCLUSIONS

- EXPERIMENTAL SET-UP

  - Grosbeak ACSR conductor
  - μ = 1.30271 kg/m
  - T = 21778.2 N and T = 27468.0 N
  - L = 51.905 m
  - X_1 = 1.39 m
  - X_2 = 0.70 m
  - X_3 = 1.61 m

RESULTS AND CONCLUSIONS

- EXPERIMENTAL SET-UP : FRFs

Band (Hz)	n_d (Number of averages)	Accelerometers
[5, 17.5]	30	AC1, AC2 and AC3
[17.5, 30]	30	AC1, AC2 and AC3

- All the FRFs are measured with 801 equally spaced frequency points

RESULTS AND CONCLUSIONS

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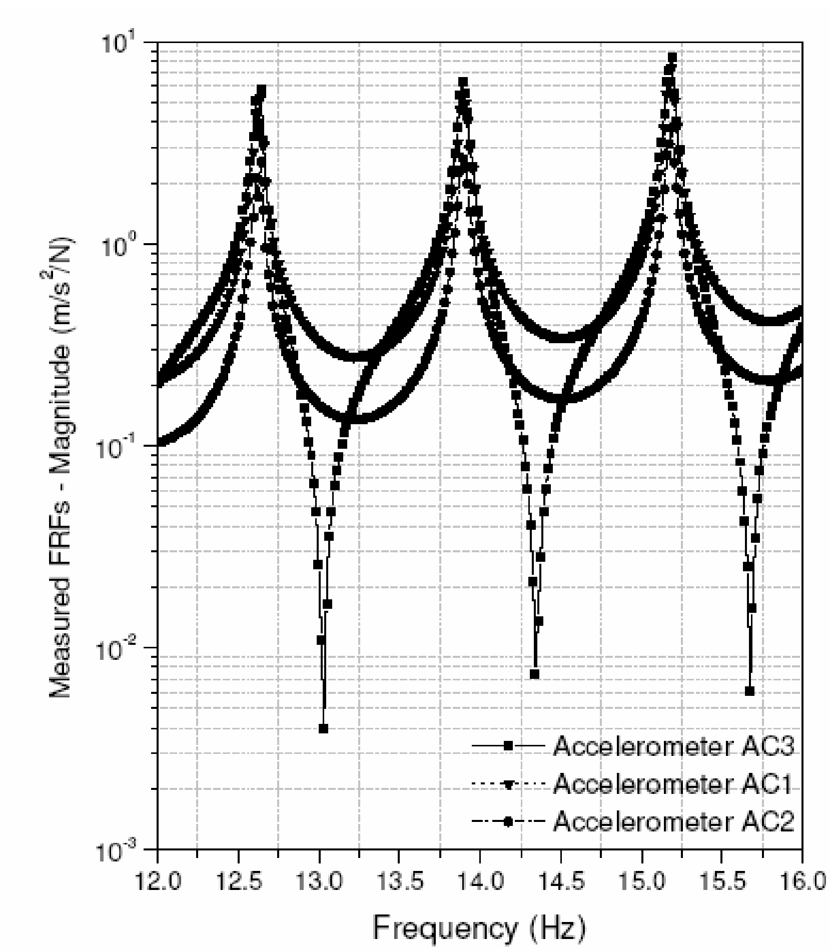
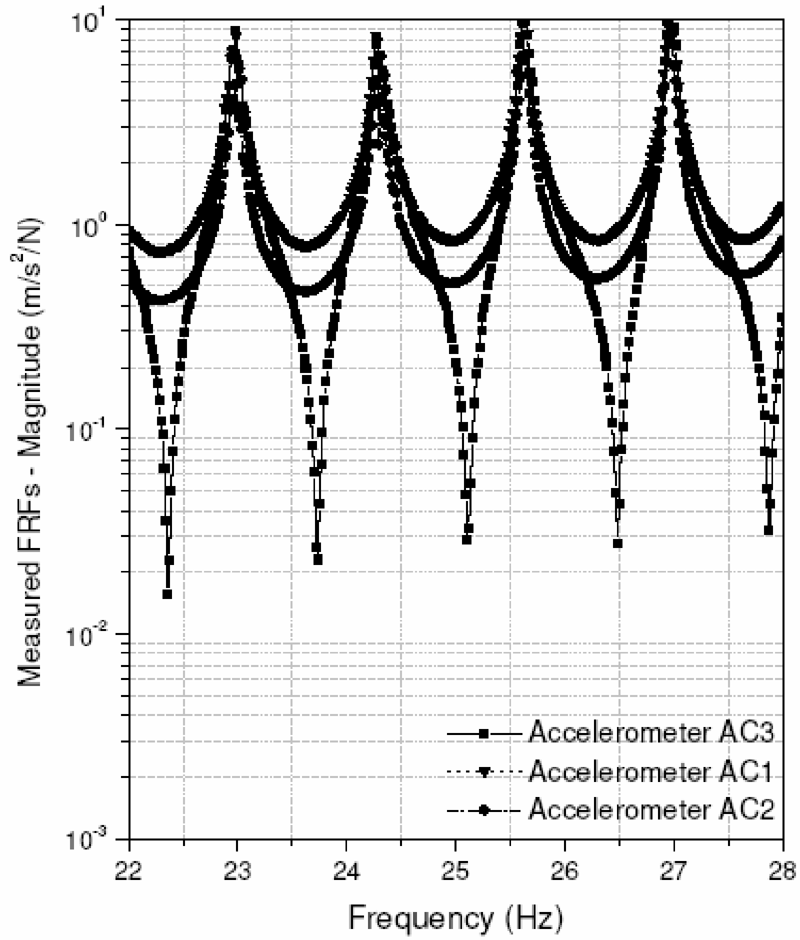
❑EXPERIMENTAL SET-UP : FRFs





