Pantograph testing for simulation models

TTI SECTOR PLENARY MEETING

MÁLAGA 2025

P. Antunes, A. Collina, M. Tur

University of Huddersfield
Institute of Railway Research

Politecnico Milano 1863
Department of Mechanical Engineering

Universitat Politècnica de València
I2MB Instituto de Ingeniería Mecánica y Biomecánica

Outline

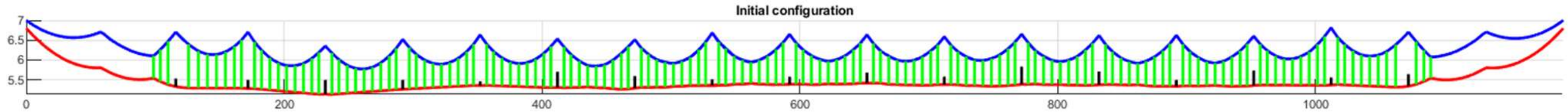
1. Simulation of overhead contact line
2. Pantograph models
3. Test bench
4. Pantograph testing

   Harmonic functions

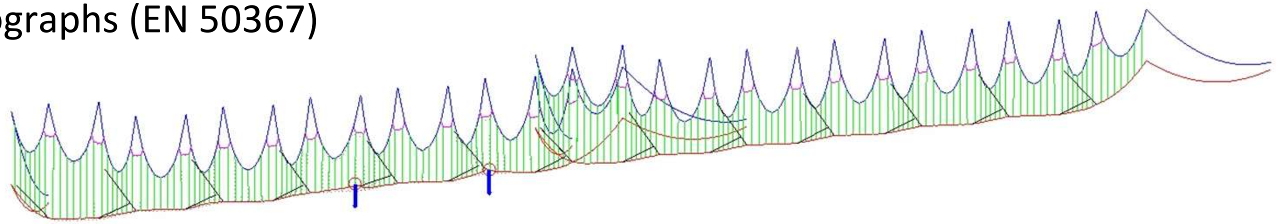
   Limitations: Non-linear response
5. Testing for simulation

   Guidelines for choosing the model & test for each application
6. HiL testing

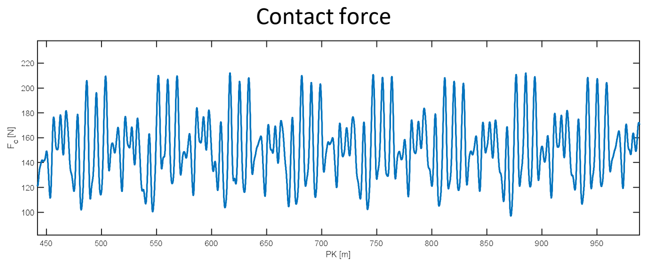
1. Simulation of OHL

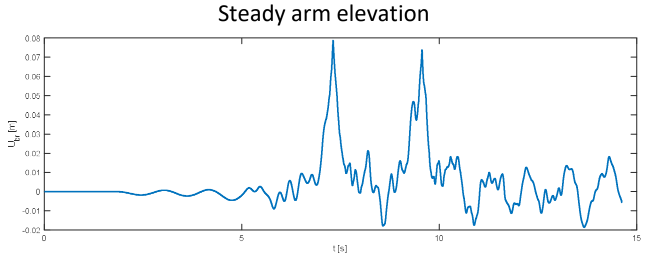


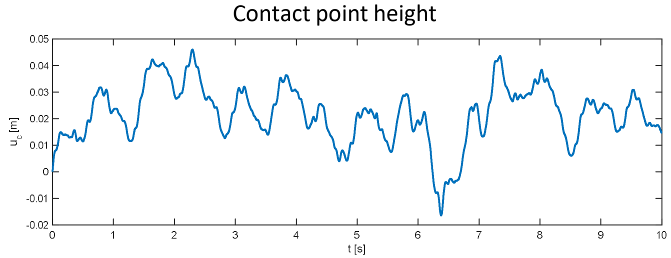
- Numerical simulations are becoming increasingly important in the transport sector
  - Ensure operational safety
  - Used for homologation of new lines / pantographs (EN 50367)
    Conformity assessment



  - Deliver results for designing new lines:

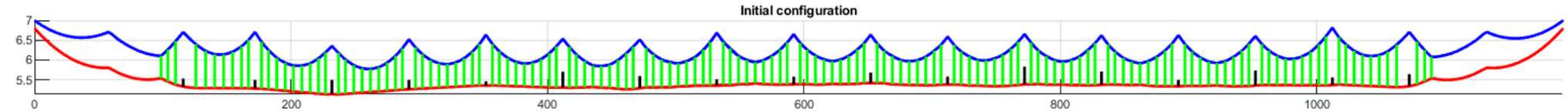






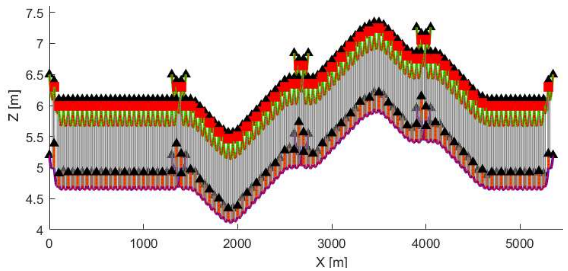
- Long-term goal:
  - Virtual homologation: replace on-track tests with numerical simulations as much as possible
  - Maintain the same level of safety and reliability
  - Resilience: system response under extreme or unexpected events

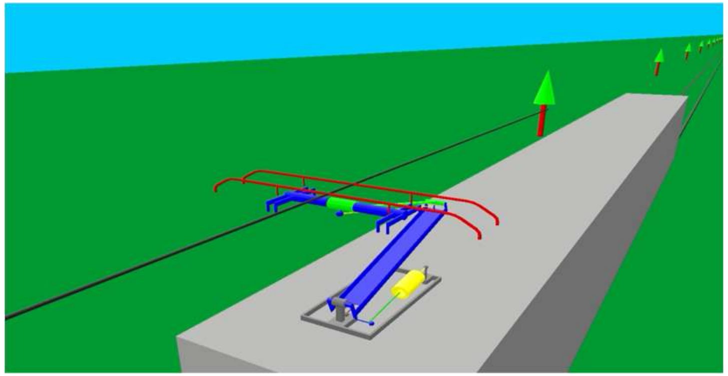
1. Simulation of OHL



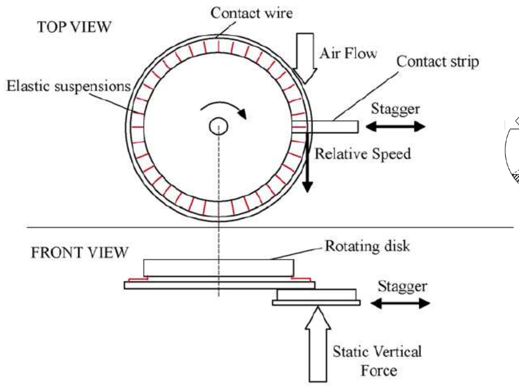
- Advanced simulations in Research Institutes

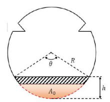
Catenary with gradient 1:625





Wear prediction using simulation results

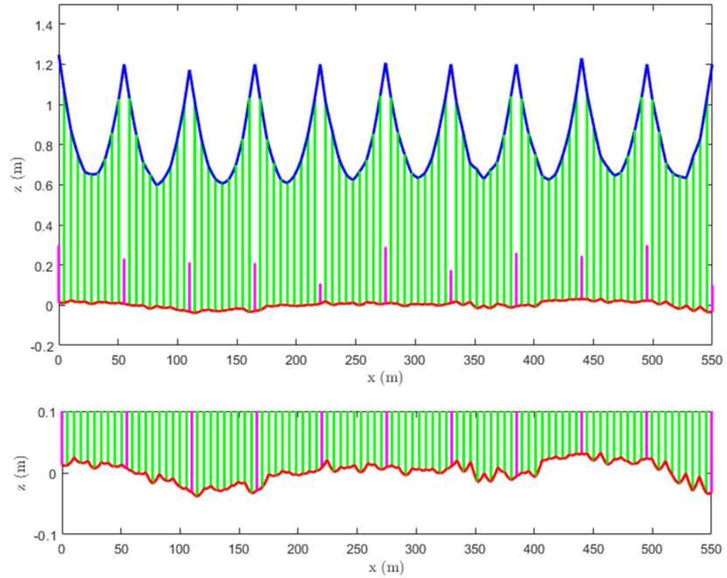




$$NWR = k_1\left(\frac{1}{2}\left(1+\frac{I_c}{I_0}\right)\right)^{-\alpha}\left(\frac{F_c}{F_0}\right)^{\beta}\frac{F_c}{H} + k_2\frac{R_c I_c^2}{Hv}(1-u) + k_3\frac{V_a I_c}{vH_m\rho}u$$

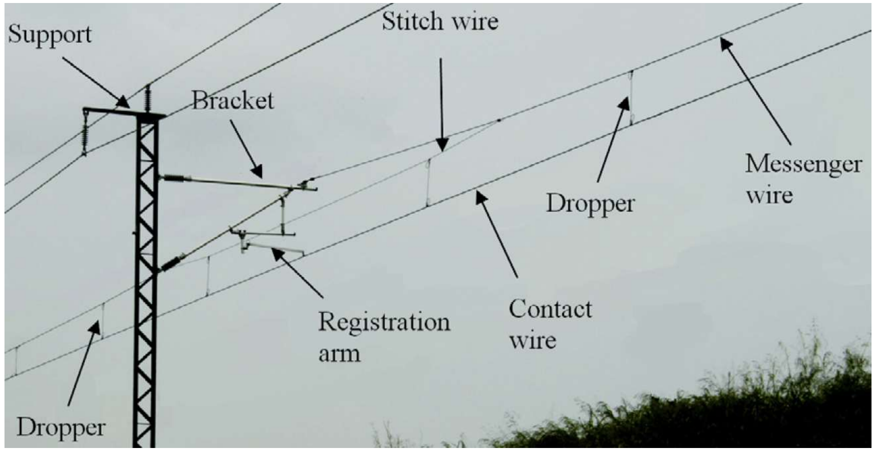
Mechanical Wear Electric Wear

Fast simulation: Parametric analysis and geometric optimization



1. Simulation of OHL - Components

- Catenary model
  - Designed geometry: dropper length, bracket position
  - Material properties: Young modulus, damping,
  - Cable properties: inertia, section, …
  - Tensioning devices



