Mechanical System Dynamics

Hovenring – Assessment of the tension in the stay cables

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Aim of the laboratory

Assessment of the tension of the stay cables of a real system through an experimental campaign.

Lecture outline:

- System description: geometry and mechanical properties
- Tension force assessment procedure
- FE model of the physical system
- Experimental setup
    - Measurement system
    - Input: system excitation
    - Output: what to measure
- Data treatment
- Comparison with FE model

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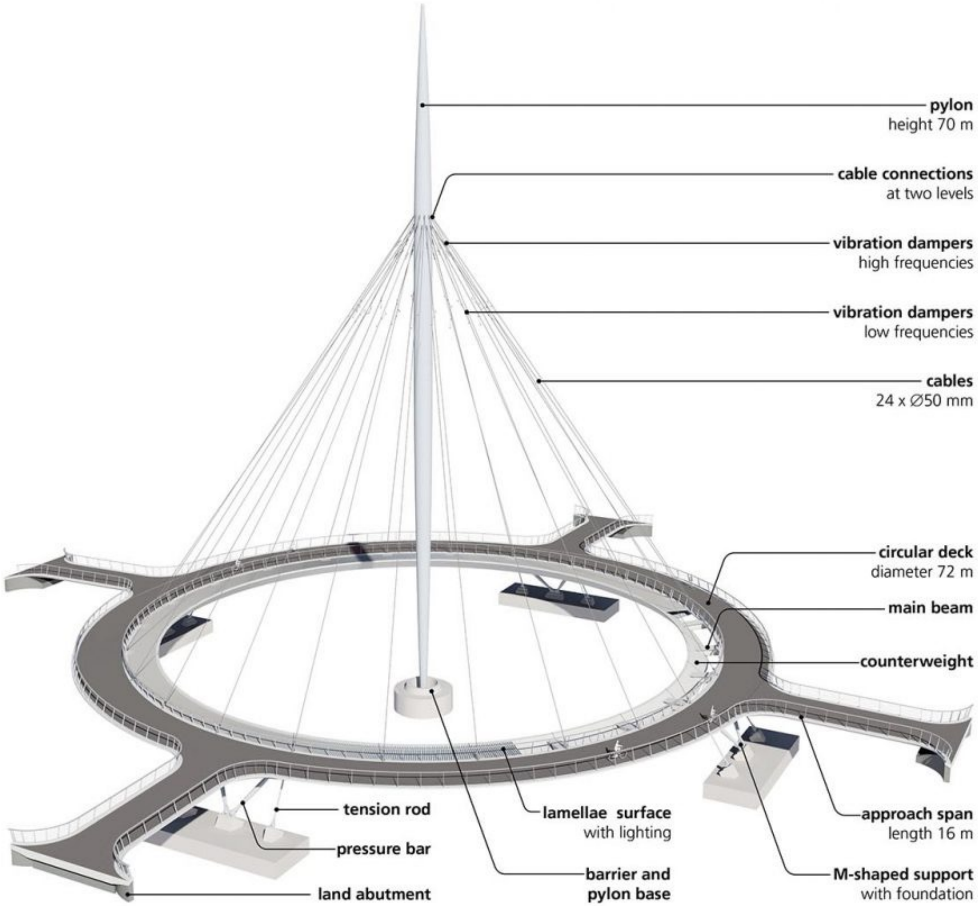
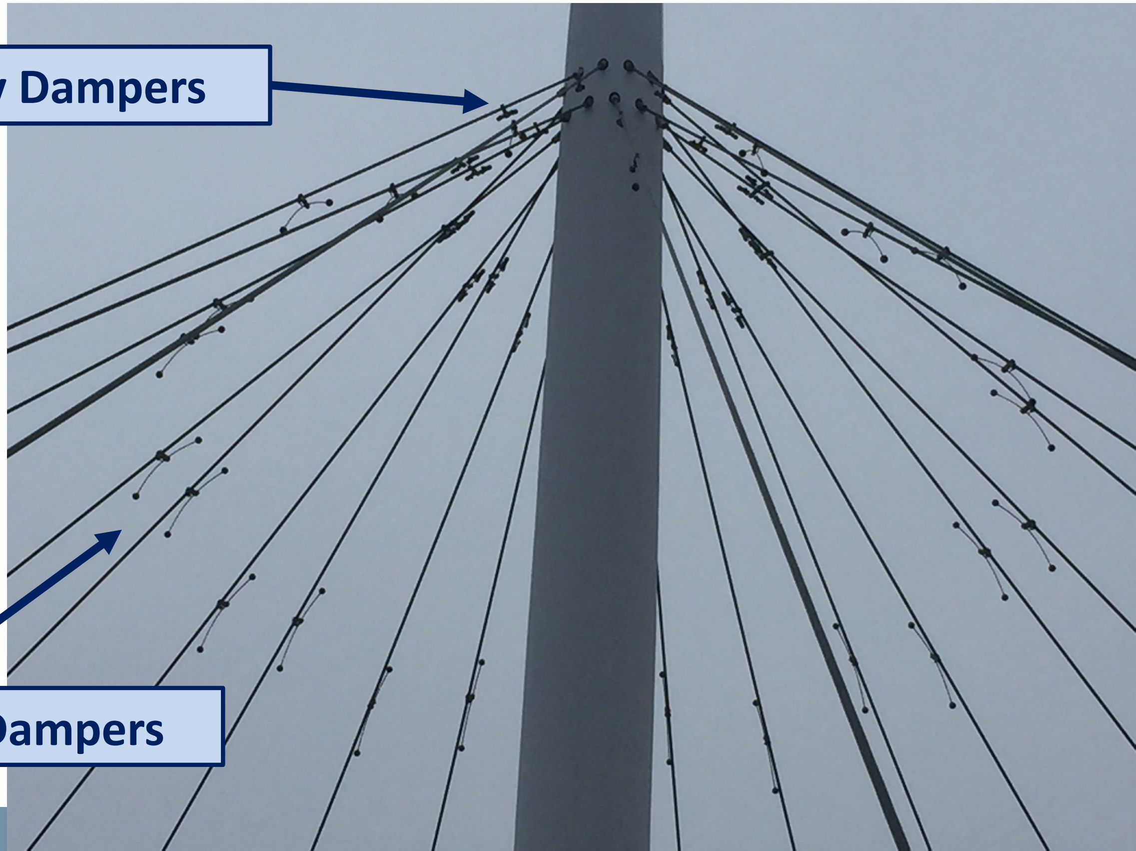
Hovenring Bridge – System description

