Active Damping of Suspension Bridges

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ULB

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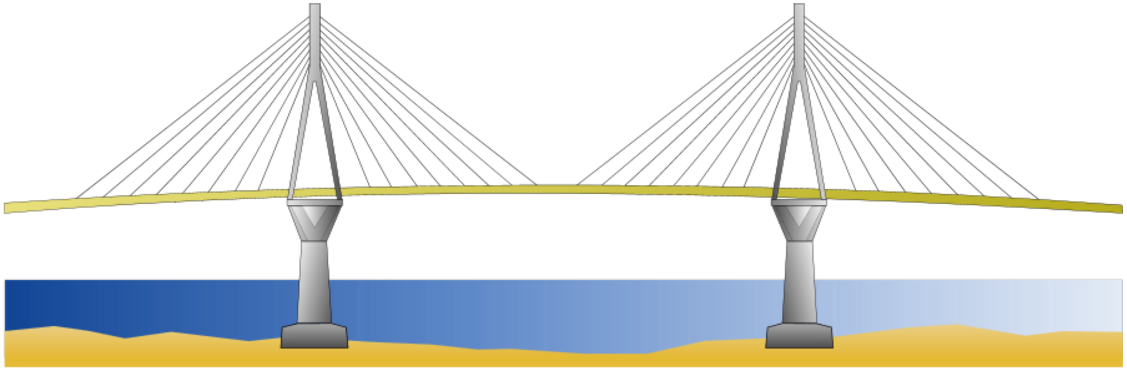
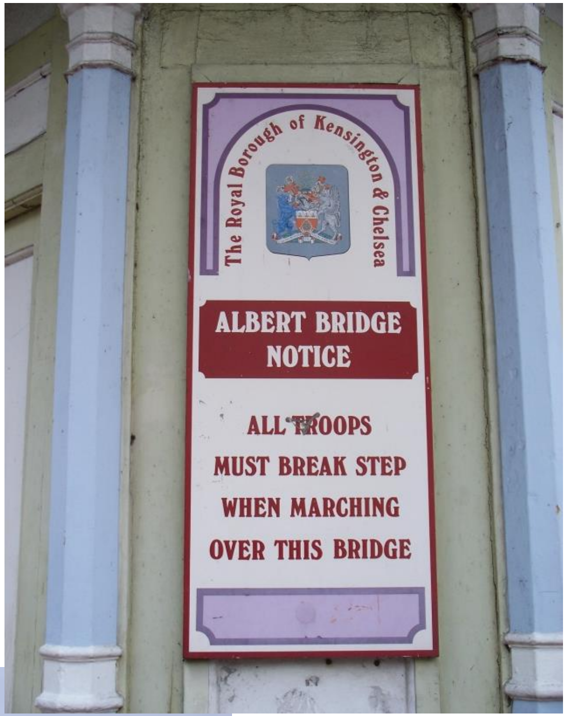
Cable-stayed bridge