RESULTS AND CONCLUSIONS

- RESULTS: CASE C1
  - $T = 21778.2$ N
  - [5, 17.5] Hz
  - Kelvin-Voigt model
  - Unknown parameters α and EI and for case C1 it is considered that $\xi I = 10^{-4}$ N.m^{2}s^{-1}.
  - Initial Guess for EI and α ?

RESULTS AND CONCLUSIONS

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❑RESULTS: CASE C1

- We do not have any information about a suitable intial guess for α , therefore we have considered $\alpha^{(0)} = 10^{-2}$N.s.m^{-2}.

- Concerning the parameter EI, the reports by CIGRE provide the maximum and minimum values: $EI^{min} = 28$ N.m^2 and $EI^{max} = 1027$ N.m^2.

- Parameterization $EI=p_1 x10^3$ and $\alpha = p_2$.

RESULTS AND CONCLUSIONS

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- RESULTS: CASE C1

Estimated bending stiffness and aerodynamic damping coefficient (Case $C1$).

GITT					FEM				
$EI^{(0)}$	EI	α	$\frac{\sigma_{EI}}{\sigma}$	$\frac{\sigma_\alpha}{\sigma}$	$EI^{(0)}$	EI	α	$\frac{\sigma_{EI}}{\sigma}$	$\frac{\sigma_\alpha}{\sigma}$
28	748.9	0.355	2.8	0.012	28	742.2	0.3494	2.8	0.0114
527.5	748.9	0.355	2.8	0.012	527.5	741.9	0.3495	2.8	0.0114
1027	748.9	0.355	2.8	0.012	1027	741.9	0.3495	2.8	0.0114

- DEFINITION: Normalized norm

$$|\mathbf{q}^{est}|_N = \frac{(\mathbf{q}^{exp} - \mathbf{q}^{est})^H (\mathbf{q}^{exp} - \mathbf{q}^{est})}{(\mathbf{q}^{exp})^H \mathbf{q}^{exp}}$$

RESULTS AND CONCLUSIONS

- RESULTS: CASE C1

  - Definition of a normalized norm of the FRFs

$$|\mathbf{q}^{est}|_N = \frac{(\mathbf{q}^{exp} - \mathbf{q}^{est})^H (\mathbf{q}^{exp} - \mathbf{q}^{est})}{(\mathbf{q}^{exp})^H \mathbf{q}^{exp}}$$

  - Norms for case C1

Band (Hz)	$AC1$	$AC2$	$AC3$
[5,17.5]	0.6761	0.6665	0.6894

RESULTS AND CONCLUSIONS

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- RESULTS: CASE C2

  - [17.5, 30] Hz
  - Use the results provided by case C1 as *a priori* information.
  - Unknown parameters α and EI and ξI.
  - Parameterization: $EI = p_1 x 10^3$, $\alpha = p_2$ and $\xi I = p_3 x 10^{-2}$
  - The components of the covariance matrix **V** and vector $\mathbf{p}_\mu$ associated to EI and α are obtained from case C1.

RESULTS AND CONCLUSIONS

CEPEL Grupo Eletrobrás

UERJ COPPE

- RESULTS: CASE C2

  - What about the components of the covariance matrix **V** and vector $\mathbf{p}_\mu$ for parameter ξI ?

  - As we do not have any information concerning I we simply consider that its mean is a small number and its standard deviation is a large number; therefore we have chosen 10^{-5} and 10^{10}, respectively.

$$\mathrm{p}_\mu = \{0.7419, 0.3495, 10^{-5}\}^T$$

$$\mathbf{V} = \sigma^2 \times \begin{pmatrix} 7.91 \times 10^{-6} & -2.78 \times 10^{-7} & 0 \\ -2.78 \times 10^{-7} & 1.20 \times 10^{-4} & 0 \\ 0 & 0 & 10^{10} \end{pmatrix}$$

RESULTS AND CONCLUSIONS

CEPEL Grupo Eletrobrás

- RESULTS: CASE C2

FEM					
EI	α	ξI	$\frac{\sigma_{EI}}{\sigma}$	$\frac{\sigma_{\alpha}}{\sigma}$	$\frac{\sigma_{\xi I}}{\sigma}$
678.9	0.393	0.029	0.347	0.008	0.0037