- 70 m high central tower
- cable connectors in two levels
- dampers (low frequencies & high frequencies)
- 24 cable (ϕ 50 mm)
- deck-cable connectors
- circular deck (diameter 72 m)



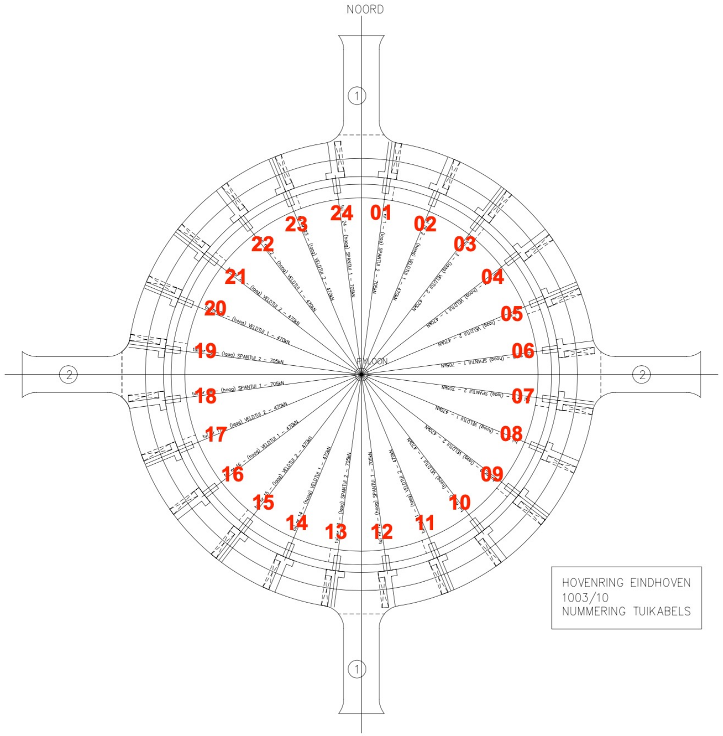
Hovenring Bridge - Dampers

High Frequency Dampers



Low Frequency Dampers

Hovenring Bridge – Cables



Number	Type	Nominal Tension [kN]	Nominal total length [m]
Cable 01	Spantui 2	705	52.647
Cable 02	Veldtui 1	470	53.423
Cable 03	Veldtui 2	470	52.647
Cable 04	Veldtui 1	470	53.423
Cable 05	Veldtui 2	470	52.647
Cable 06	Spantui 1	705	53.423
Cable 07	Spantui 2	705	52.647
Cable 08	Veldtui 1	470	53.423
Cable 09	Veldtui 2	470	52.647
Cable 10	Veldtui 1	470	53.423
Cable 11	Veldtui 2	470	52.647
Cable 12	Spantui 1	705	53.423
Cable 13	Spantui 2	705	52.647
Cable 14	Veldtui 1	470	53.423
Cable 15	Veldtui 2	470	52.647
Cable 16	Veldtui 1	470	53.423
Cable 17	Veldtui 2	470	52.647
Cable 18	Spantui 1	705	53.423
Cable 19	Spantui 2	705	52.647
Cable 20	Veldtui 1	470	53.423
Cable 21	Veldtui 2	470	52.647
Cable 22	Veldtui 1	470	53.423
Cable 23	Veldtui 2	470	52.647
Cable 24	Spantui 1	705	53.423

Lecture outline

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Assessment procedure for the tension force in each cable

1. A FE model for the cables is created, including the effects due to the TMDs of the structure together with a suitable representation of the constraints
2. **For each cable, the first eigenfrequency was measured by mean of free motion tests**
3. A direct measurement of the tension force is performed in 4 cables with a jacking system
4. The FE model of the cable is validated using such “direct” measurement of the tension values, the exact cable length and the experimental frequencies

Direct force measurement + First eigenfrequency detection → Validated FEM

5. **The tension of the remaining 20 cables is estimated using the validated FE model and the experimental results**

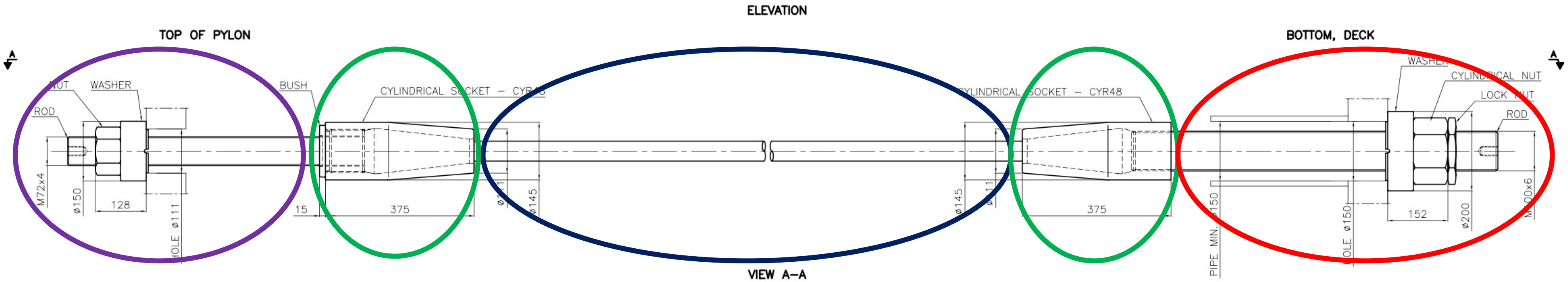
The estimated tension values are finally compared with the nominal design values.

FE model

The stay cables are modelled using an equivalent tensioned beam finite-element scheme.