Structural components:

- Masts and supports
- Registration and steady arms
- Brackets

Cables:

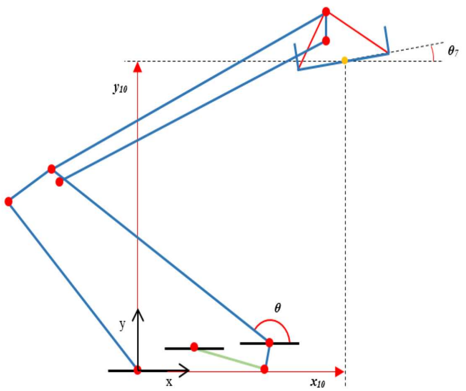
- Messenger wire
- Contact wire
- Droppers
- Stitch wire

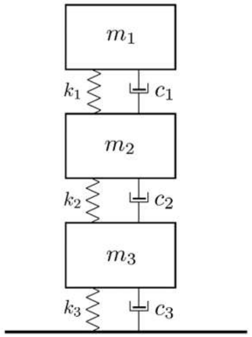
- Simulation code & user parameters
  - Algorithm parameters: time increment, …
  - Load cases to be solved: speed of the vehicle, number of pantographs, …
  - Regulation: EN 50318
  - International benchmark

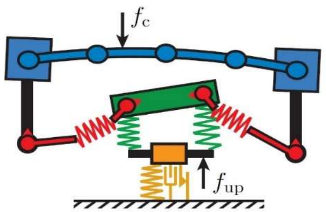
- Pantograph model

- Noticeable influence on the results
- Important to have affordable models
- How tune models with lab test

2. Pantograph model - Multibody . Lumped mass . Improved lumped





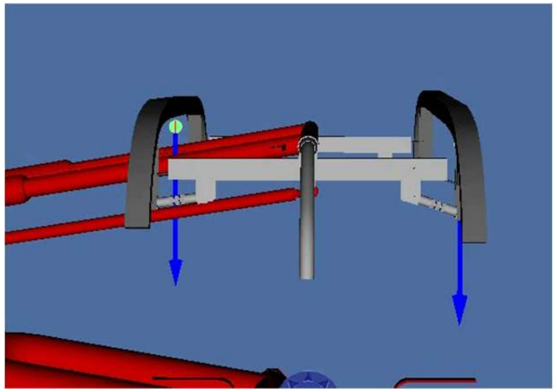


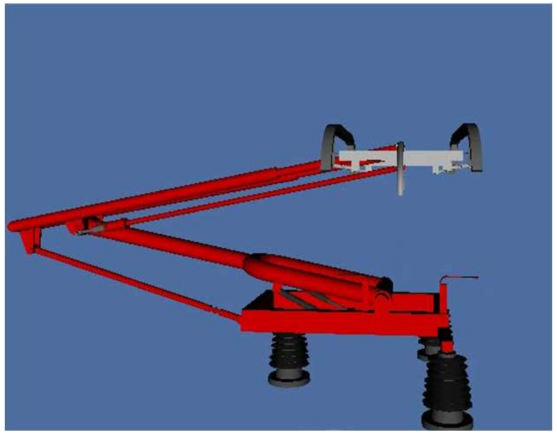
2. Pantograph model - Multibody . Lumped mass . Improved lumped

Physical Pantograph:

CAD Model:

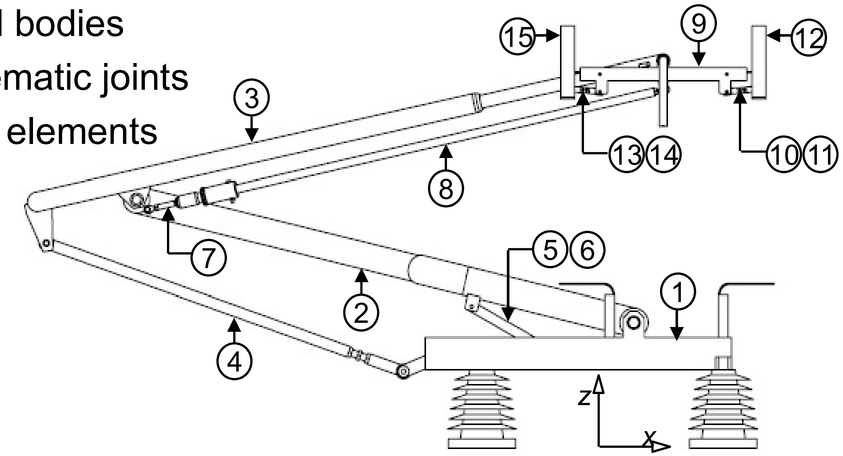
Multibody Model Animation:





Multibody Model:

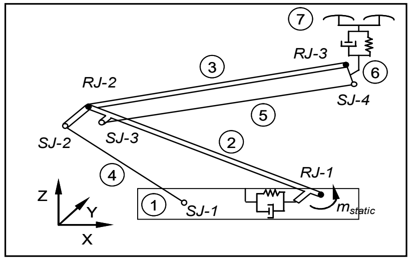
- 15 rigid bodies
- 22 kinematic joints
- 7 force elements

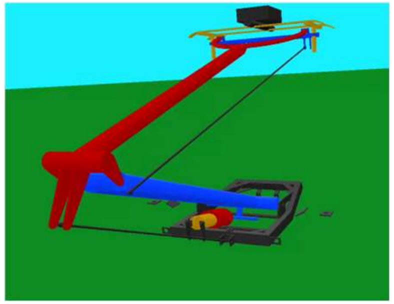


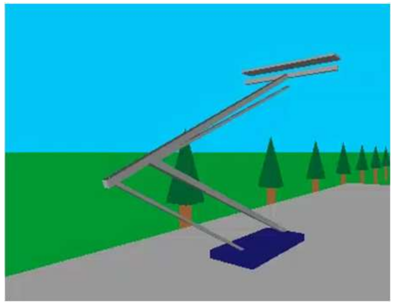
ID	Rigid Body	Mass [kg]
1	Base	34.86
2	Lower Arm	31.20
3	Upper Arm	22.61
4	Lower Link	3.216
5	Sp. Damper L.	0.862
6	Sp. Damper H.	2.094
7	Upper Link L.	0.939
8	Upper Link H.	3.233
9	Stabilization Arm	7.177
10	Head Link 1	0.377
11	Head Link 2	0.377
12	C. Strip Front	4.939
13	Head Link 3	0.377
14	Head Link 4	0.377
15	C. Strip Back	4.939

2. Pantograph model - Multibody . Lumped mass . Improved lumped

Technical Design Data







Testing can be used for validation

- Pros & cons

  + Build from design information

  + Only technical data is required. No laboratory tests

  + Model parameters have direct correspondence to the physical pantograph, allowing design optimization studies

  + Can be used for new pantograph design

  + Allow to study pantograph-catenary interaction in more complex and realistic environments: Curves on track and non linear aerodynamic effects

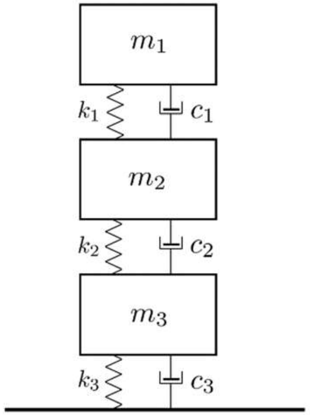
  - Difficult parameter tunning

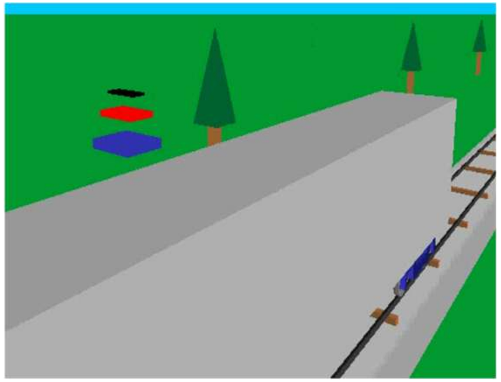
  - Information not always available

  - It is non-linear

  - Complex components: joint, spring, damper, …

2. Pantograph model - Multibody . **Lumped mass** . Improved lumped





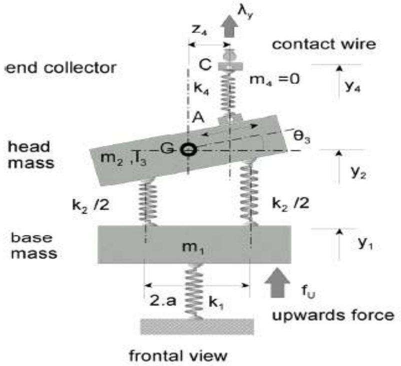
- Pros & cons
  - + Simple, dynamic equations well known
  - + Fast simulation
  - + Low number of parameters: m_1, m_2, m_3, c_1, c_2, c_3, k_1, k_2, k_3
  - + Most used – accepted by all