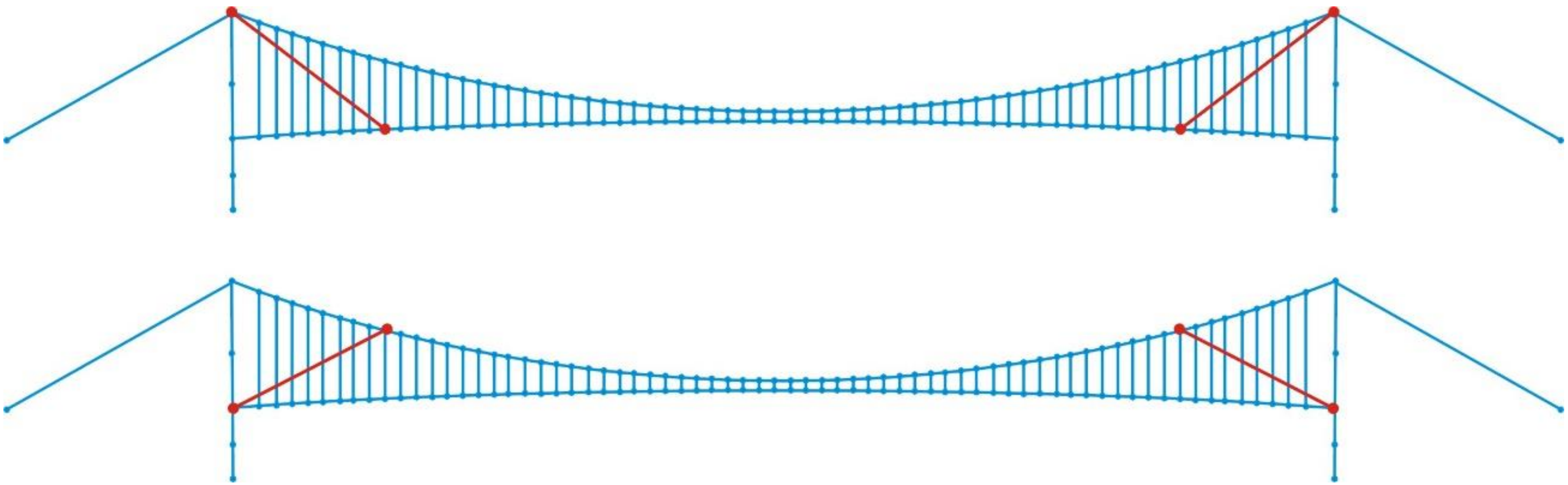


Suspension bridge

Stay cables in suspension bridges

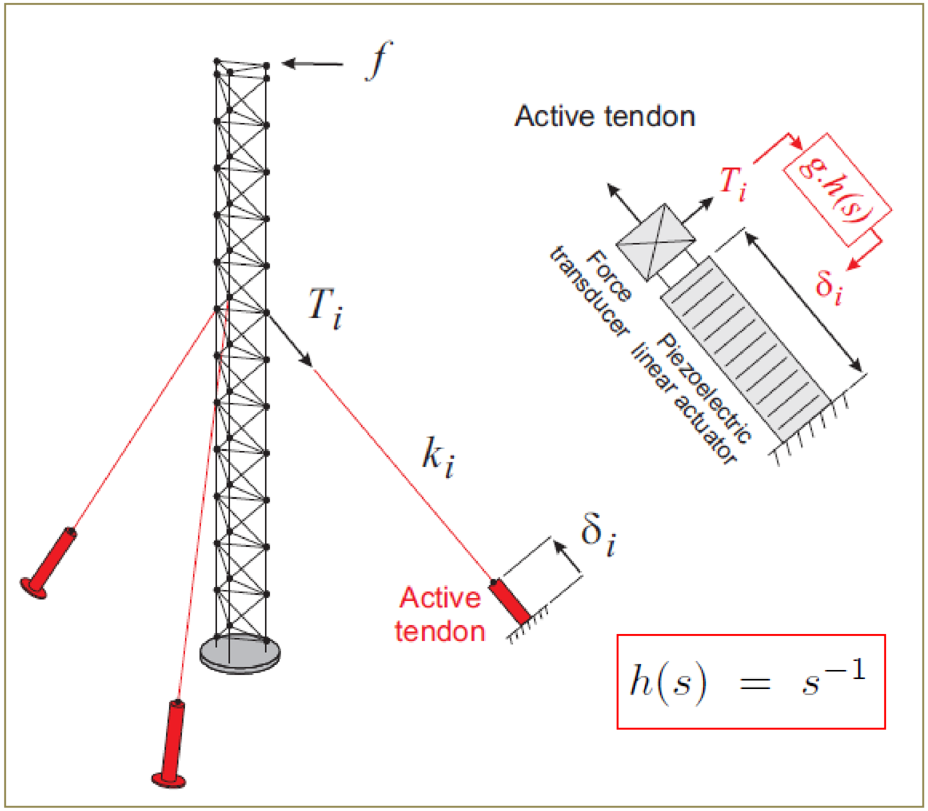


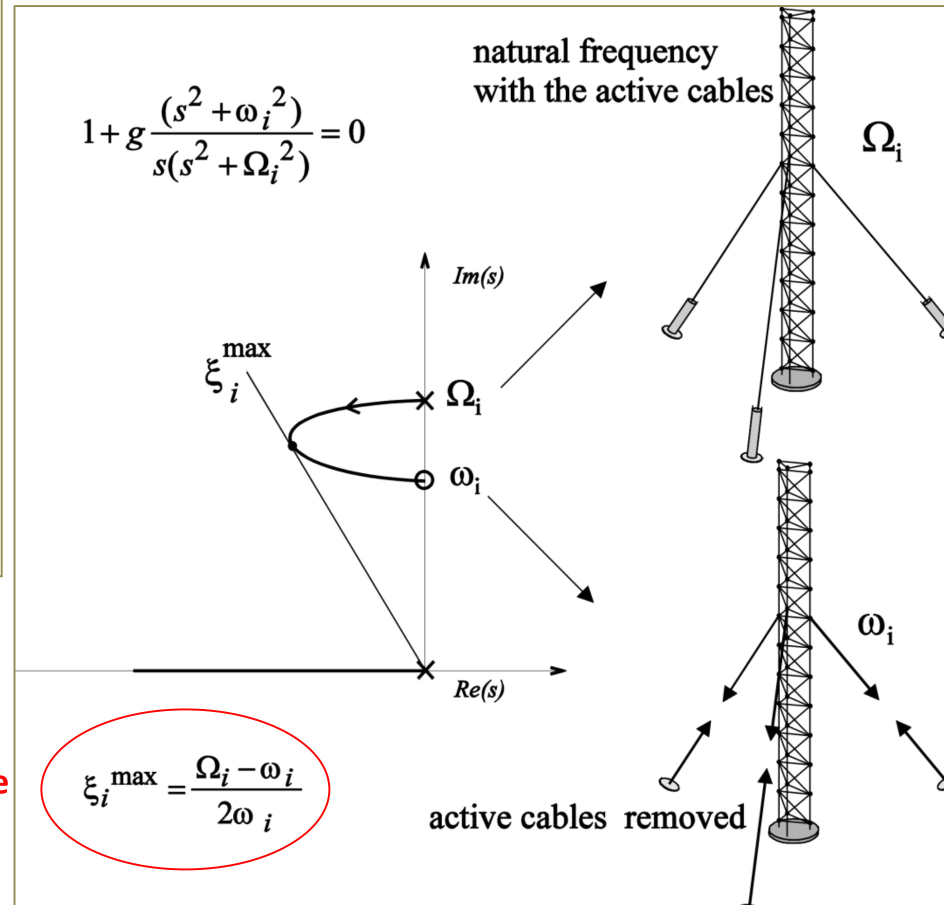
Motivation



Auperin, M., Dumoulin, C., Proc. 3rd Int. Workshop on Structural Control (Paris 6-8 July 2000)

Decentralized Collocated IFF control of cable structures





Maximum achievable damping:

$$\xi_i^{max} = \frac{\Omega_i - \omega_i}{2\omega_i}$$

A.PREUMONT: *Vibration Control of Active Structures*, 3rd Edition, Springer 2011

Recovering static stiffness: The “Beta” controller

IFF Controller: $h(s) = s^{-1}$

High-pass filter

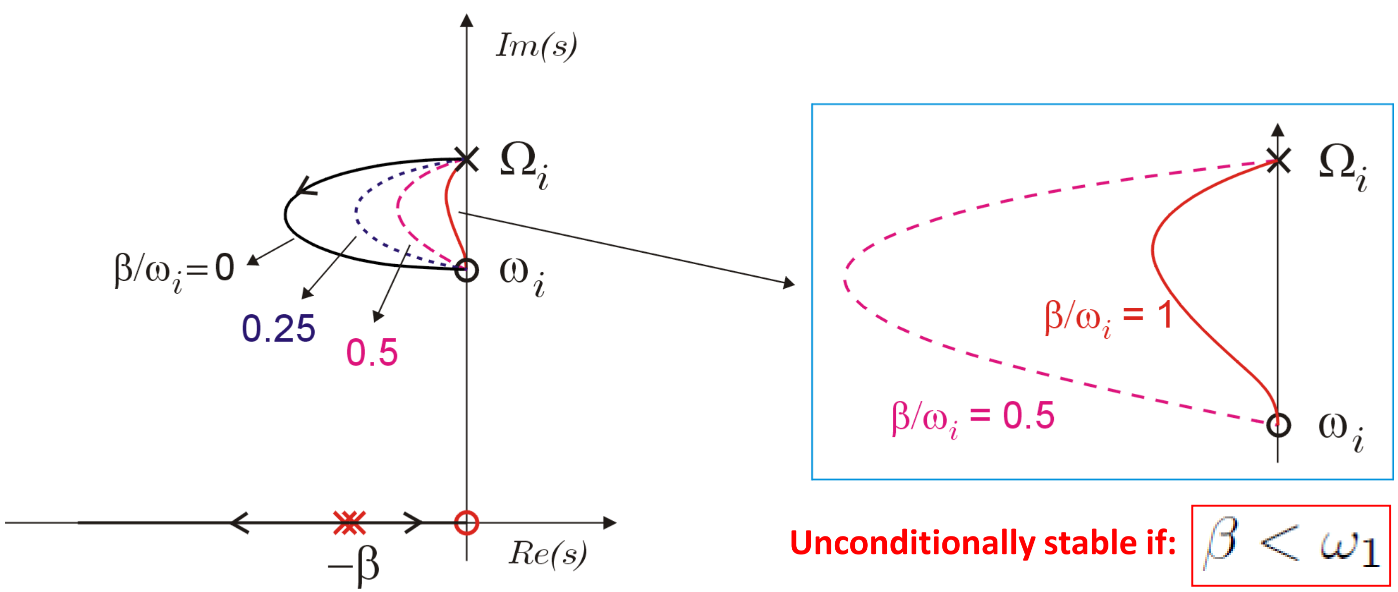
Beta Controller: $gh(s) = \frac{gs}{(s+\beta)^2}$

$$\lim_{s=0} [Ms^2 + K + \frac{s}{s+g} BK_cB^T] = K$$

$$\lim_{s=0} [Ms^2 + K + \frac{(s+\beta)^2}{gs+(s+\beta)^2} BK_cB^T] = K + BK_cB^T$$

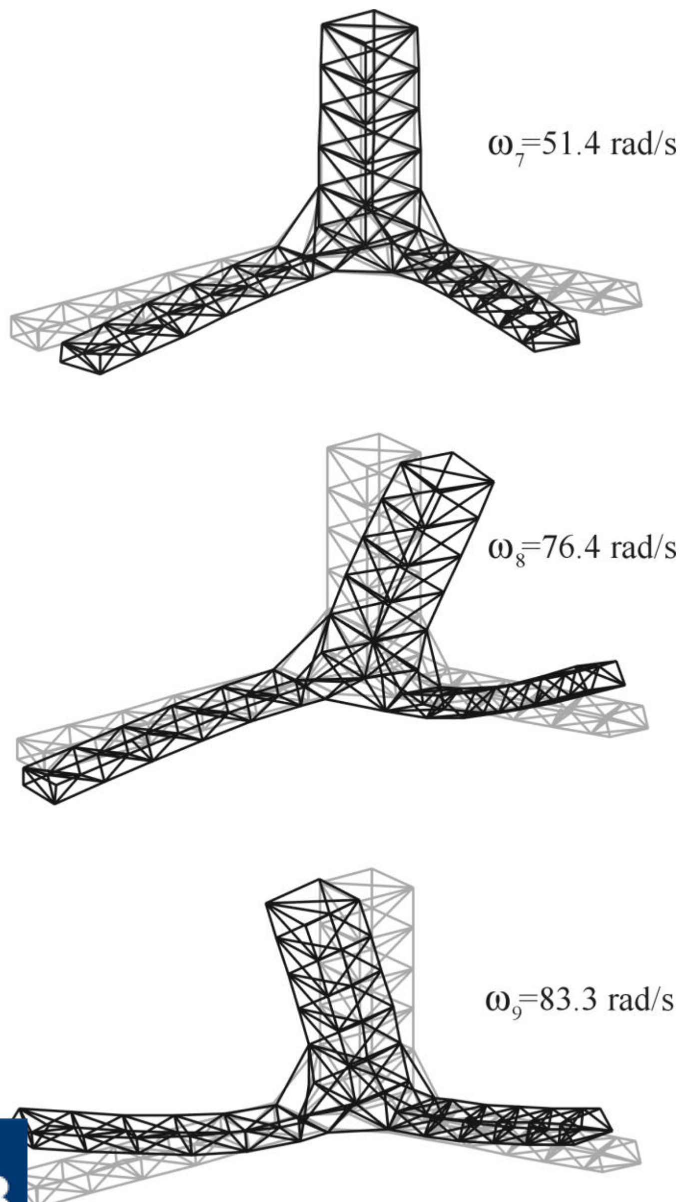
$$1 + g\frac{s^2+\omega_i^2}{s(s^2+\Omega_i^2)} = 0$$

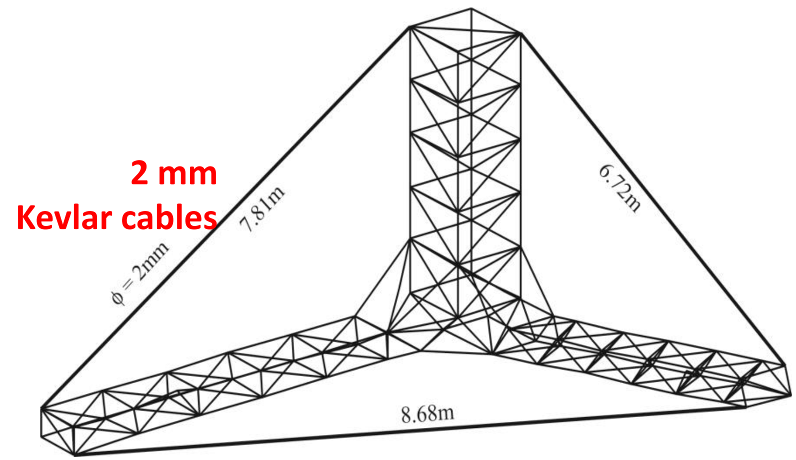
$$1 + g\frac{s(s^2+\omega_i^2)}{(s+\beta)^2(s^2+\Omega_i^2)} = 0$$