For each cable, the following elements are modelled (from deck to pylon):

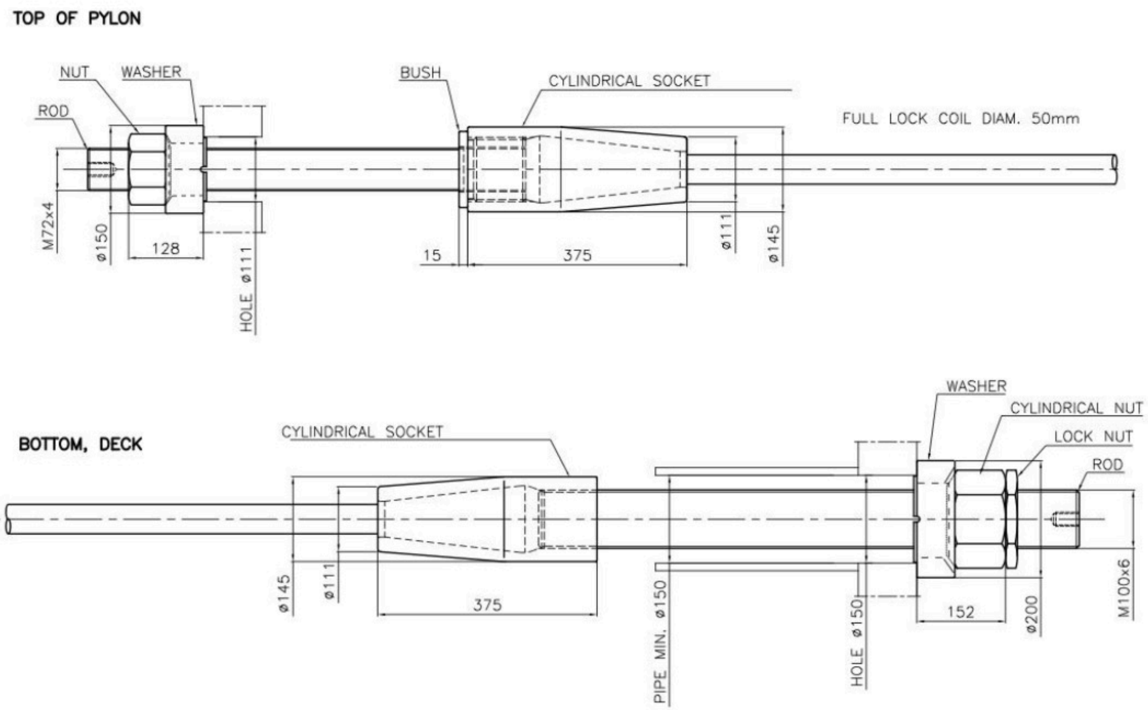
- Threaded bar M100 (inclusive of washer length at deck constraint)
- Socket
- Cable (full lock coil 50 mm)
- Socket
- Threaded bar M72 (inclusive of washer length at pylon constraint)



FE model

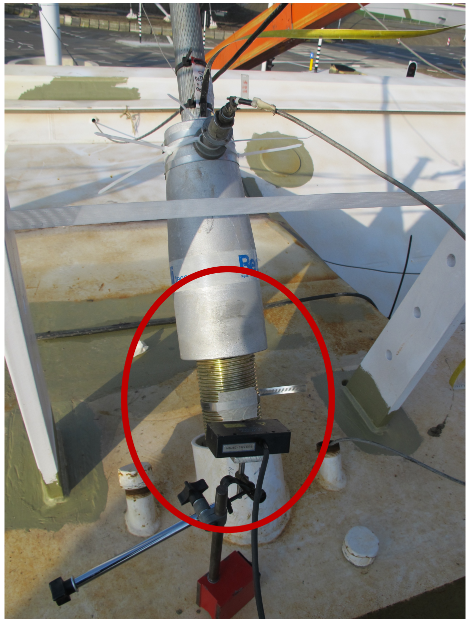
The mesh of the threaded bars and cable was carefully refined at boundary conditions, with the purpose of an optimum modelling of the structure at the locations of maximum bending.

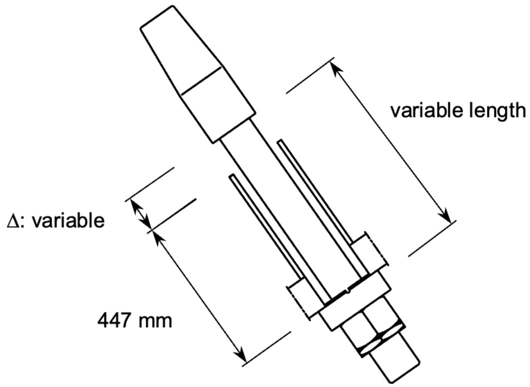
- 6 elements for the threaded bars
- 6 for the sockets
- 204 elements for the cable



FE model

Moreover, the actual length of each cable may be different from the nominal one for the threated bar length on the deck side. The threaded bar is 447 mm plus a variable length here called Δ.