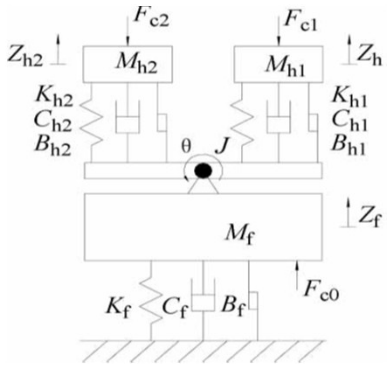
  > Linear model

  - - Parameter estimation
  - - Limitations in some cases
  - - No correspondence to the real pantograph components (don't allow design optimization)

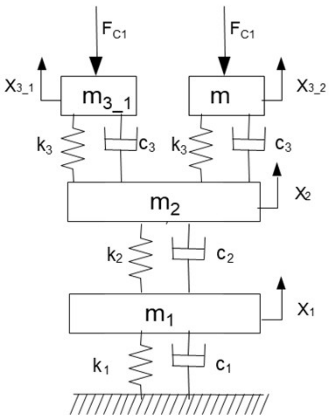
Need testing for parameter tunning and validation

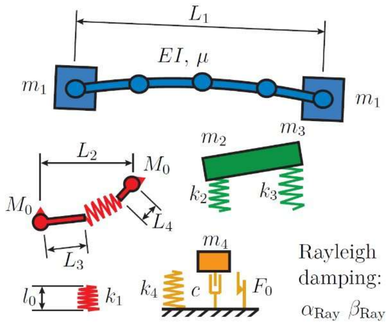
2. Pantograph model - Multibody . Lumped mass . Improved lumped

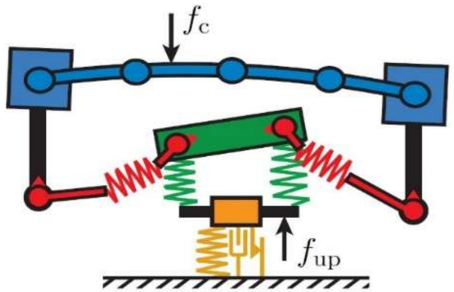




- Pros & cons
  - + Add complexity: 2D/3D, friction, strips deformation
  - + Better fitting of the real behaviour
  - - More difficult parameter estimation
  - - More complex to compute



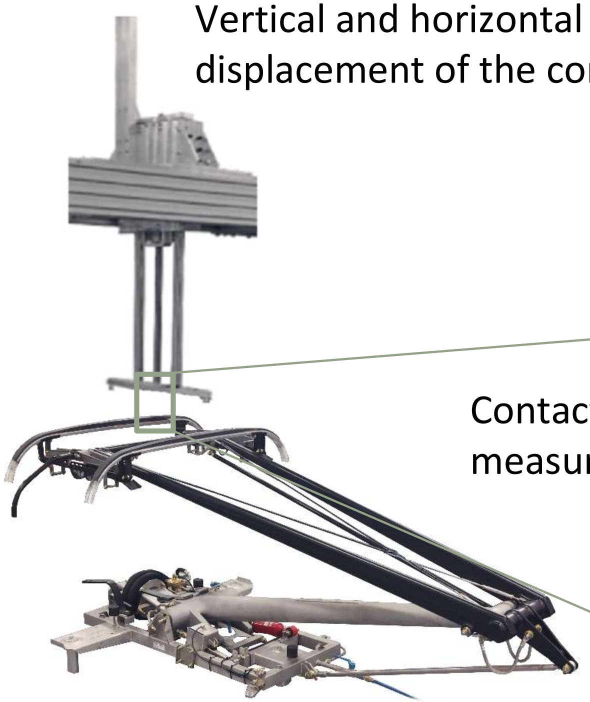




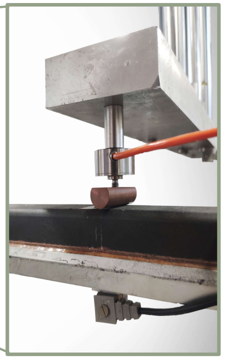
Need testing for tunning and validation

3. Test bench

Vertical and horizontal actuators: Impose displacement of the contact strips

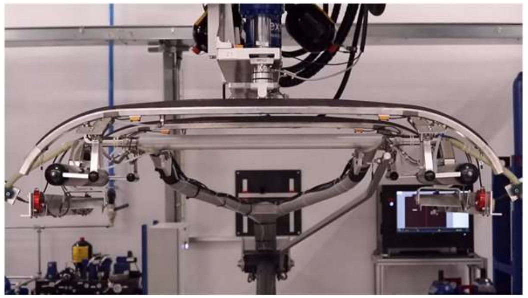


Contact force measurement



Pantograph

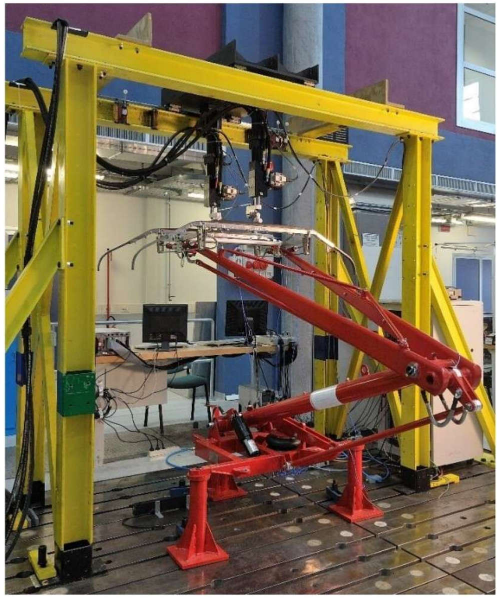
Other sensors:
- Acceleration
- Pressure
- Displacement



3. Test bench

Institute of Railway Research

POLIMI



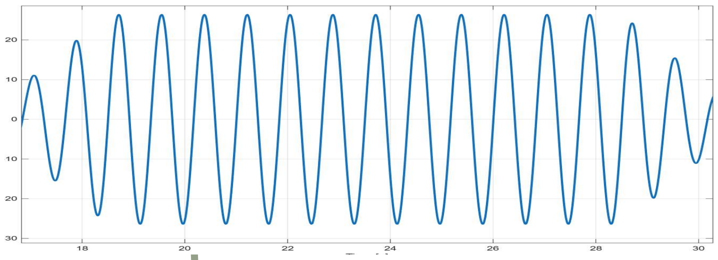
I2MB - UPV

Different actuation and control technology

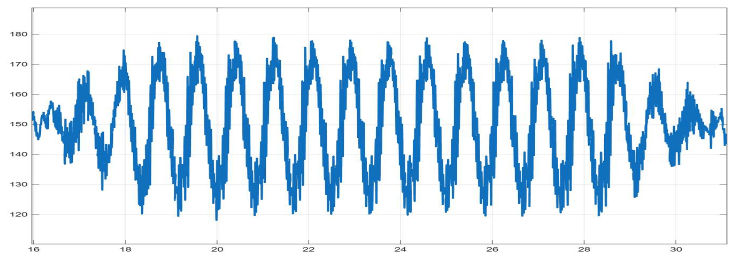
4. Pantograph testing

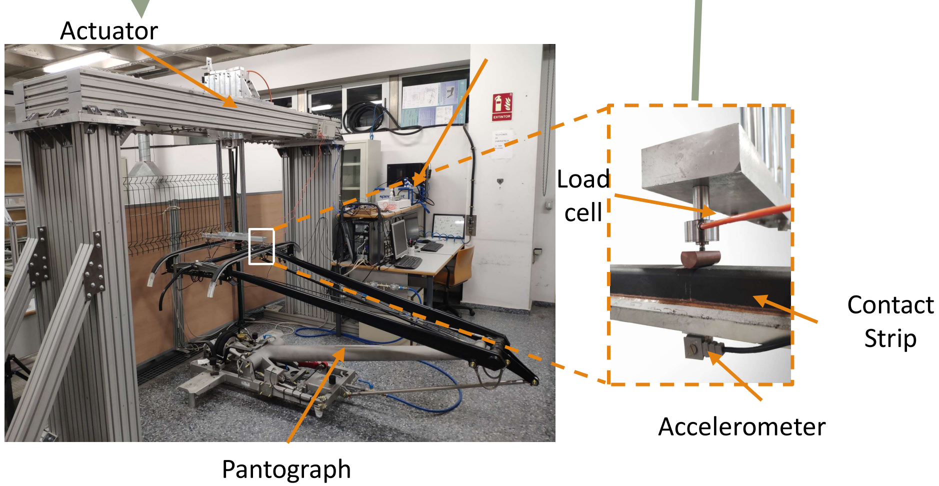
- Harmonic excitation
  - Frequency response function (Frf)

Displacement amplitude (U)

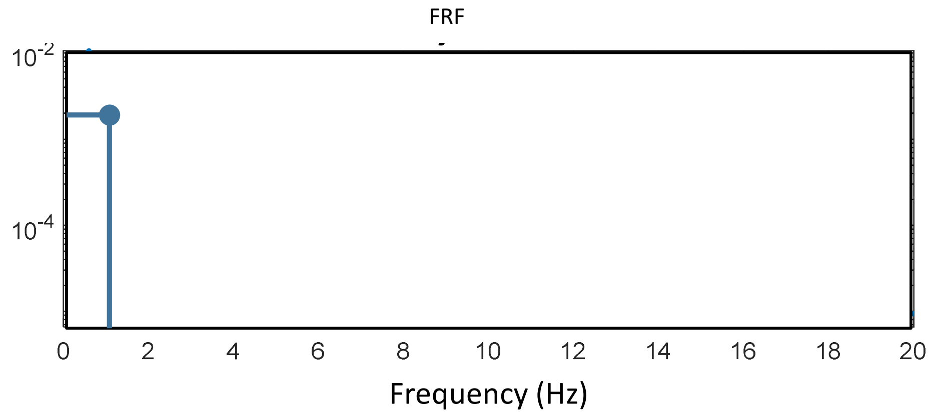


Contact force amplitude (F)