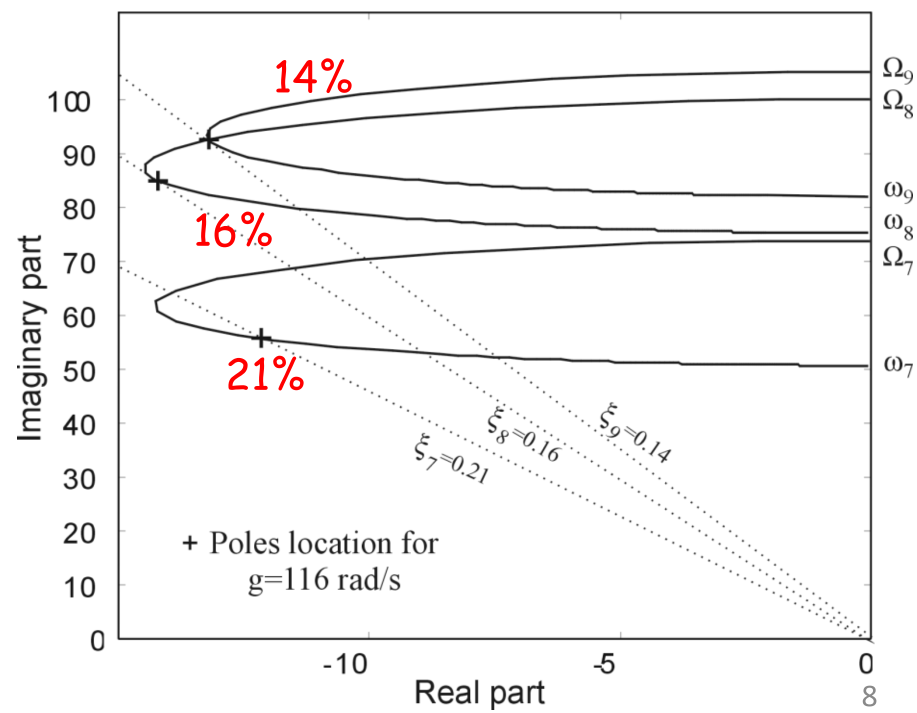


Unconditionally stable if: $\beta < \omega_1$

JPL Micropecision Interferometer testbed (simulation)