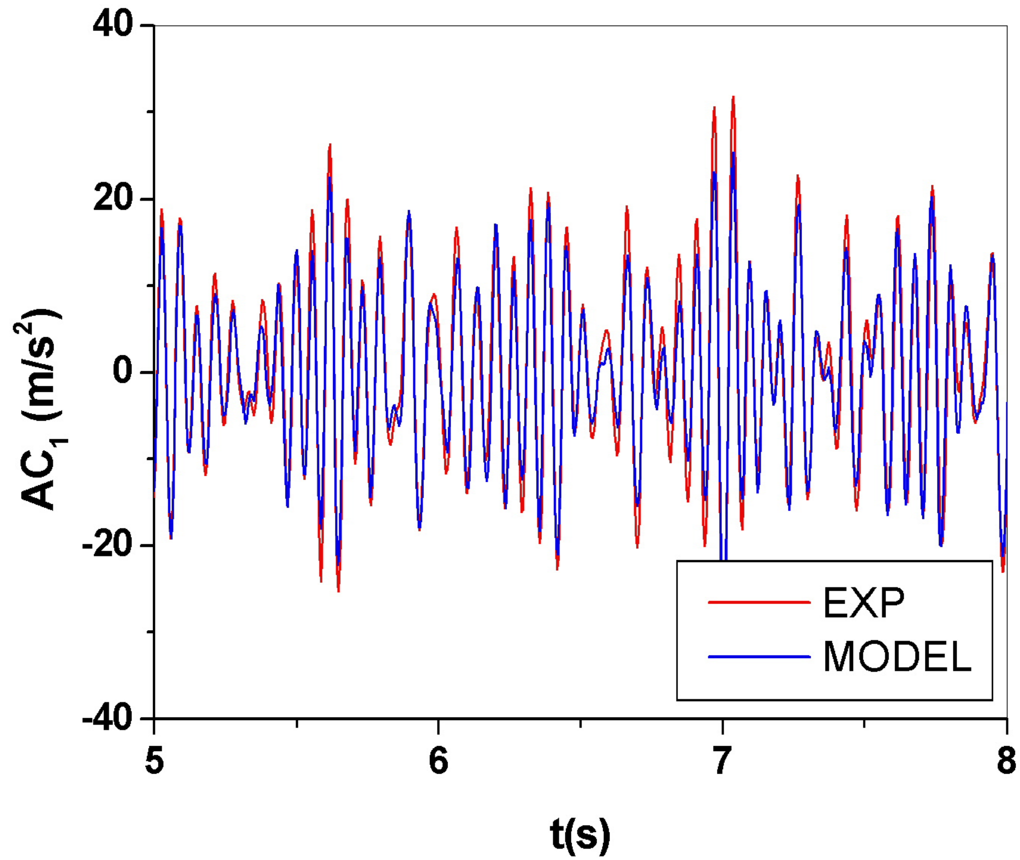
GITT					
EI	α	ξI	$\frac{\sigma_{EI}}{\sigma}$	$\frac{\sigma_{\alpha}}{\sigma}$	$\frac{\sigma_{\xi I}}{\sigma}$
682.4	0.393	0.026	0.336	0.013	0.0048

- Norms for case C2

Band (Hz)	$AC1$	$AC2$	$AC3$
[5,17.5]	0.8201	0.8084	0.8320
[17.5,30]	0.4663	0.4409	0.5032