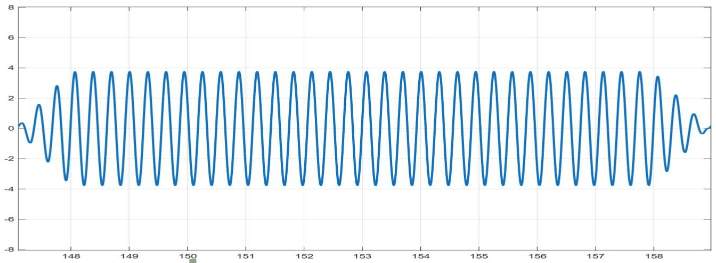
$$\text{Frf}=\frac{U}{F}$$



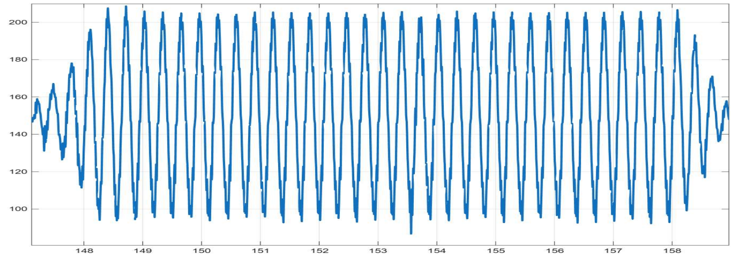
4. Pantograph testing

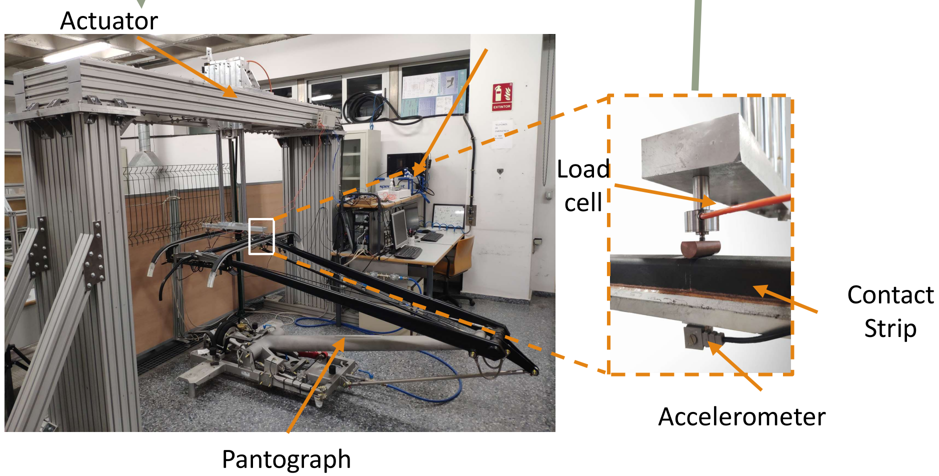
- Harmonic excitation
  - Frequency response function (Frf)

Displacement amplitude (U)

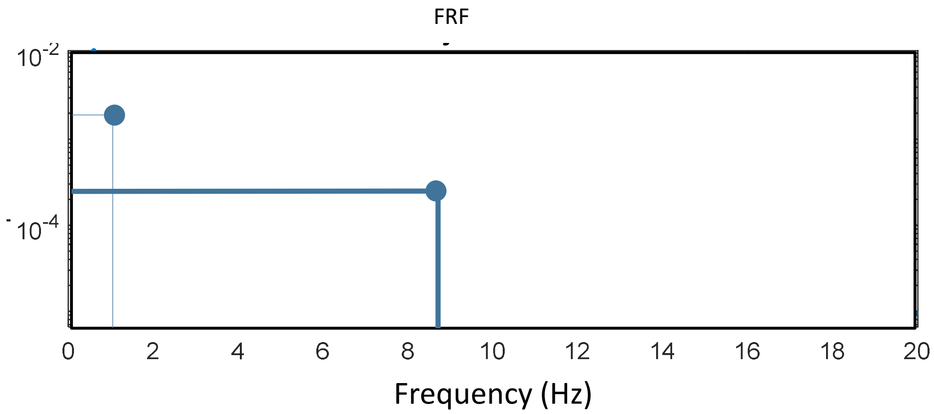


Contact force amplitude (F)





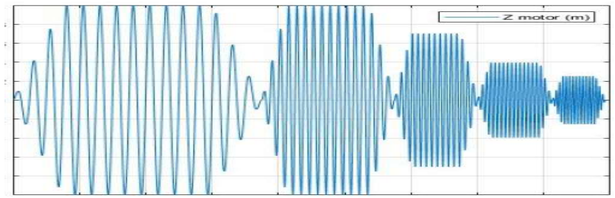
$$\text{Frf}= \frac{U}{F}$$



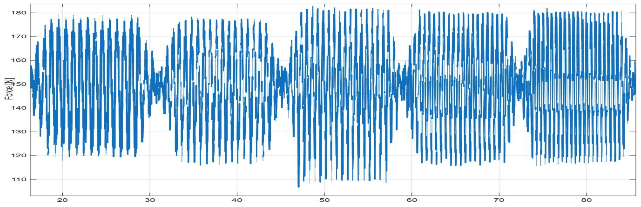
4. Pantograph testing

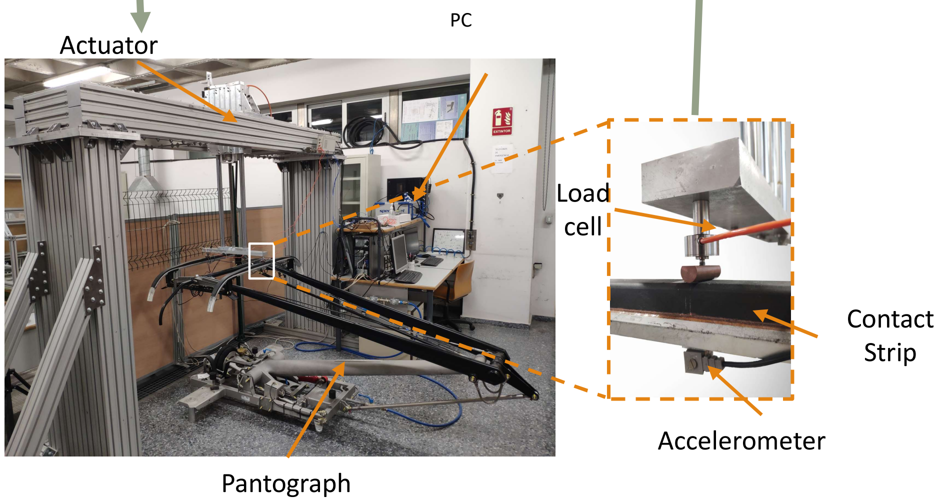
- Harmonic excitation
  - Frequency response function (Frf)

Displacement (U)



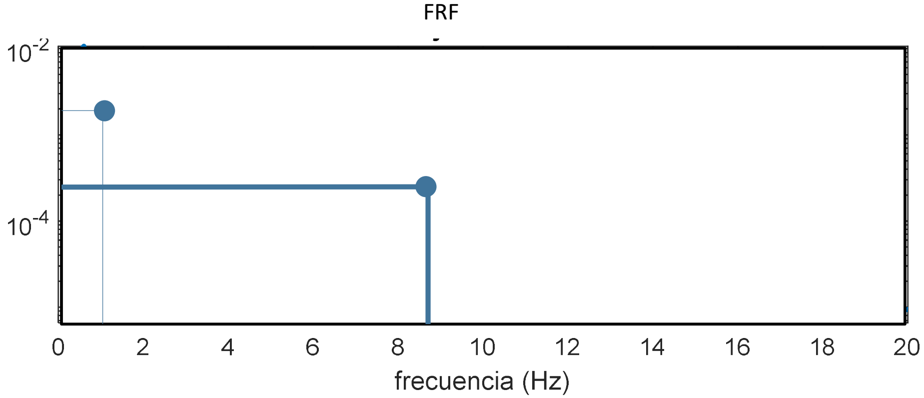
Contact force (F)





$$\text{Frf} = \frac{U}{F}$$

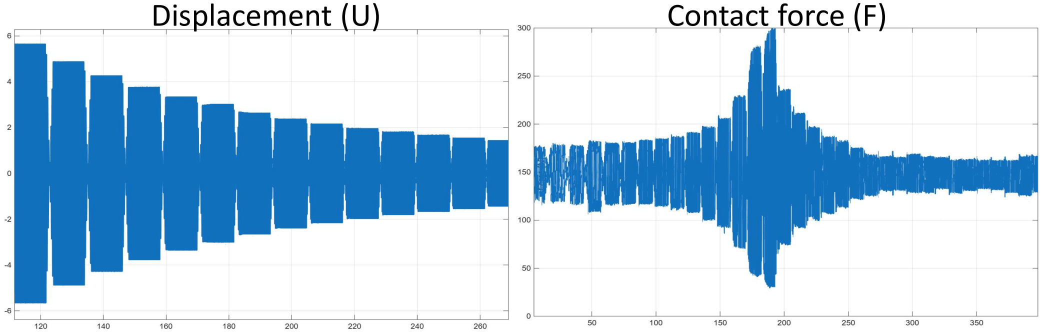
Used for tunning parameters and validation