ULB free floating truss

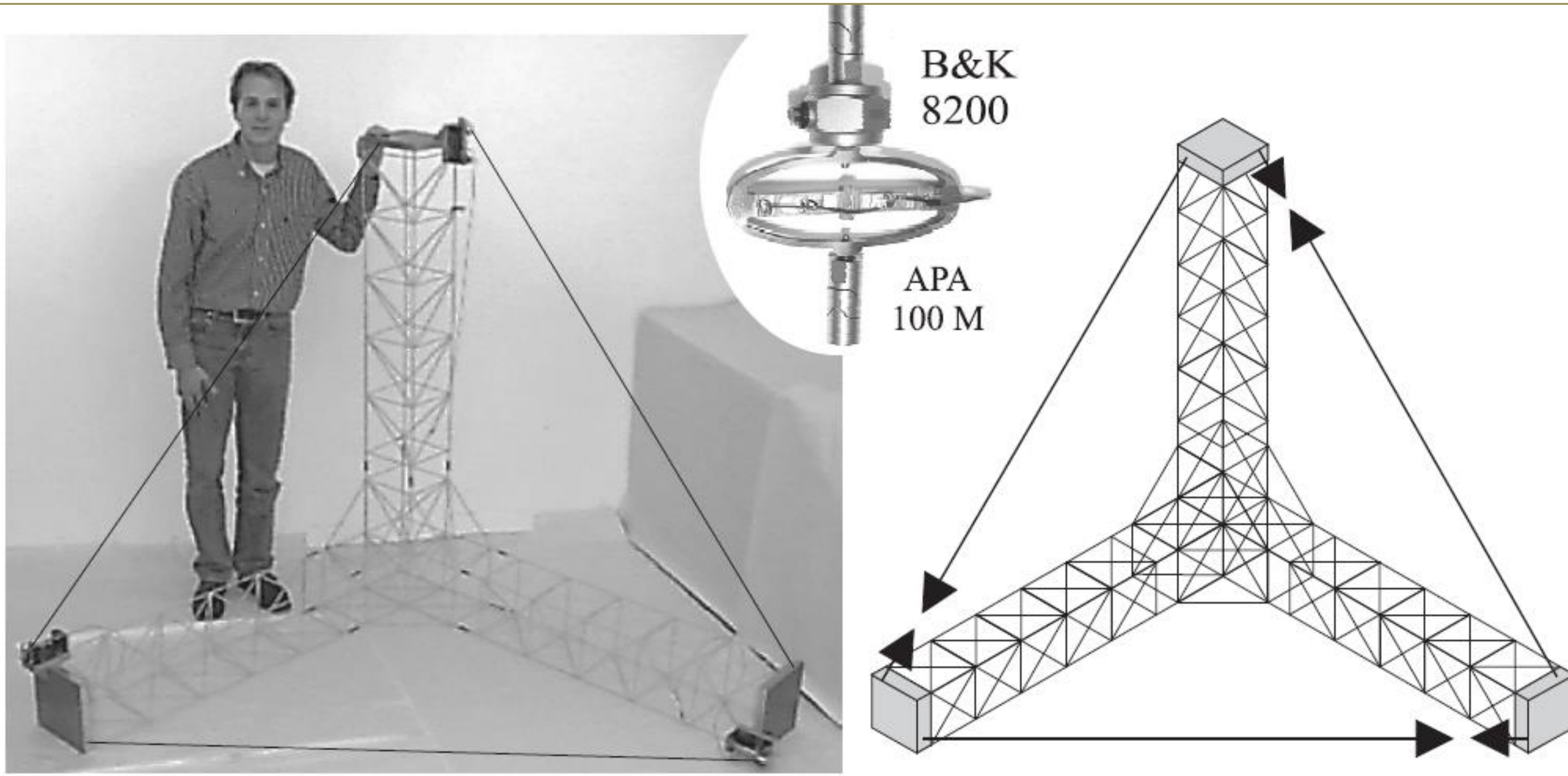
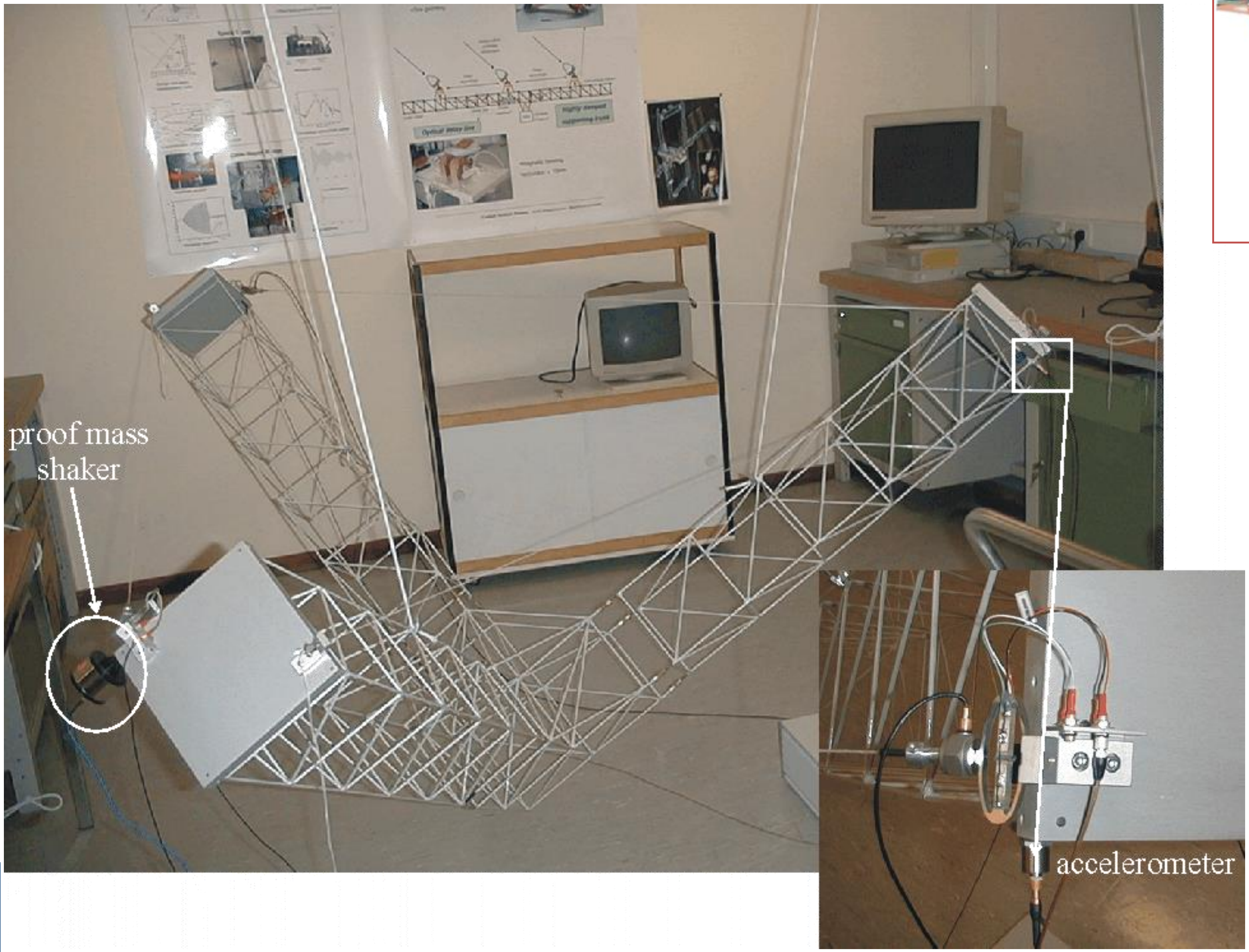
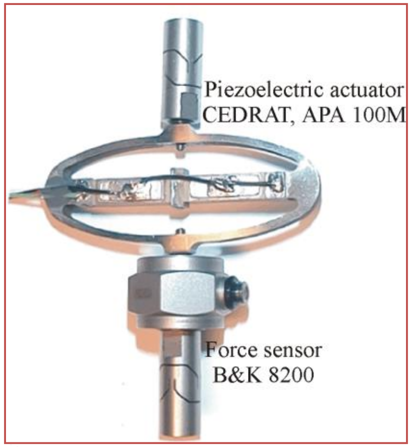


Fig. 15.13 ULB free floating truss test structure and detail of the active tendon.