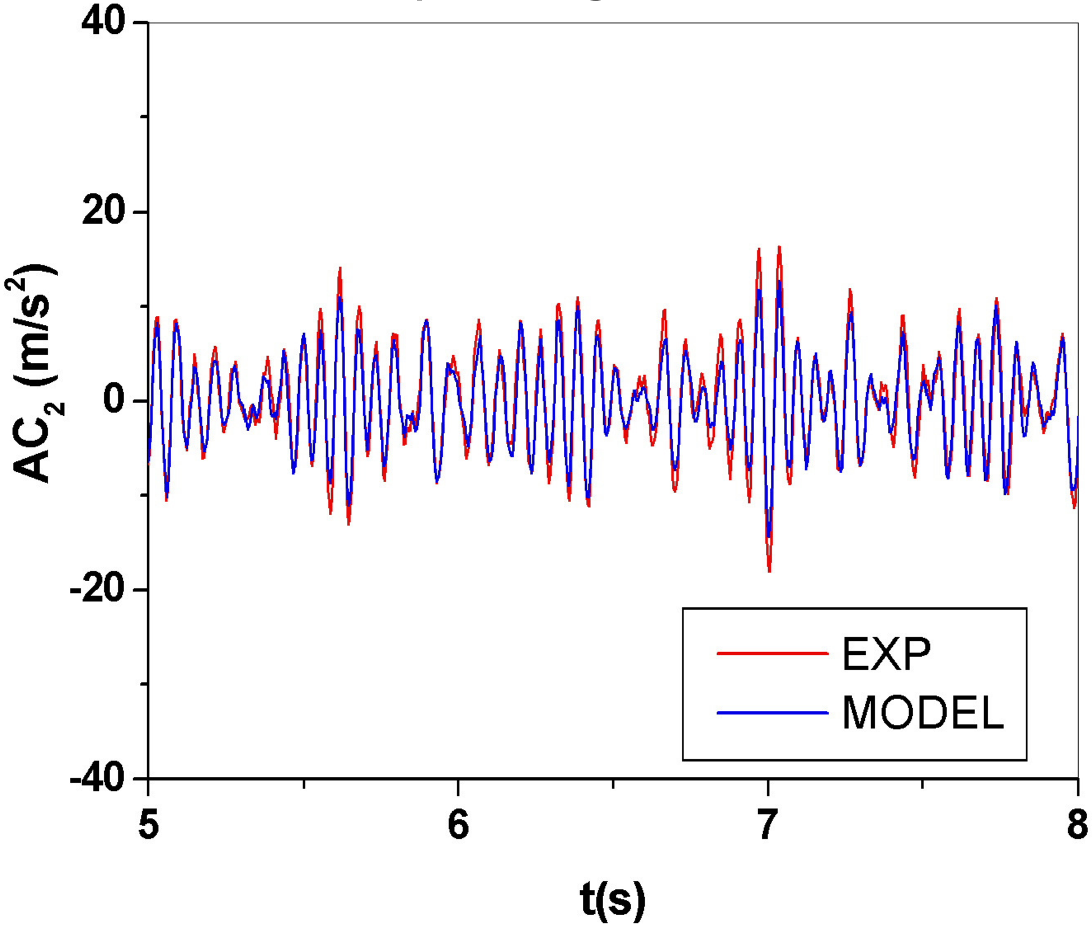
RESULTS AND CONCLUSIONS

- RESULTS: CASE C2
  - Validation in time domain with na excitation equal to a white noise enconpassing the band [5, 17.5] Hz



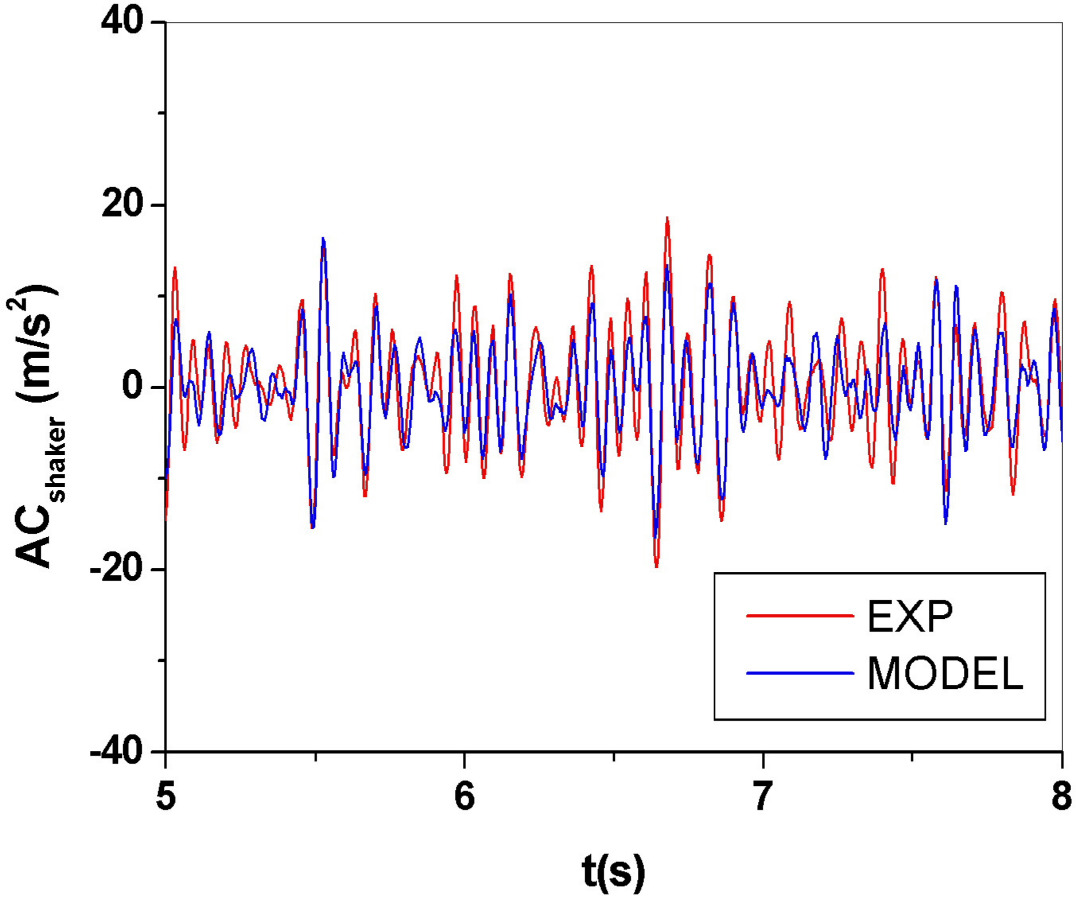
RESULTS AND CONCLUSIONS

- RESULTS: CASE C2
  - Validation in time domain with na excitation equal to a white noise enconpassing the band [5, 17.5] Hz