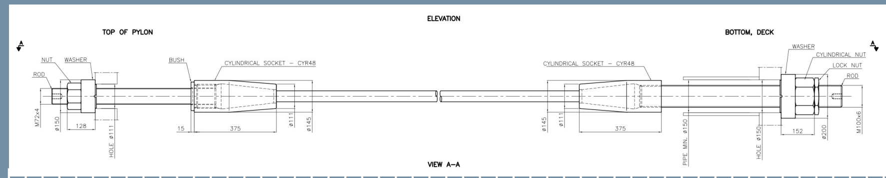


Δ is measured for each cable

FE model – Elements properties

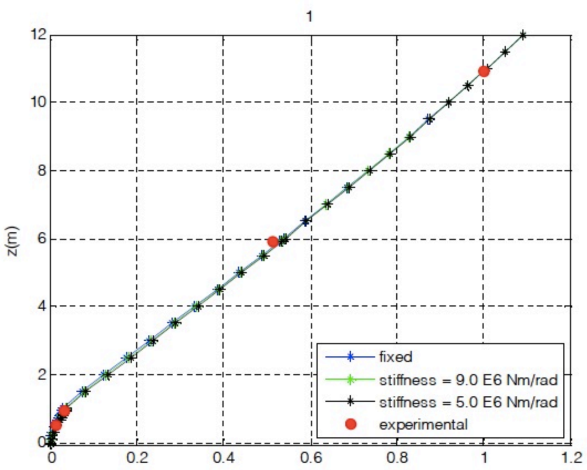
Properties	Unit	Threaded bar M100	Socket D145	Threaded bar M72	Socket D129	Cable
Ø (stiff)	[m]	0.095	0.145	0.068	0.129	0.05
Ø (stress)	[m]	0.093	0.145	0.067	0.129	0.05
E	[N/m^2]	2.06E+11	2.06E+11	2.06E+11	2.06E+11	1.65E+11
Area	[m^2]	7.01E-03	1.65E-02	3.66E-03	1.31E-02	1.68E-03
Density	[kg/m^3]	7.85	7.85	7.85	7.85	8.393
Unit mass	[kg/m]	55.1	129.6	28.8	102.6	14.1
EA	[N]	1.44E+09	3.40E+09	7.55E+08	2.69E+09	2.78E+08
J_{Stiff}	[m^4]	3.91E-06	2.17E-05	1.07E-06	1.36E-05	1.66E-07
J_{Stress}	[m^4]	3.62E-06	2.17E-05	9.95E-07	1.36E-05	-
EJ_{Stiff}	[Nm^2]	8.06E+05	4.47E+06	2.20E+05	2.80E+06	2.75E+04
W	[m^3]	7.81E-05	2.99E-04	2.97E-05	2.11E-04	5.34E-06

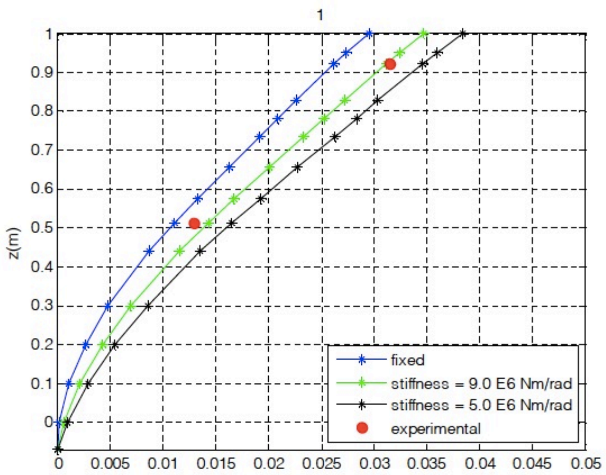
FE model - Constraints



Boundary conditions have been set at the washer-nut interface locations. Because of friction and the high-tension force, the spherical nuts and washers act more as clamps than as hinges.

Therefore, <u>a hinge and a lumped torsional stiffness</u> have been considered for a realistic model of the constraints.





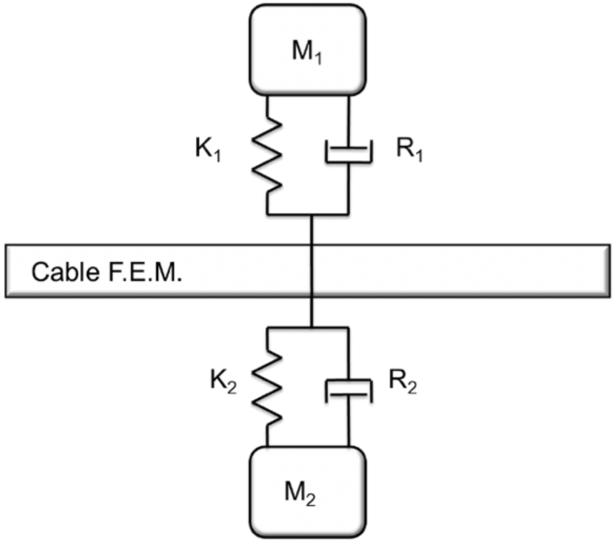
Best fitting procedure between the experimental and numerical first modal shape of the system

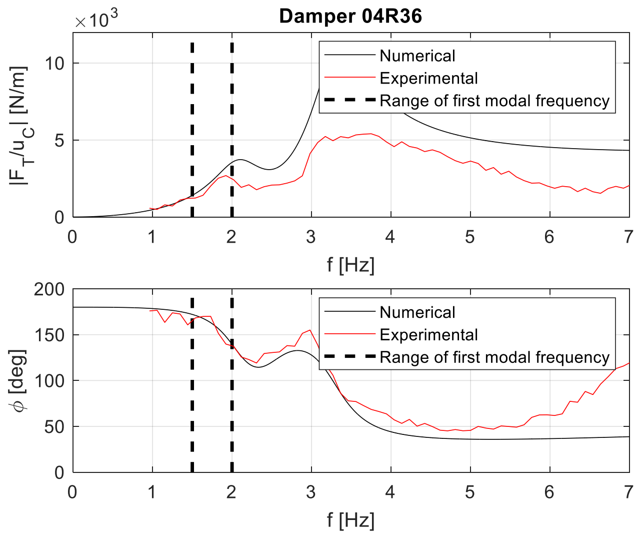
$K_T = 9.0 \times 10^6$ Nm/rad for the torsional spring

FE model – Damper model

In the FE cable model, both dampers are modelled as 1 Degrees of Freedom lumped mass models.

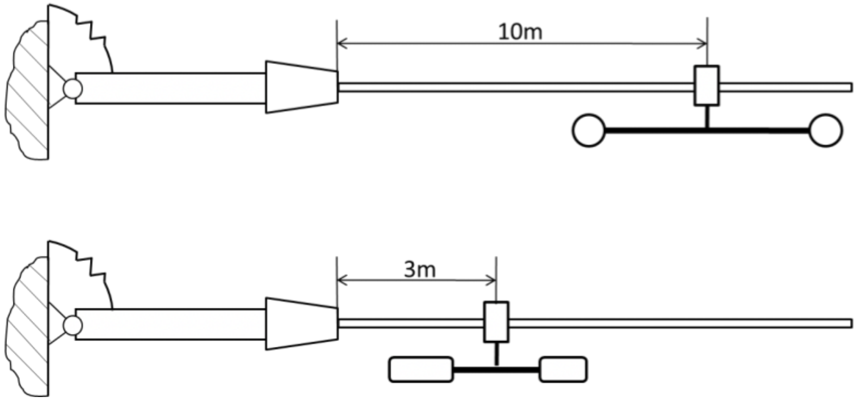
The parameters $M_{1,2}$ $K_{1,2}$ $R_{1,2}$ of each equivalent 1 DoFs models have been identified such that the experimental transfer function is matched by the simplified models, both in terms of magnitude and phase.