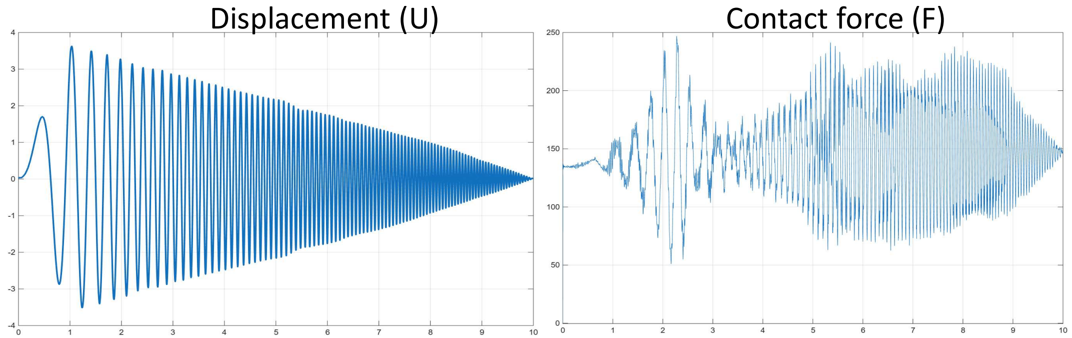
4. Pantograph testing

- Other excitation signals
  - Frequency response function (Frf)

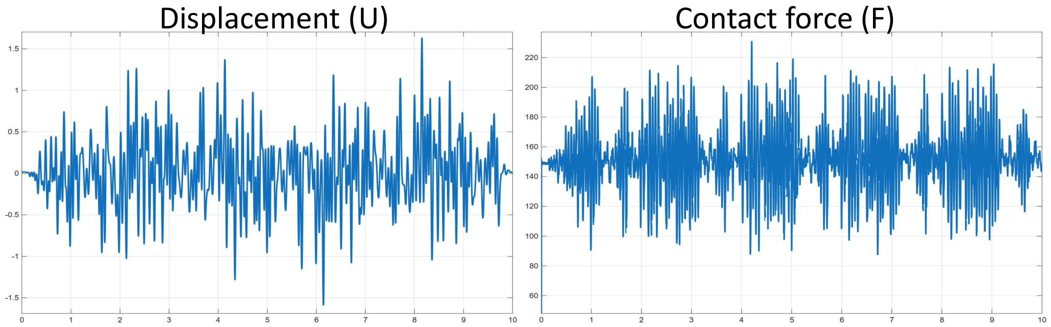
Slow sine sweep



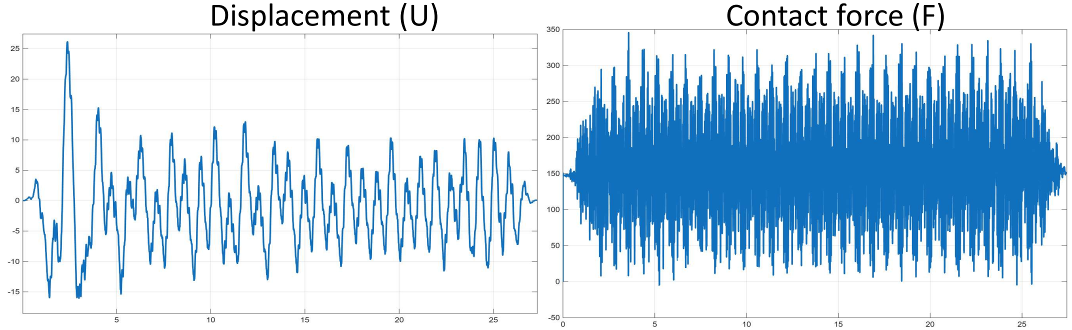
Chirp



Pseudo random

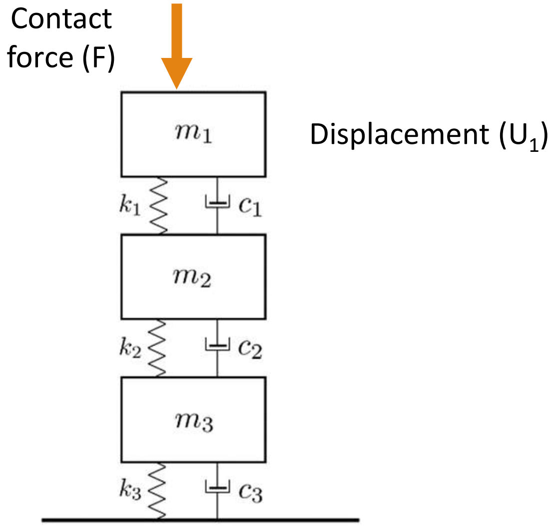


Pantograph-catenary interaction



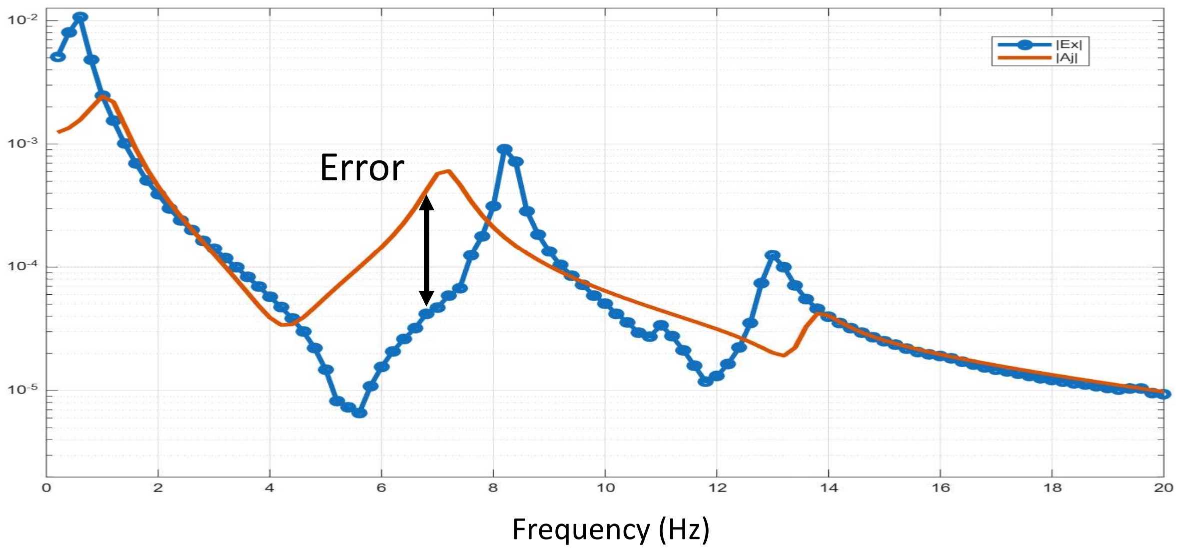
4. Pantograph testing

- Model fitting
  - Frequency response function (Frf)



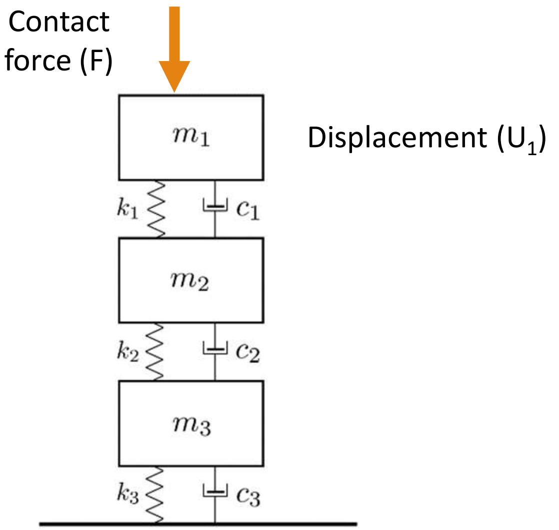
$$\mathrm{Frf} = \frac{U_1}{F}$$

$$\left(-\omega^2\begin{bmatrix} m_1 & 0 & 0 \\ 0 & m_2 & 0 \\ 0 & 0 & m_3 \end{bmatrix} + j\omega\begin{bmatrix} c_1 & -c_1 & 0 \\ -c_1 & c_1+c_2 & -c_2 \\ 0 & -c_2 & c_2+c_3 \end{bmatrix} + \begin{bmatrix} k_1 & -k_1 & 0 \\ -k_1 & k_1+k_2 & -k_2 \\ 0 & -k_2 & K_2+k_3 \end{bmatrix}\right)\begin{Bmatrix} U_1 \\ U_2 \\ U_3 \end{Bmatrix} = \begin{Bmatrix} F_c \\ 0 \\ F_0 \end{Bmatrix}$$



4. Pantograph testing

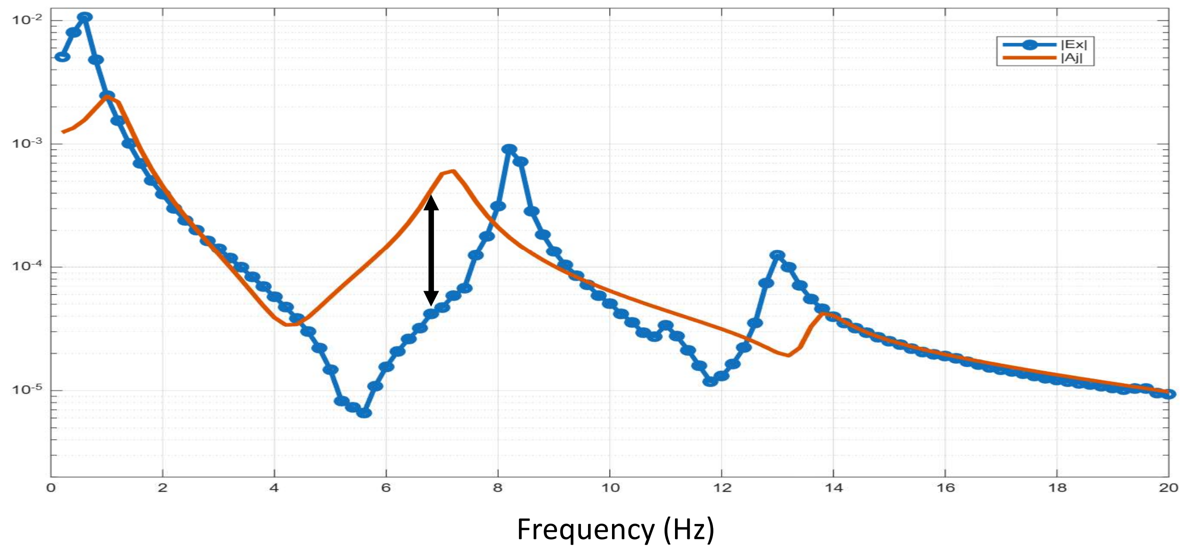
- Model fitting
  - Frequency response function (Frf)



$$Error = \sum_{i=1}^{Np}\left(Frf_{test}(\omega_i) - Frf_{model}(\omega_i)\right)^2$$