RESULTS AND CONCLUSIONS

- RESULTS: CASE C2
  - Validation in time domain with na excitation equal to a white noise enconpassing the band [5, 17.5] Hz



RESULTS AND CONCLUSIONS

- RESULTS: CASE C3
  - [17.5, 30] Hz
  - Use the results provided by case C1 as *a priori* information.
  - Hysteretic damping model. Unknown parameters α and EI and ηI.
  - Parameterization: $EI = p_1 x 10^3$, $\alpha = p_2$ and $\eta I = p_3$
  - The components of the covariance matrix **V** and vector $\mathbf{p}_\mu$ associated to EI and α are obtained from case C1.

RESULTS AND CONCLUSIONS

- RESULTS: CASE C3

  - What about the components of the covariance matrix **V** and vector $\mathbf{p}_\mu$ for parameter ηI ?

  - As we do not have any information concerning I we simply consider that its mean is a small number and its standard deviation is a large number; therefore we have chosen 10^{-5} and 10^{10}, respectively.

$$\mathrm{p}_\mu = \{0.7419, 0.3495, 10^{-5}\}^T$$

$$\mathbf{V} = \sigma^2 \times \begin{pmatrix} 7.91 \times 10^{-6} & -2.78 \times 10^{-7} & 0 \\ -2.78 \times 10^{-7} & 1.20 \times 10^{-4} & 0 \\ 0 & 0 & 10^{10} \end{pmatrix}$$

RESULTS AND CONCLUSIONS

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- RESULTS: CASE C3

FEM					
EI	α	$\bar{\eta}\, I$	$\frac{\sigma_{EI}}{\sigma}$	$\frac{\sigma_{\alpha}}{\sigma}$	$\frac{\sigma_{\eta I}}{\sigma}$
678.9	0.3771	6.0481	0.3504	0.009	0.679

- Norms for case C3

Band (Hz)	$AC1$	$AC2$	$AC3$
[5,17.5]	0.8220	0.8101	0.8339
[17.5,30]	0.4659	0.4407	0.5026

RESULTS AND CONCLUSIONS

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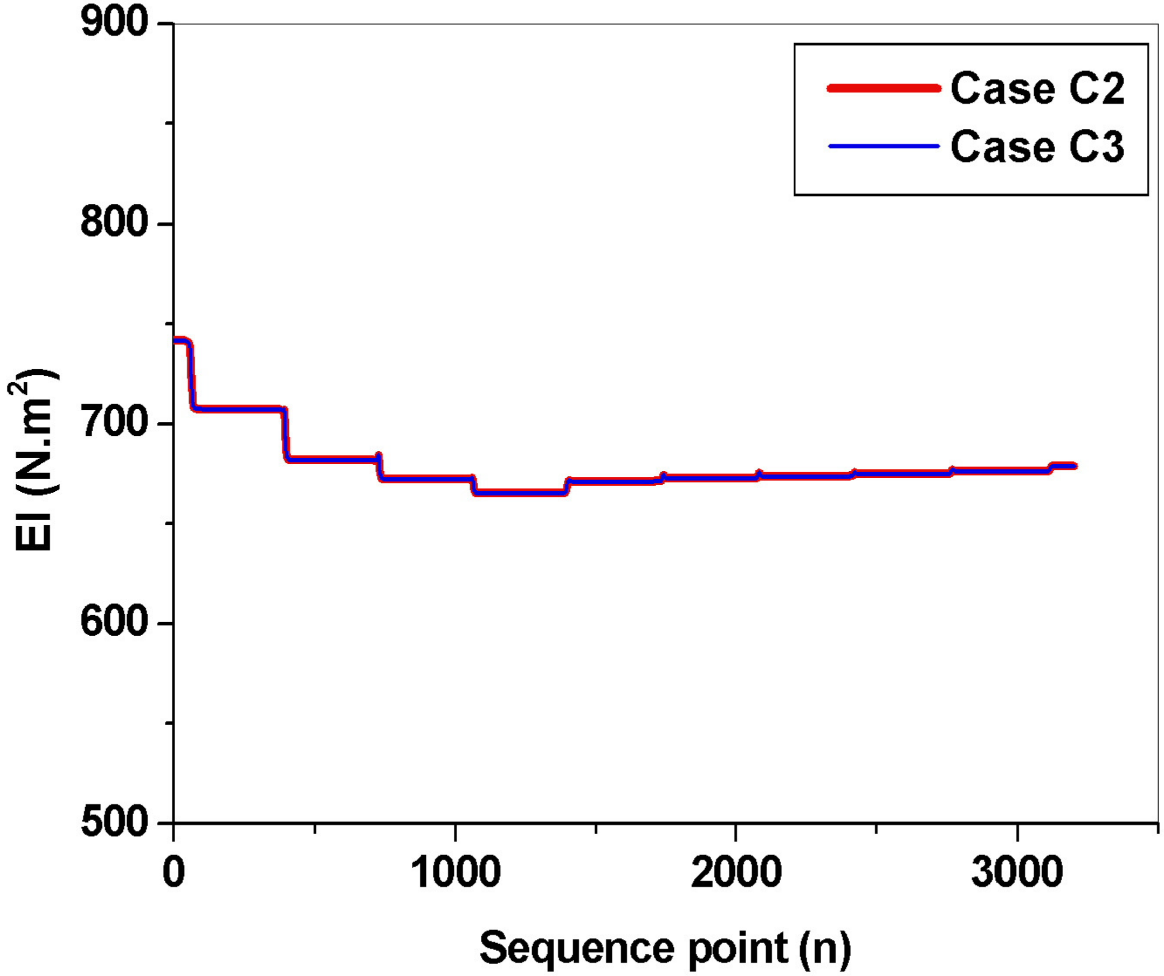
UERJ COPPE