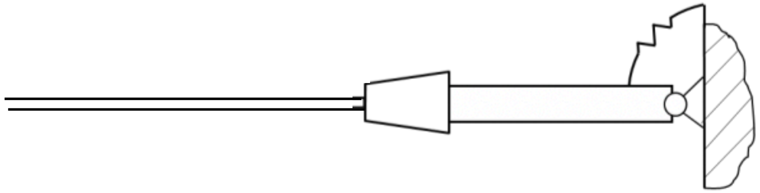


Good matching between the numerical model and the experimental results in the first frequency range

FE model – Constraints and dampers



Sketch and position of the dampers and the constraints in the cable model, pylon side



Sketch of the constraints in the cable model, deck side

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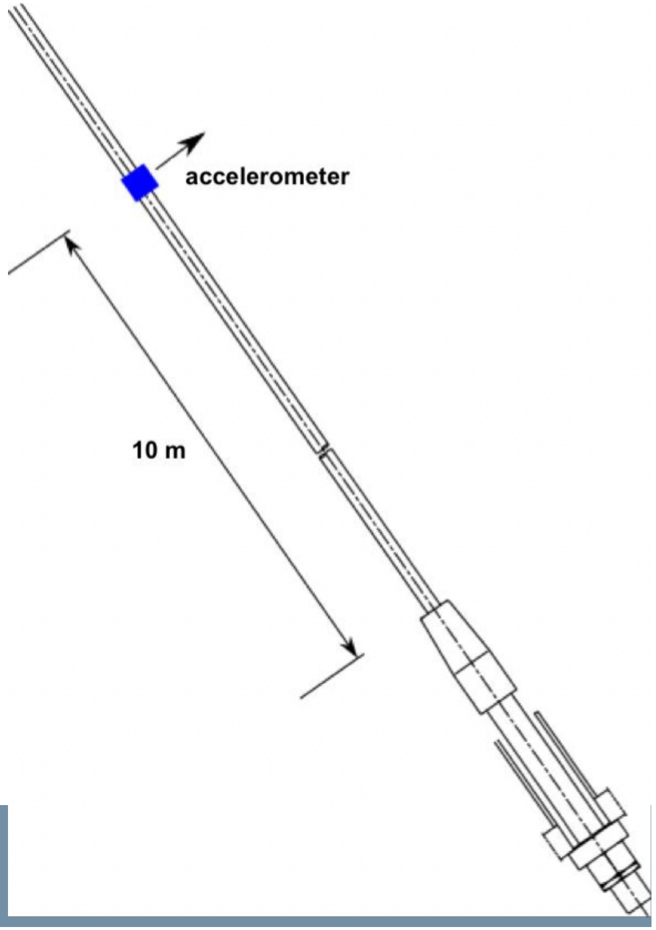
Experimental setup – Measurement system

Each cable is instrumented with a triaxial accelerometer placed at 10 m from the cable socket.

The measurement system consists of a Lord G-Link-200 sensor, that has an on-board triaxial MEMS accelerometer allowing high-resolution data acquisition with low noise. The sampling frequency is 128 Hz and the acquisition time is 100 s.



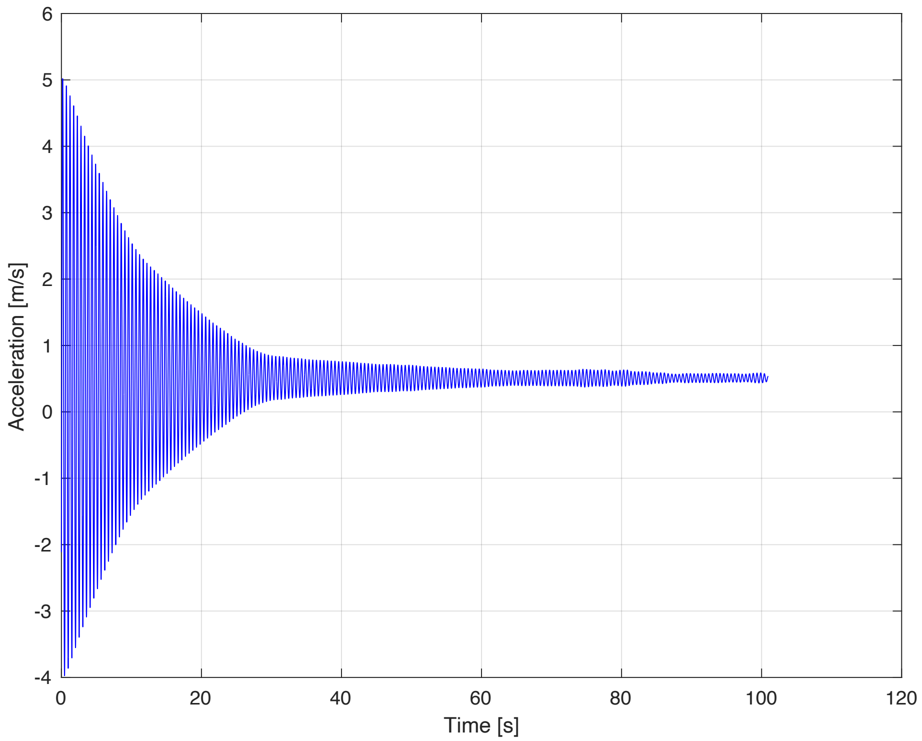
Experimental setup – System excitation

The free decay test method consists in exciting the cable by hand according to the frequency of first vibration mode, and then, once a steady condition of the vibration mode is reached, the cable is let to move freely.

The operator was on a cherry picker, model JLG 450AJ of total mass about 7600 kg, that was standing on the bike road on the bridge, near the tested cable.