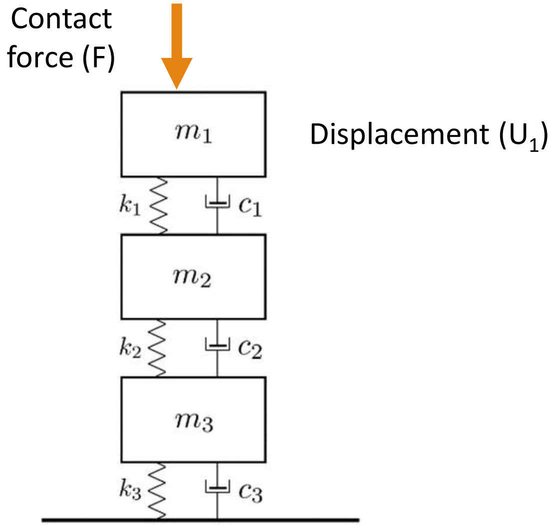
$$\text{Frf} = \frac{U_1}{F}$$

$$\left(-\omega^2\begin{bmatrix} m_1 & 0 & 0 \\ 0 & m_2 & 0 \\ 0 & 0 & m_3 \end{bmatrix} + j\omega\begin{bmatrix} c_1 & -c_1 & 0 \\ -c_1 & c_1+c_2 & -c_2 \\ 0 & -c_2 & c_2+c_3 \end{bmatrix} + \begin{bmatrix} k_1 & -k_1 & 0 \\ -k_1 & k_1+k_2 & -k_2 \\ 0 & -k_2 & K_2+k_3 \end{bmatrix}\right)\begin{Bmatrix} U_1 \\ U_2 \\ U_3 \end{Bmatrix} = \begin{Bmatrix} F_c \\ 0 \\ F_0 \end{Bmatrix}$$



4. Pantograph testing

- Model fitting
  - Frequency response function (Frf)

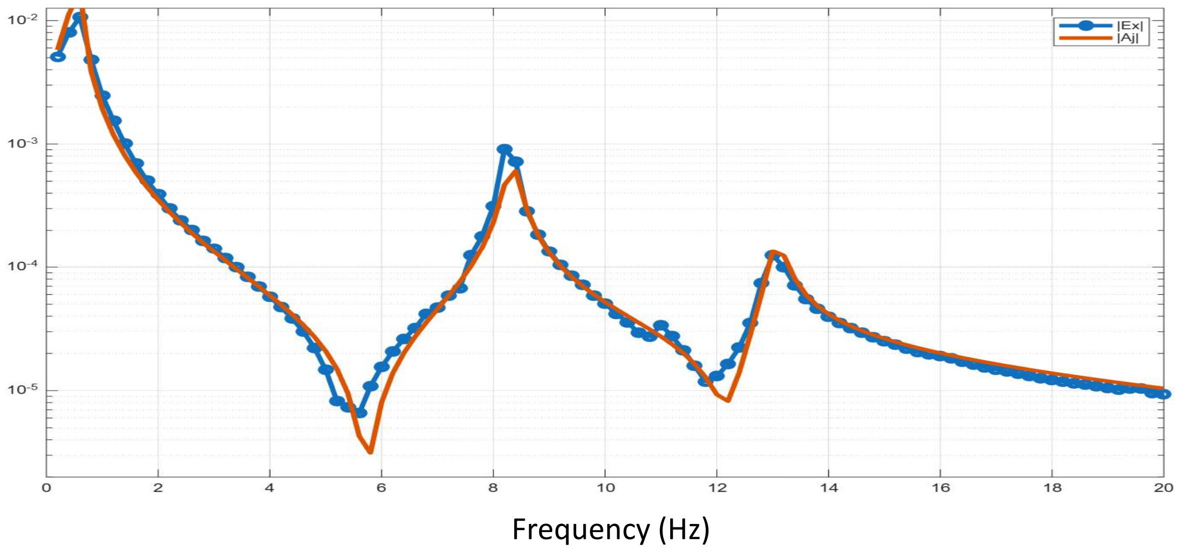


$$\left(-\omega^2\begin{bmatrix} m_1 & 0 & 0 \\ 0 & m_2 & 0 \\ 0 & 0 & m_3 \end{bmatrix} + j\omega\begin{bmatrix} c_1 & -c_1 & 0 \\ -c_1 & c_1+c_2 & -c_2 \\ 0 & -c_2 & c_2+c_3 \end{bmatrix} + \begin{bmatrix} k_1 & -k_1 & 0 \\ -k_1 & k_1+k_2 & -k_2 \\ 0 & -k_2 & K_2+k_3 \end{bmatrix}\right)\begin{Bmatrix} U_1 \\ U_2 \\ U_3 \end{Bmatrix} = \begin{Bmatrix} F_c \\ 0 \\ F_0 \end{Bmatrix}$$

Weighted error

$$Error = \sum_{i=1}^{Np} W_i\left(Frf_{test}(\omega_i) - Frf_{model}(\omega_i)\right)^2$$

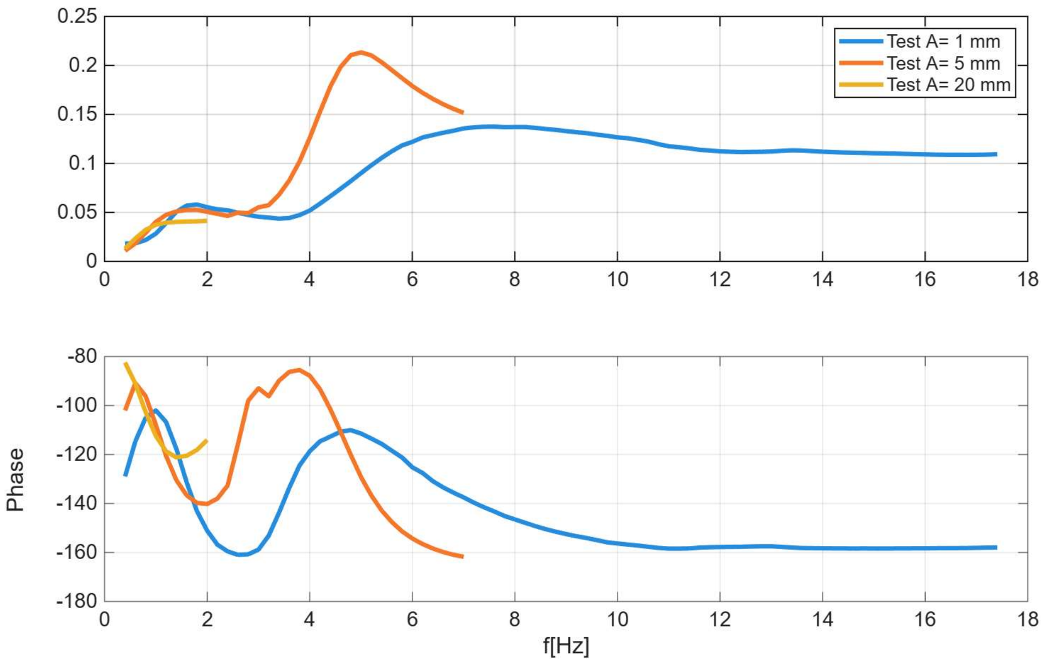
$$\text{Frf} = \frac{U_1}{F}$$



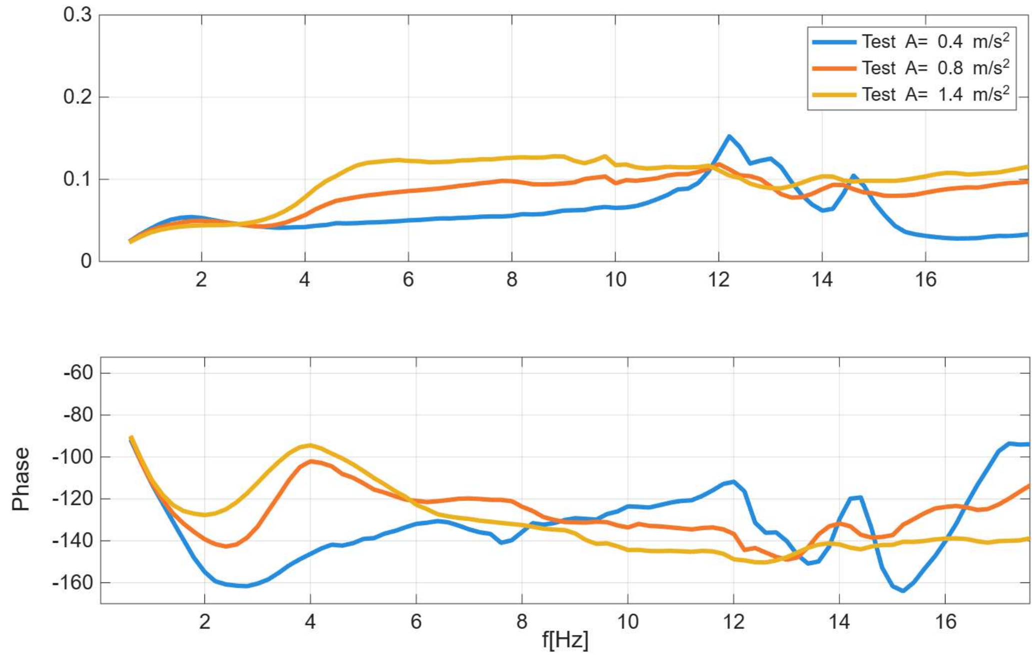
4. Pantograph testing

- Limitations
  - Variation of the Frf with amplitude of the input
  - Pneumatic system, Non-linear springs, joint friction