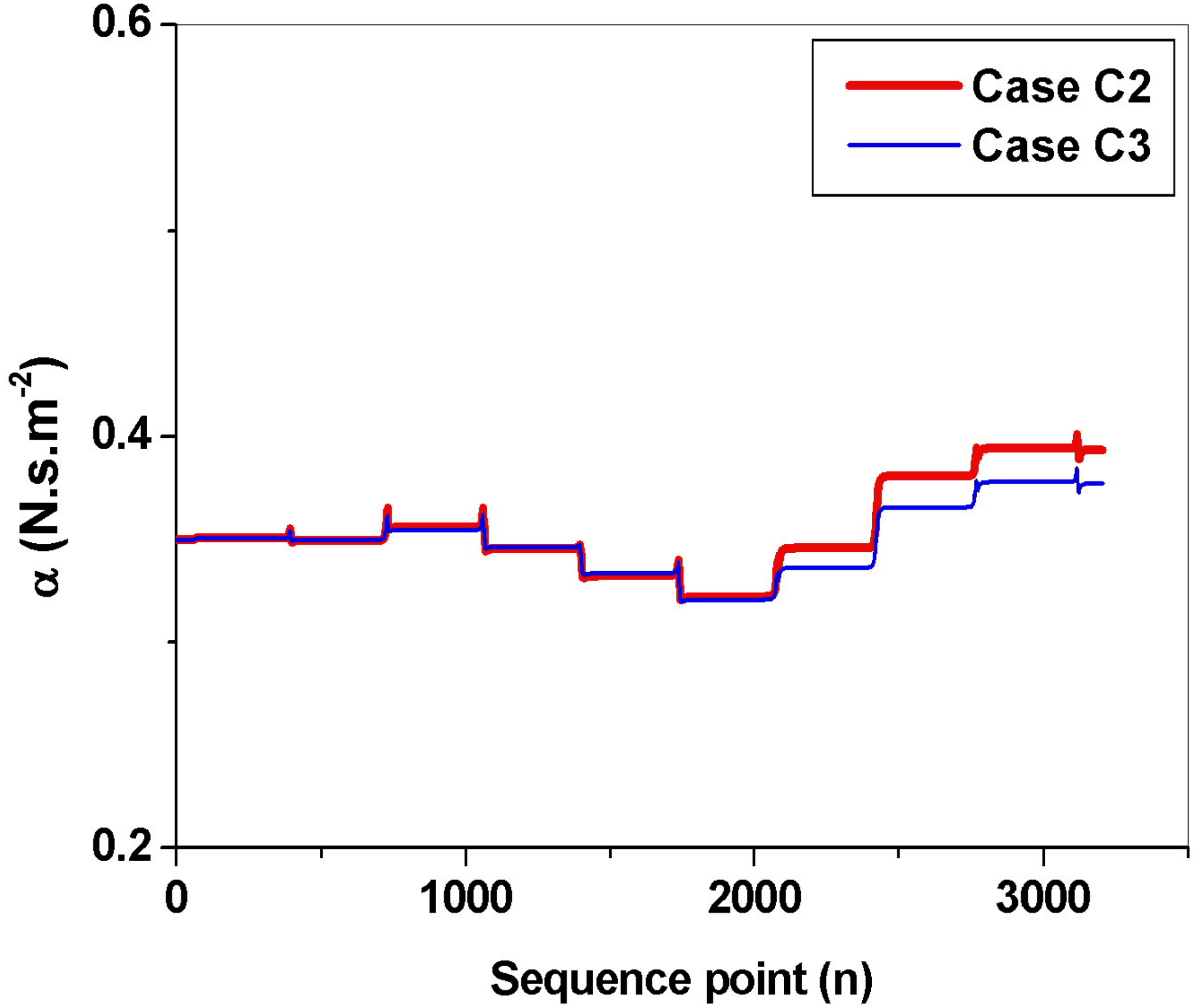
❑Sequential evolution of the estimated parameters for cases C2 e C3