Experimental setup – System excitation

Experimental setup – Output example, cable 24



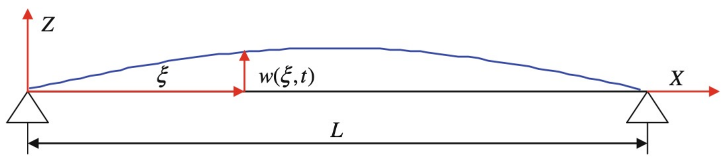
Three different regions are identified:

1. Large amplitudes region → non linear effects
2. Smaller amplitudes and so slightly smaller damping ratio
3. in the last interval the TMD is not efficient resulting in the lowest damping ratio

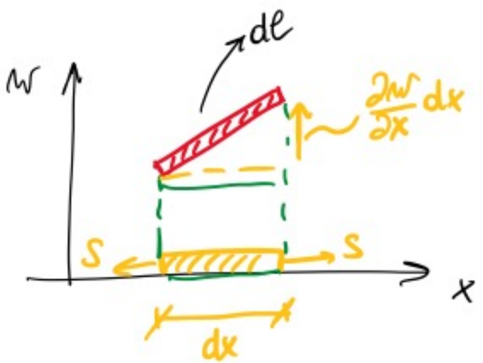
Experimental setup – Output example
Large amplitudes region - Non linear effects

What happens at the very beginning?

- Largest amplitudes → what about the small displacements hyphotesis?



Deformed shape with amplitude ≈ 0.2 m



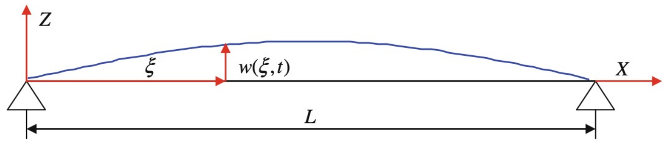
$$dL = dx\sqrt{1+\frac{\partial w}{\partial x}^{2}}$$

$$L_{final} = \int_0^L \sqrt{1+\frac{\partial w}{\partial x}^{2}}\,dx$$

Experimental setup – Output example
Large amplitudes region - Non linear effects

Assuming, as first approximation, that the first mode shape is the one for the pinned pinned cable, we have:

$$\Phi_1(x) = Asin\left(\frac{\pi}{L}x\right)$$



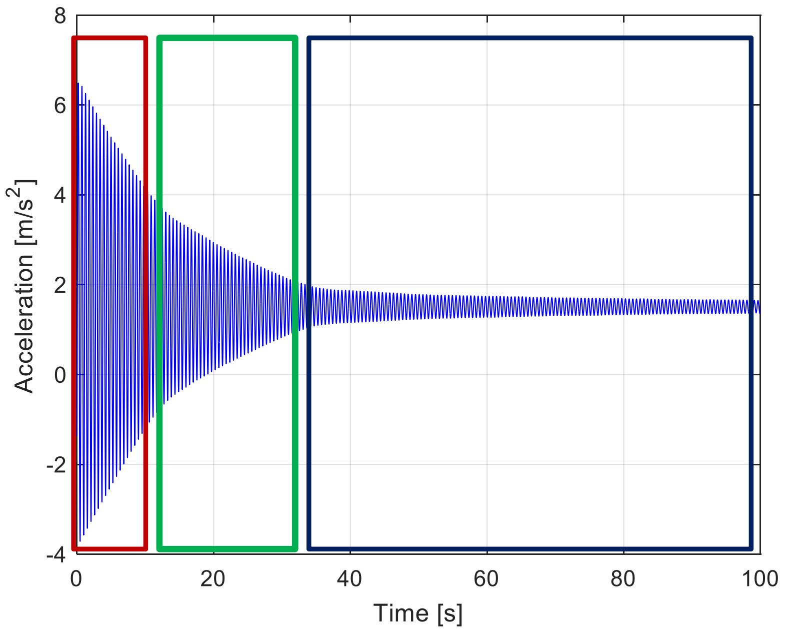
If A = 0.2 m and L = 53.631 m (as an example for the cable 24), the cable length in the deformed configuration is

$$L_{final} = \int_0^L \sqrt{1 + \left[A\frac{\pi}{L} * cos\left(\frac{\pi}{L}x\right)\right]^2} dx = 53.6347m$$

$$\varepsilon = \frac{L - L_{final}}{L} = 0.007\% \longrightarrow \Delta T \approx EA_{cable} * \varepsilon \approx 19.4kN$$