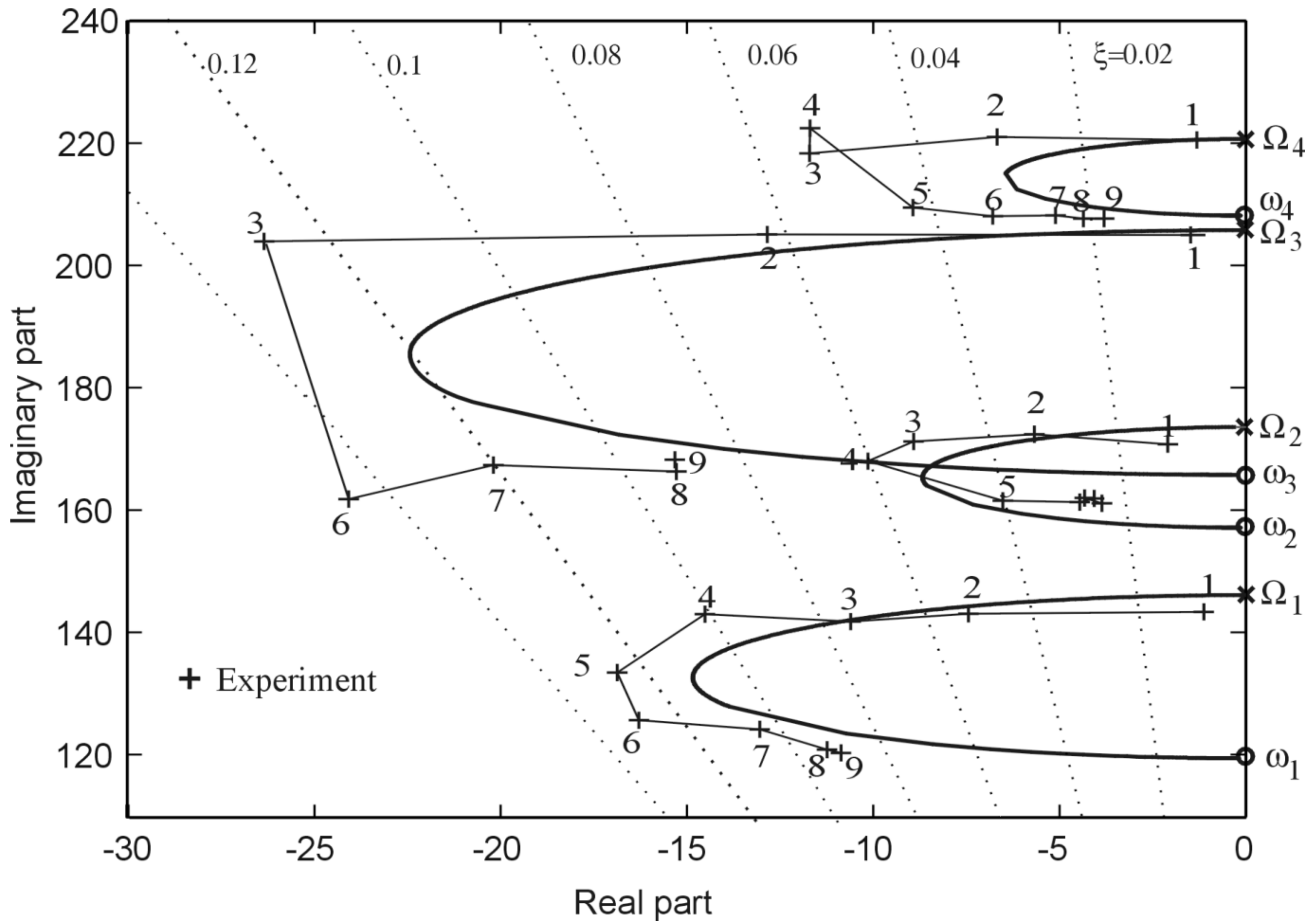
ULB free floating truss



Active tendon



ULB free floating truss
(Theory vs. Experiment)



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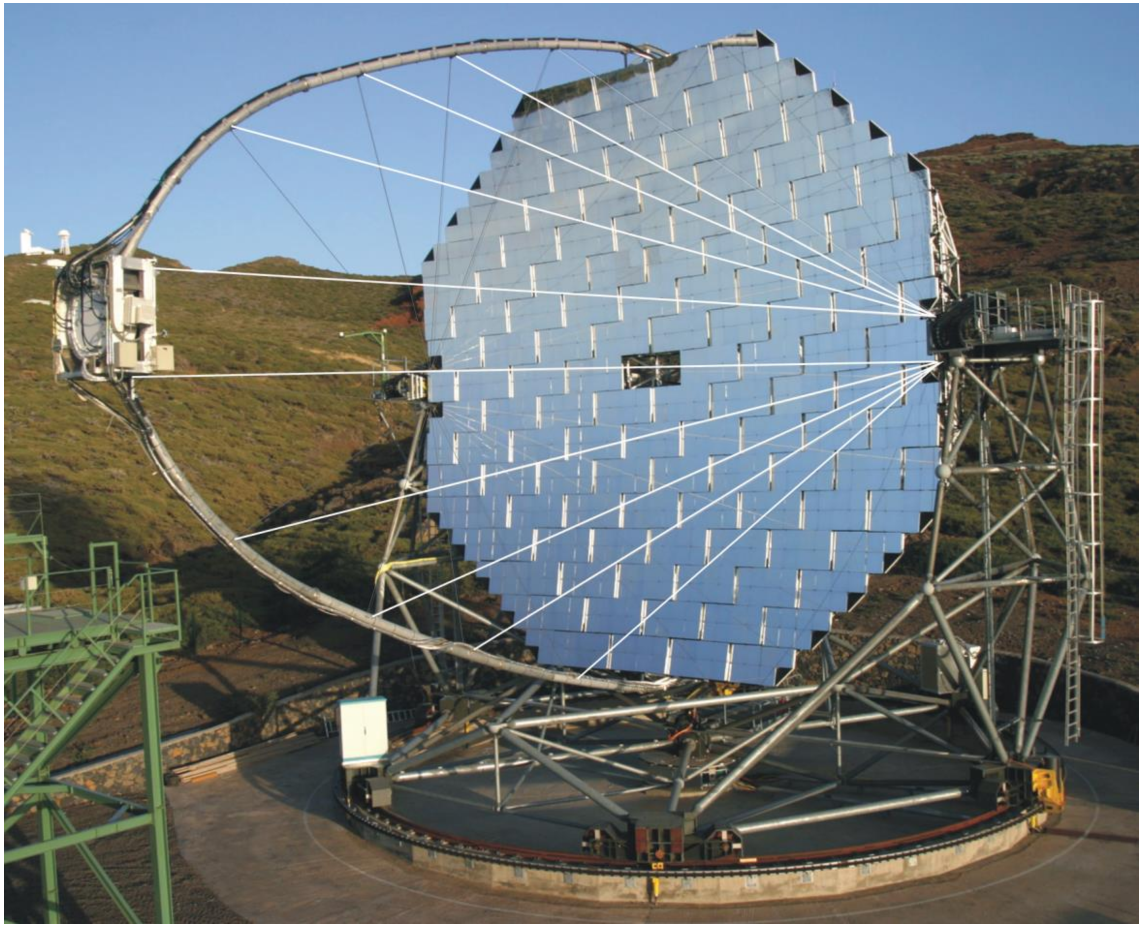
MAGIC – **M**ajor **A**tmospheric **G**amma-ray **I**maging **C**herenkov **T**elescope