RESULTS AND CONCLUSIONS

CEPEL Grupo Eletrobrás

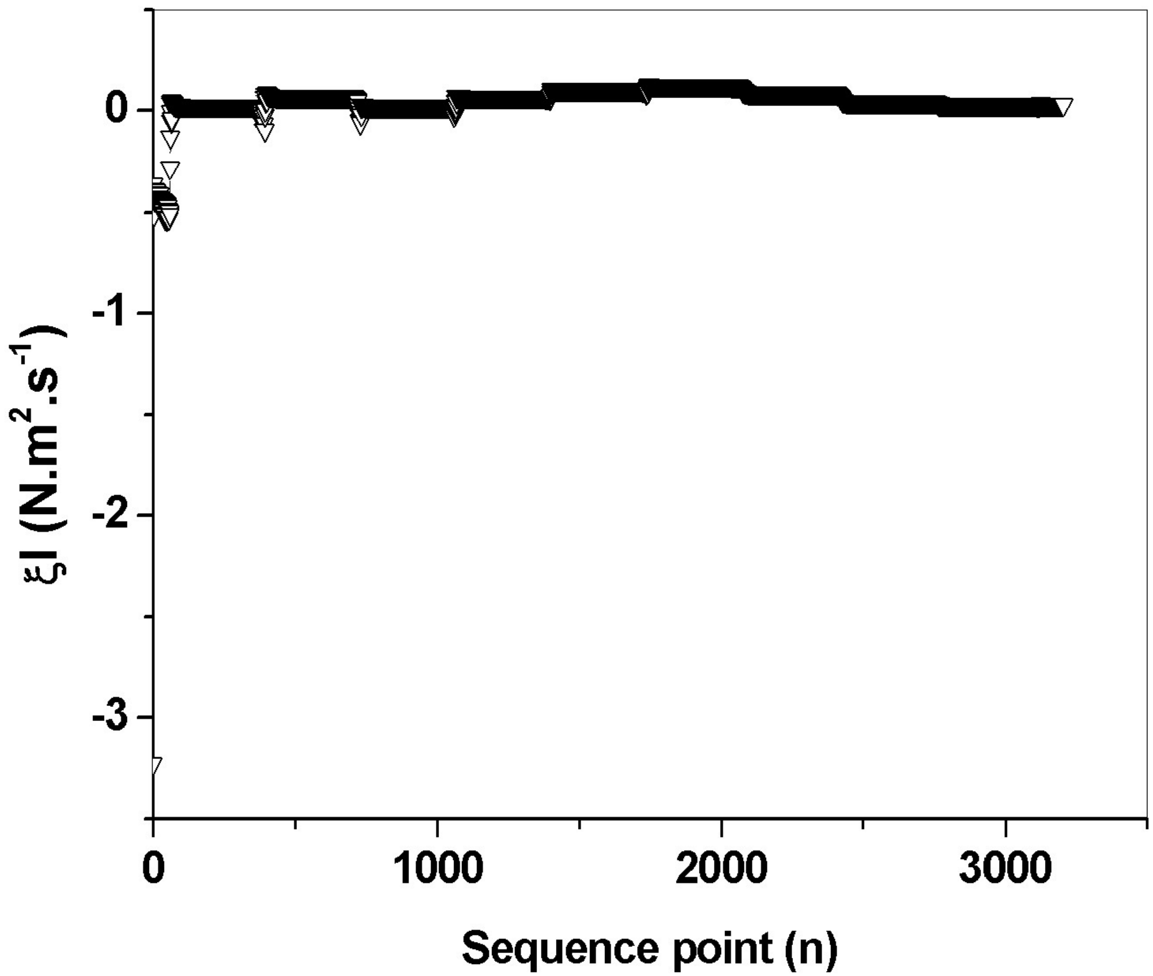
- Sequential evolution of the estimated parameters for cases C2 e C3