Acceleration Frf (Pantograph 1)



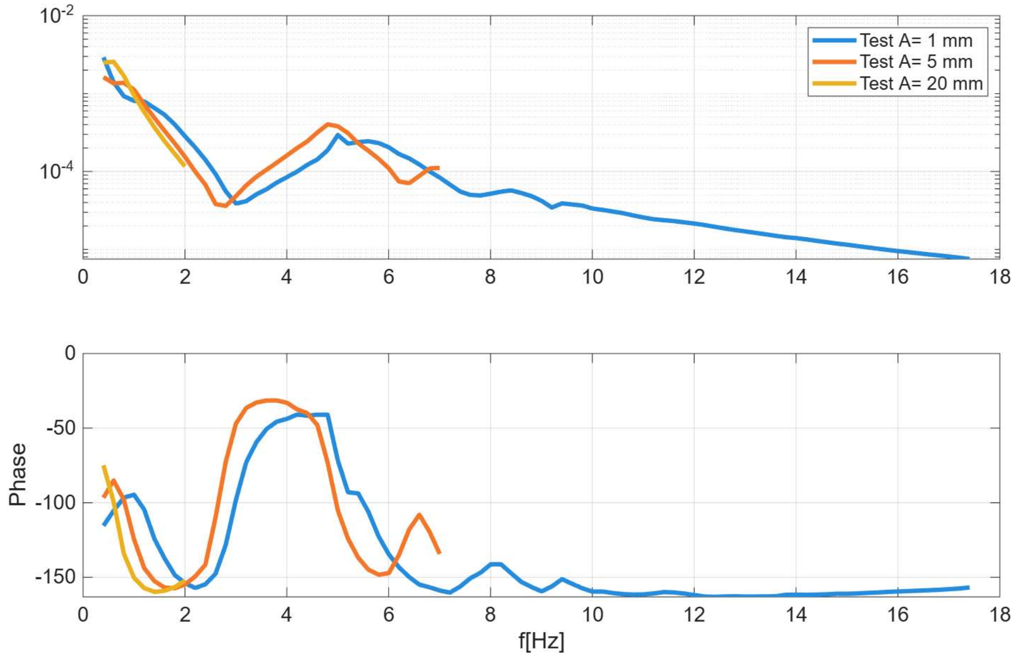
Acceleration Frf (Pantograph 1)



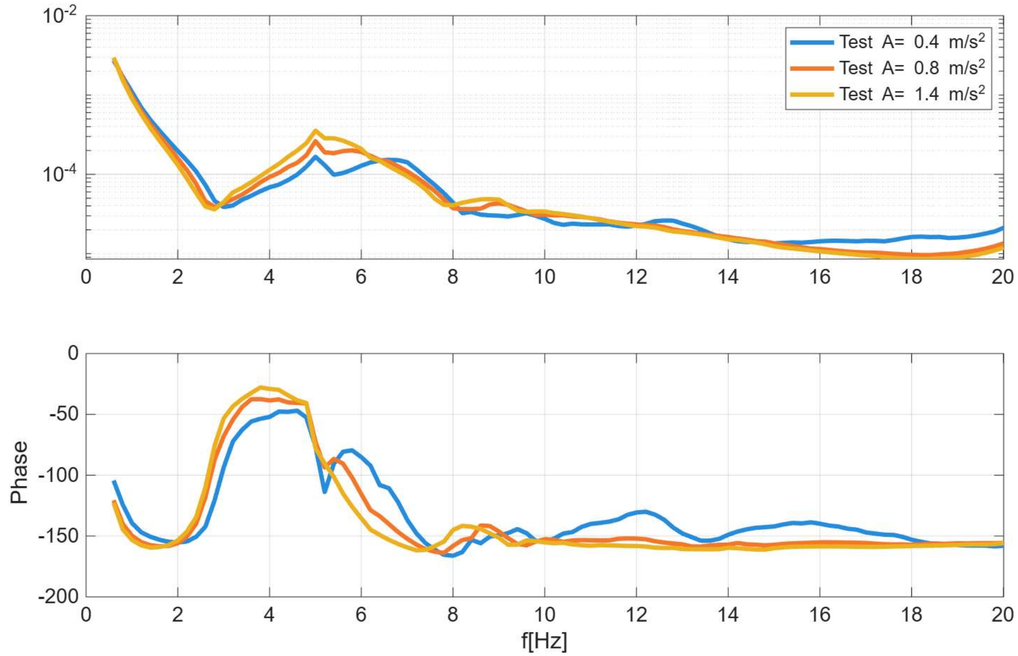
4. Pantograph testing

- Limitations
  - Variation of the Frf with amplitude of the input
  - Pneumatic system, Non-linear springs, joint friction

Displacement Frf (Pantograph 2)



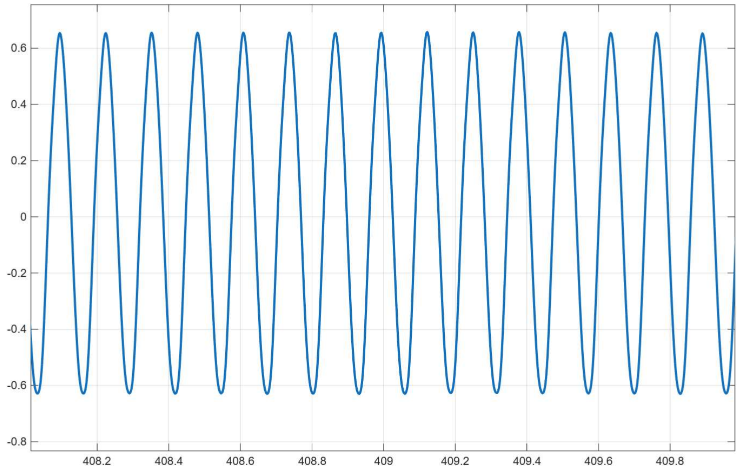
Displacement Frf (Pantograph 2)



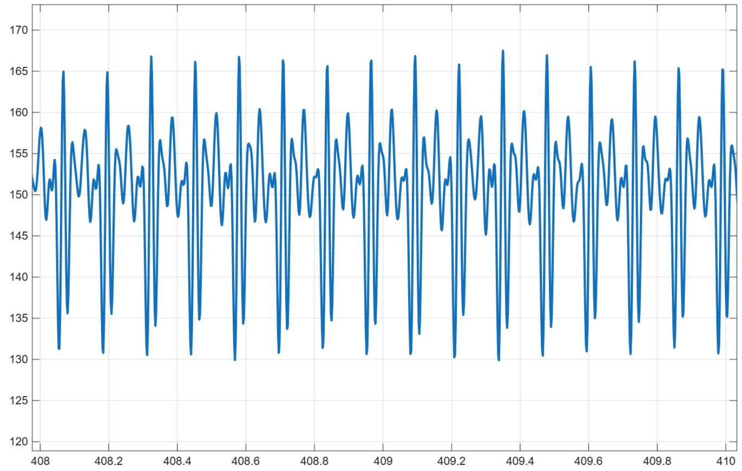
4. Pantograph testing

- Limitations (Non-linear response)
  - Sinusoidal displacement → Non-sinusoidal force
  - Influence of mean pantograph height
  - Influence of mean contact force

Displacement (Z)

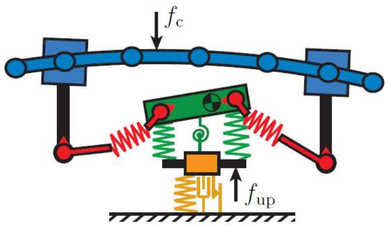


Contact force (F)



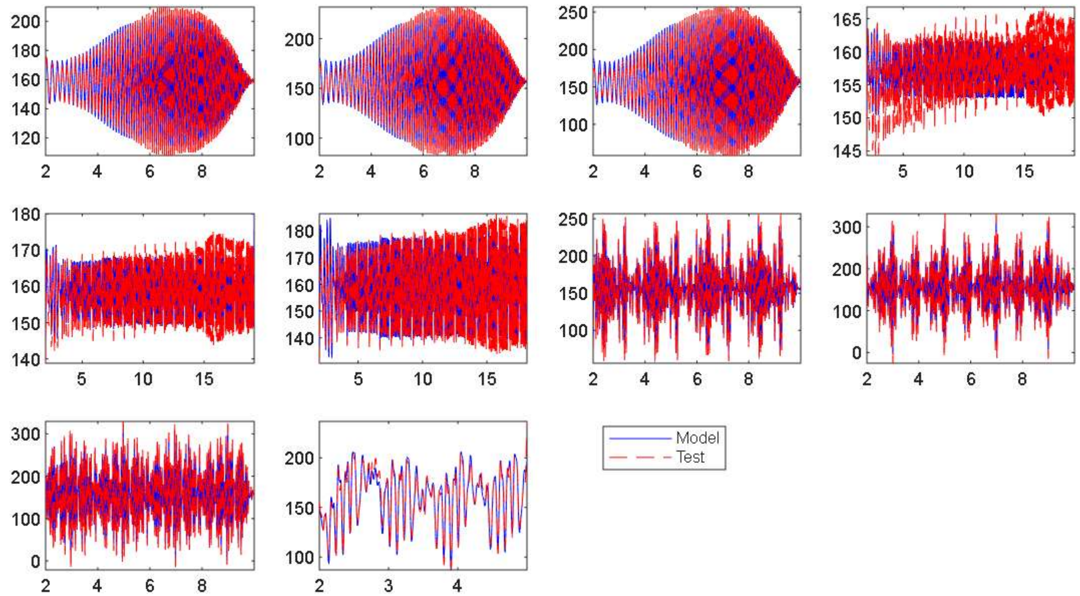
4. Pantograph testing

- Fitting with advanced models
  - **Time domain** vs frequency domain
  - 19 parameters (Genetic Algorithm)