Focal length:17 m
Mirror diameter :17 m
Camera Mass: 0.75 t
Total Mass:72 t
Mirror support: CFR tubes
Camera Mast – Stiffened by prestressed cables

M. SMRZ, et al. Active Damping of the Camera Support Mast of a Cherenkov Gamma Ray Telescope, *Nuclear Instruments and Methods in Physics Research, A 635* (2011)

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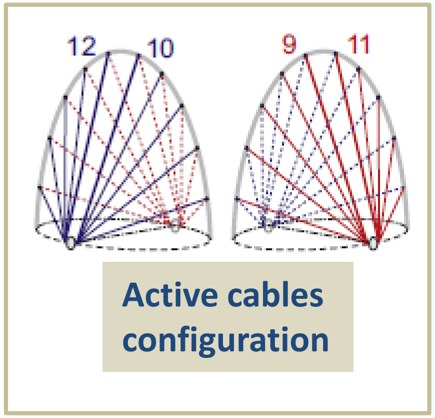
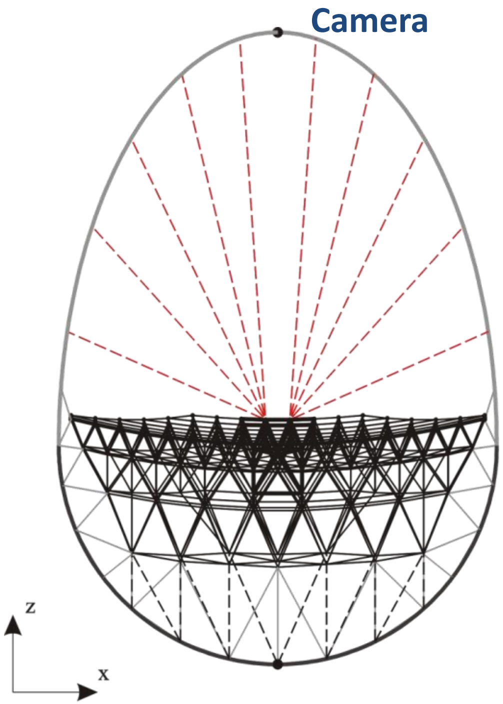
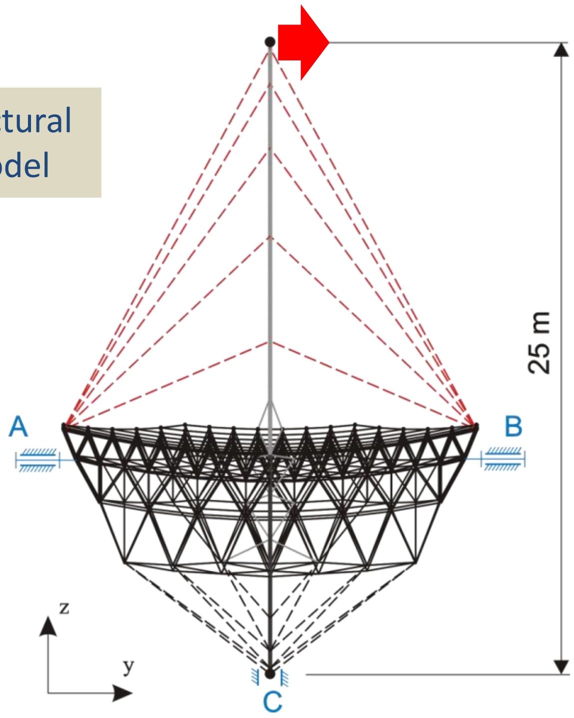
Magic Telescope