→ **We obtain a variation of the tension of the cable!**

Experimental setup – Post process

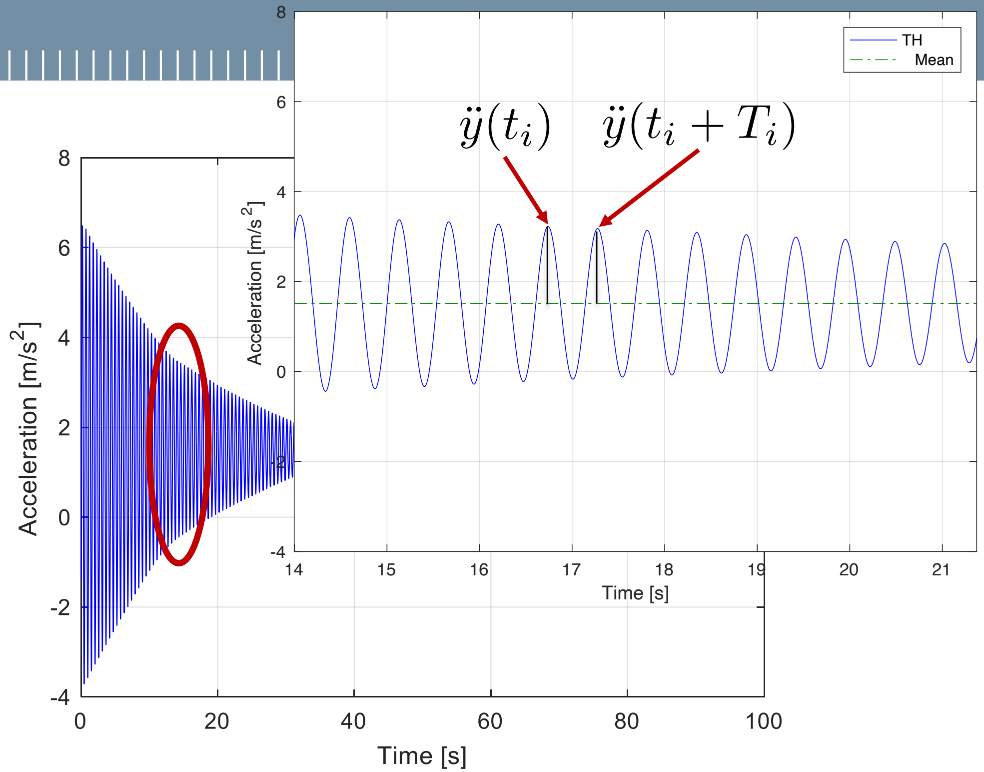


Three different regions are identified:

1. Large amplitude in cable vibrations → non linear effects
2. Smaller amplitudes and so smaller damping ratio. TMD is in the standard operative amplitude
3. in the last interval the TMD is not efficient resulting in the lowest damping ratio

The FEM model is able to reproduce the system behaviour assuming a <u>constant tension force and dampers' behaviour in their operative condition</u>, at which they were characterized, i.e. in the time interval 15-35 s for this example.

Experimental setup – Output example



Time history of the free decay response

- Logarithmic decrement $\boldsymbol{\delta}_i$:

$$\delta_i = log(\frac{\ddot{y}(t)}{\ddot{y}(t+T_i)})$$

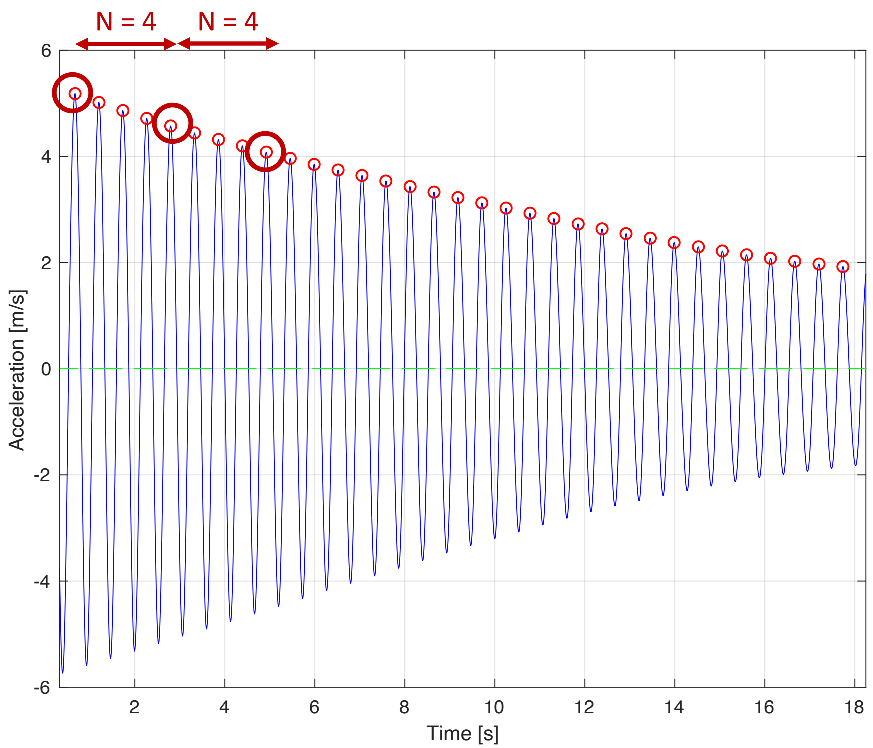
- Nondimensional damping h_i

$$h_i = \frac{\delta_i}{2\pi}$$

- Oscillation period T_i

$$T_i = t(i+1) - t(i)$$

Experimental setup – Post process

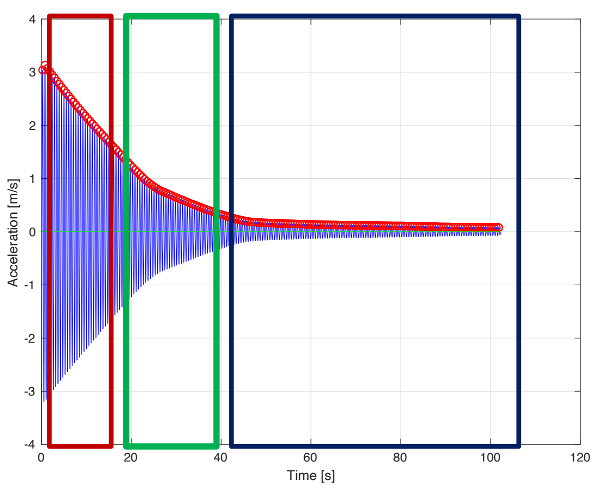


- The mean value is subtracted by the signal
- The peaks in the time history are identified, allowing the computation of the logarithmic decrement, the non-dimensional damping and the oscillation period.
- In principle, you should be able to pick any two neighbouring peaks. It is often more accurate to estimate the damping ratio and the natural frequency by considering one peak every three/four…
- Formulas previously introduced are to be modified accordingly:

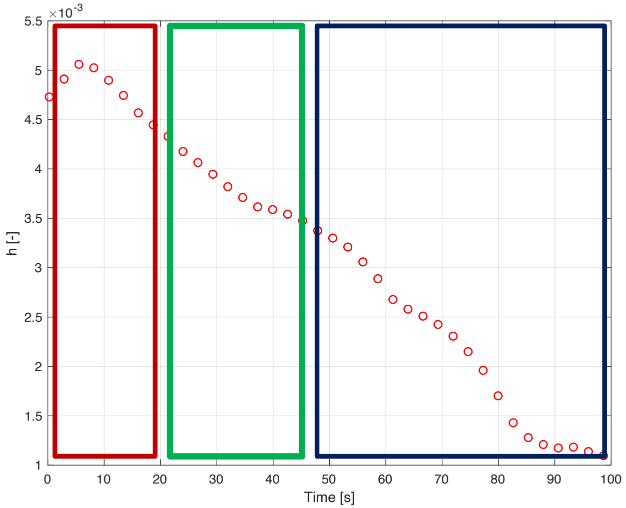
$$\delta_i = \frac{1}{N} \cdot log(\frac{\ddot{y}(t_i)}{\ddot{y}(t_{i+N})}) \qquad T_i = \frac{t(i+N)-t(i)}{N}$$