RESULTS AND CONCLUSIONS

CEPEL Grupo Eletrobrás

- Sequential evolution of the estimated parameters for cases C2 e C3

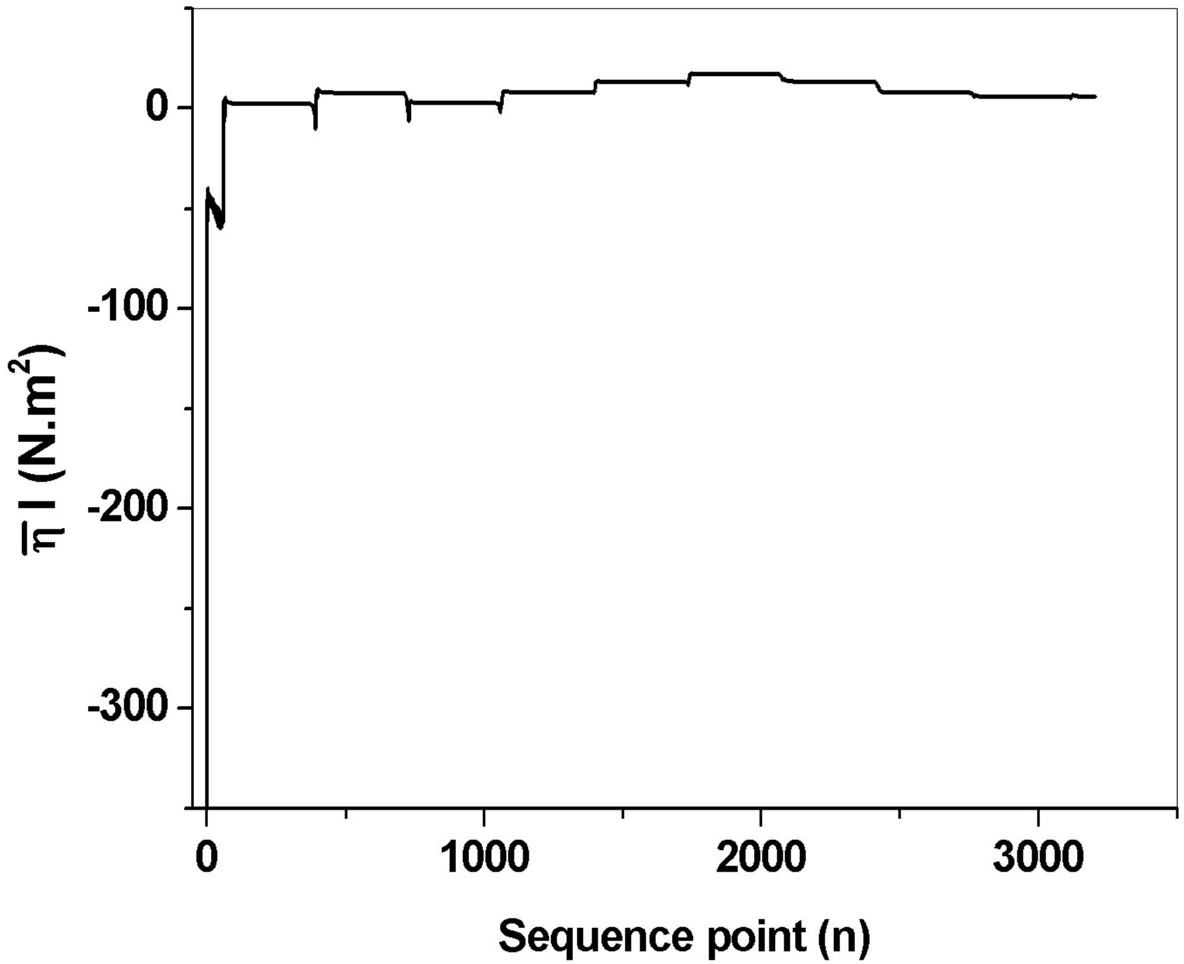


RESULTS AND CONCLUSIONS

CEPEL Grupo Eletrobrás

UERJ COPPE

❑Sequential evolution of the estimated parameters for cases C2 e C3



RESULTS AND CONCLUSIONS

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- RESULTS: CASE C4

  - Exactly equal to case C1 e C2 in sequence but with axial tension equal to T = = 27468.0 N

  - $EI = 615.8\ N.m^2$

  - $\alpha = 0.3674\ N.s.m^{-2}$

  - $\xi I = 2.8186 \times 10^{-2}\ N.m^2.s^{-1}$

FINAL REMARKS

- TLC's were modelled as homogeneous beams with viscous and structural damping
- Based on experimental data it was chosen a linear model to represent the system.
- Two classical damping models have been used
- Their bending stiffness and damping parameters were estimated based on inverse analysis
- Direct problem associated to estimation process was solved by two approaches: FEM and GITT
- Inverse problem was solved through Levenberg-Marquardt iterative procedure and the sequential estimation technique.

FINAL REMARKS (cont.)

- MAIN CONCLUSIONS
  - Objective function much more sensitive to α than to *EI* in the frequency range (0,20 Hz)
  - Estimates for α were in good agreement with its true value
  - Estimated parameters pratically unaffected by noise level
  - Uncertainty in span length affects much more *EI*
  - Uncertainty in mechanical load largely affects both parameters
- MAIN CONTRIBUTIONS
  - The estimation of bending stiffness and damping parameter of TLC
  - Use of GITT approach to solve direct problem associated to estimation process
  - Numerical analysis of the effects of model uncertainties on estimated parameters what, to authors belief, are not considered previously in the literature for this specific problem

FUTURE WORKS

- Estimate these parameters for different span lengths and different axial tractions

- Investigate a suitable mechanical model for the StockBridge damper

- Analyze the coupled system TLC and damper based on the estimated models and evaluate it based on experimental data.