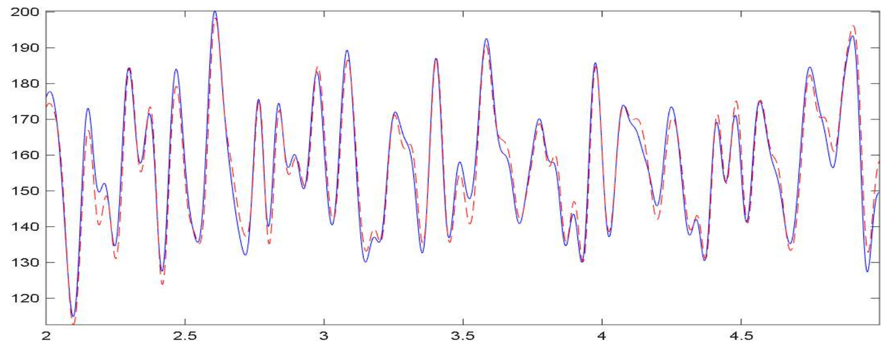


- Flexibility of the contact strips
- Rotational friction of the collector head suspension springs
- Rotation of contact strips and pantograph upper frame
- Validation up to 60 Hz

Trainning data



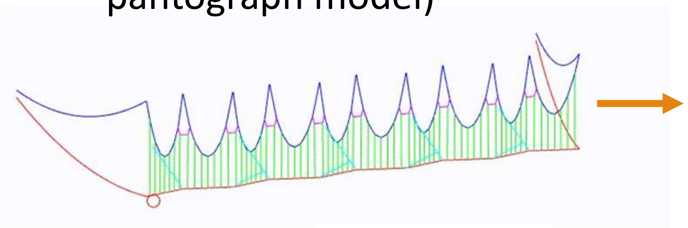
Validation (Contact force vs time)

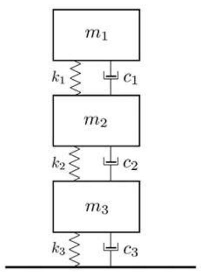


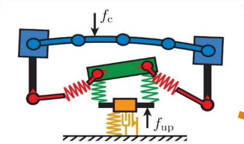
5. Testing for simulation models

- IDEA: Depending on the problem (type of catenary, speed, pantograph) a suitable pantograph model should be used
  - The simplest model that provide acceptable accuracy
  - Guidelines for pantograph testing methods to build models

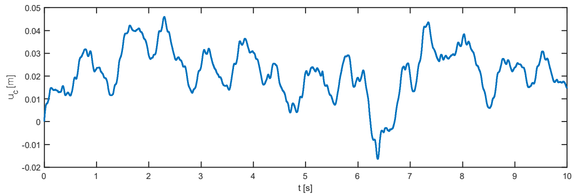
Simulation (chosen pantograph model)



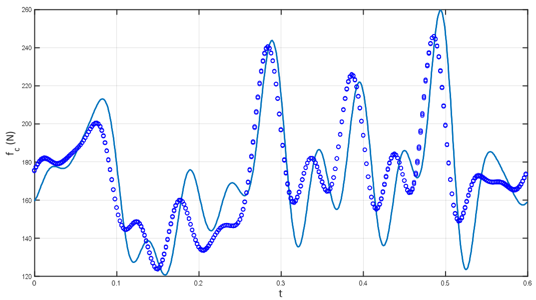




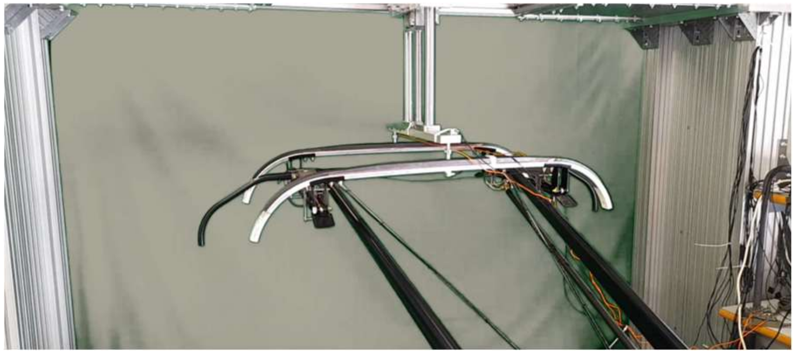
Contact wire height



Contact force (simulation and test)

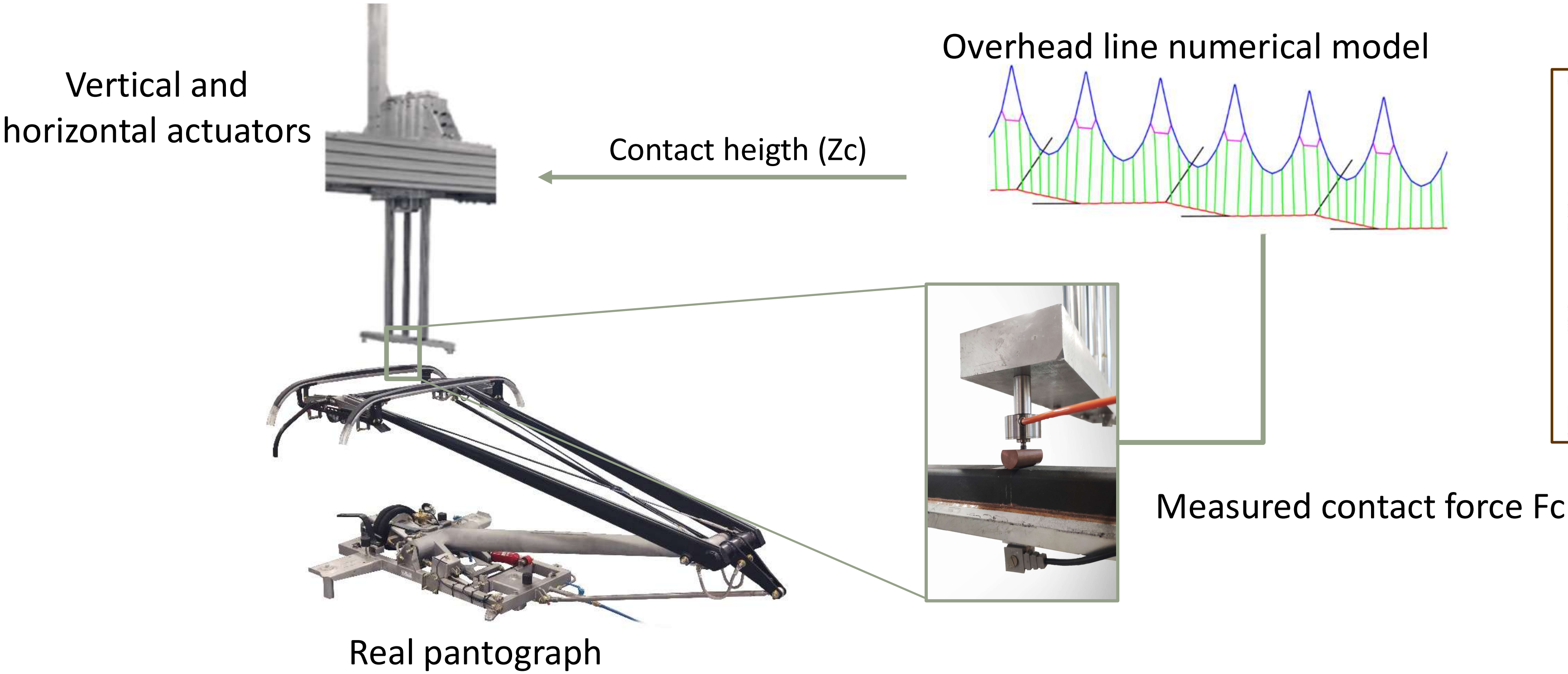


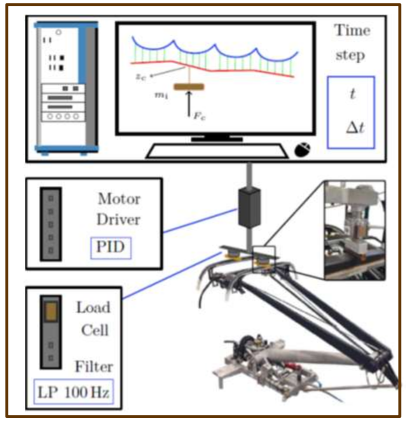
Test rig



6. Hardware-in-the-Loop

- HiL is a compromise between pure numerical simulation and on-track tests





- In the HiL test, the real pantograph interacts with a simulated OCL.
  - Tests can be carried out both in real time and off-line.
  - Experiences in this field have been already given by different research teams using different technologies

6. Hardware-in-the-Loop

- HiL is a compromise between pure numerical simulation and on-track tests