Experimental setup – Post process

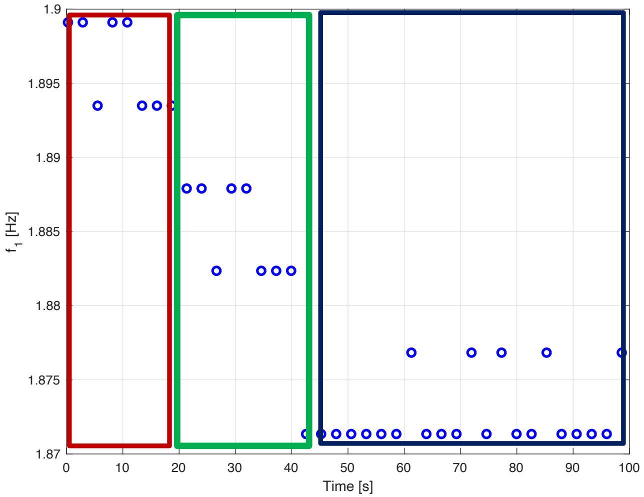
h and f_1 are computed as the mean value in the green interval



Time history of the free decay



Non-dimensional damping ratio h



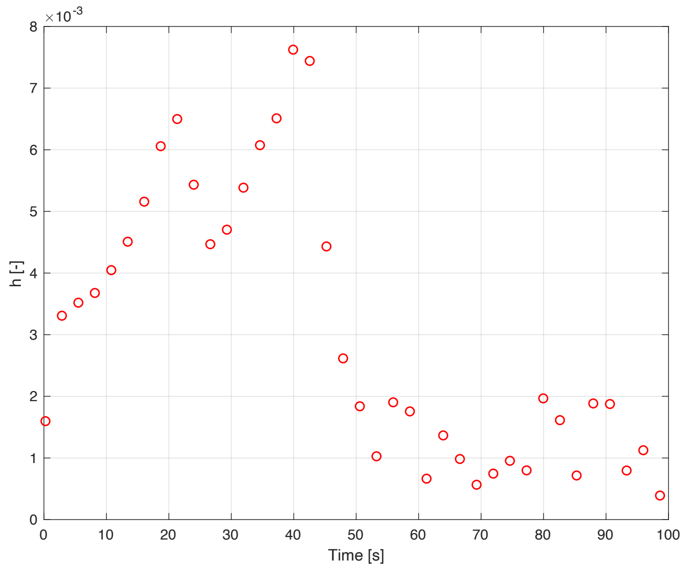
First eigenfrequency

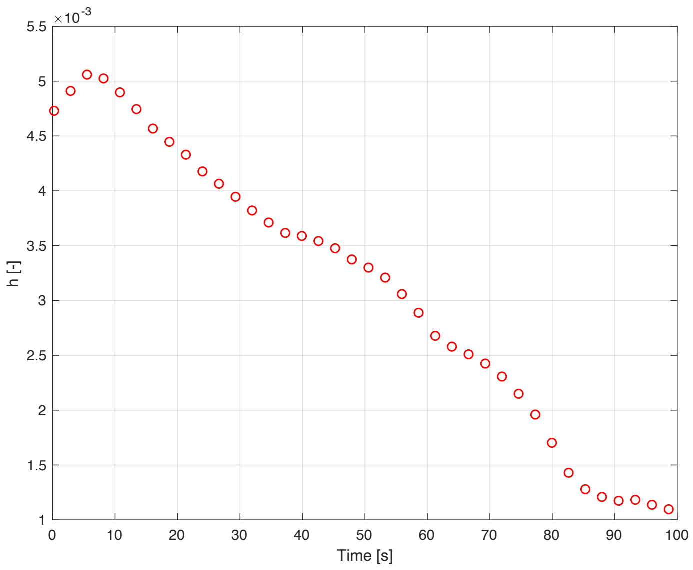
h = 4 ‰

f_1 = 1.885 Hz

Experimental setup – Post process

Non-dimensional damping ratio h: to get a smoother shape, a moving average filter is applied to the results





Tension force estimation

The tension force of the cables can be estimated by applying the following steps:

- The actual length of the threaded bar is set in the numerical model (*the provided input file already accounts for the actual length of cable*).
- The tension of the numerical cable is varied until the experimental and numerical frequencies match.

The estimated tension is expected to be within the range +/- 5% of the actual tension value.

Finally, a comparison between the assessed tension values and the nominal design values for the considered cables can be carried out.

Provided data – HovenringAssignment.zip

- `FEM Code`
- `FEM input cables` input file for the FEM code
    - `Cable05_VELDTUI2.inp` input file for cable 05
    - `Cable06_SPANTUI1.inp` input file for cable 06
    - `Cable08_VELDTUI1.inp` input file for cable 08
    - `Cable13_SPANTUI2.inp` input file for cable 18
- Experimental Data
    - `Cable05.mat` free decay for cable 05
    - `Cable06.mat` free decay for cable 06
    - `Cable08.mat` free decay for cable 08
    - `Cable13.mat` free decay for cable 18

Each `*.mat` file contains:

- *time* vector of seconds
- *acc* accelerometer time history
- *fsamp* sampling frequency for the accelerometer

Assignment

Cable tension identification

1. Identification of the damping ratio
2. Identification of the first natural frequency
3. Tension force is estimated by the FE model, provided that the experimental and numerical frequencies match
4. Comparison nominal Vs actual tension values

For the oral examination...

...short report, for each cable, the identification results (items 1, 2) plus the force estimation by the FE model (item 3, you can show the several attempts you have done, T vs $f_{1,FEM}$)
Collect the results in table form (for each cable, items 1 to 4).

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