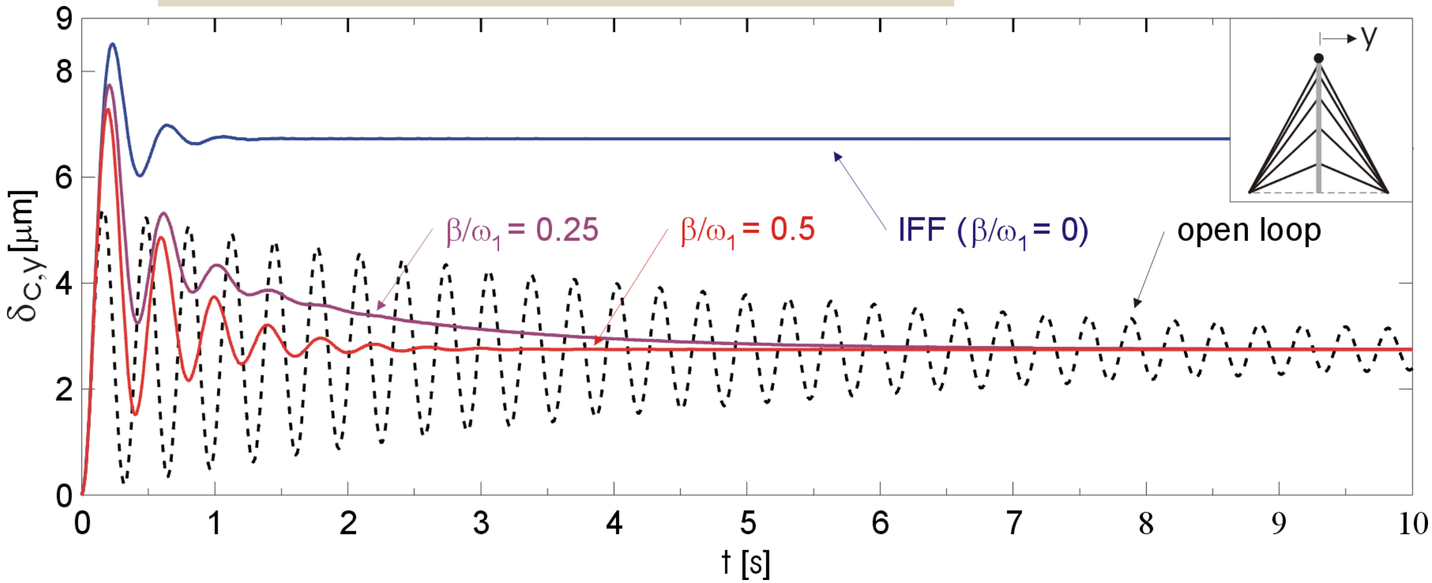




Structural model



Step response at the camera with 4 active cables



Cable-stayed bridge
« ACE » project (2000)
Laboratory experiment

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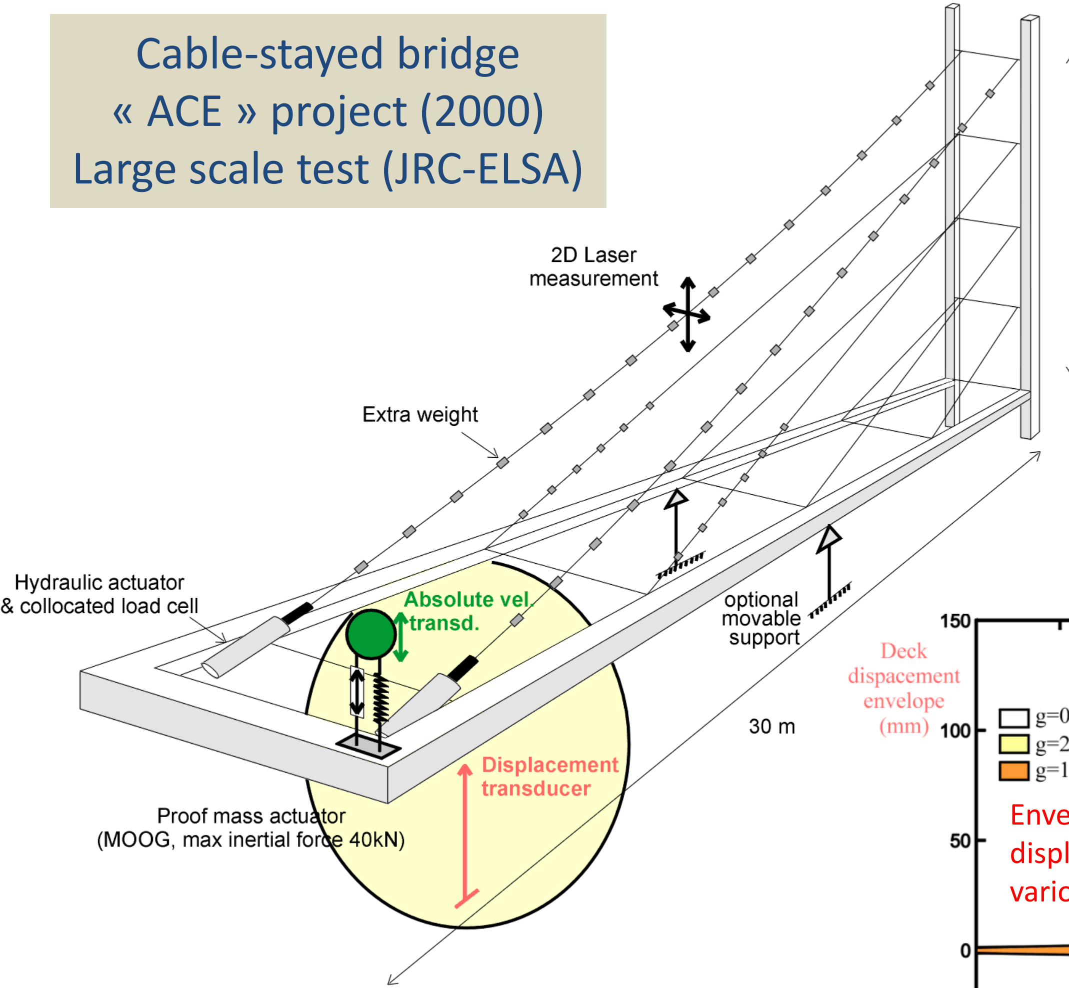
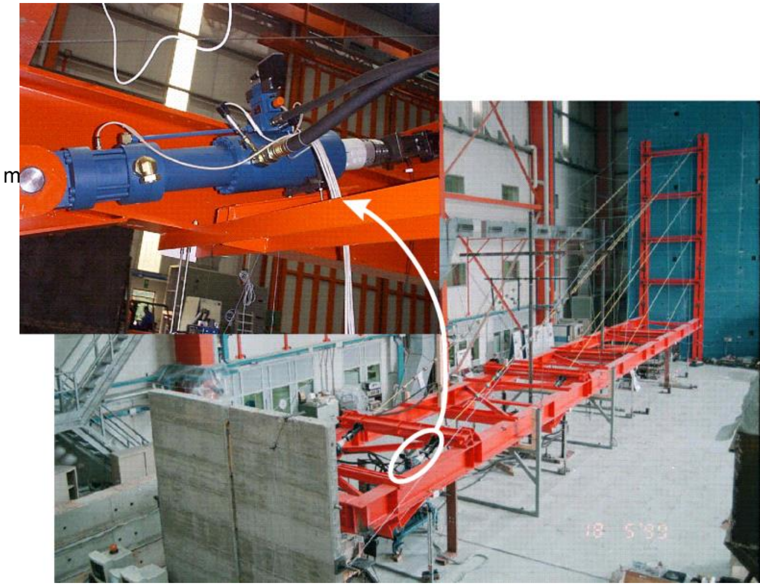
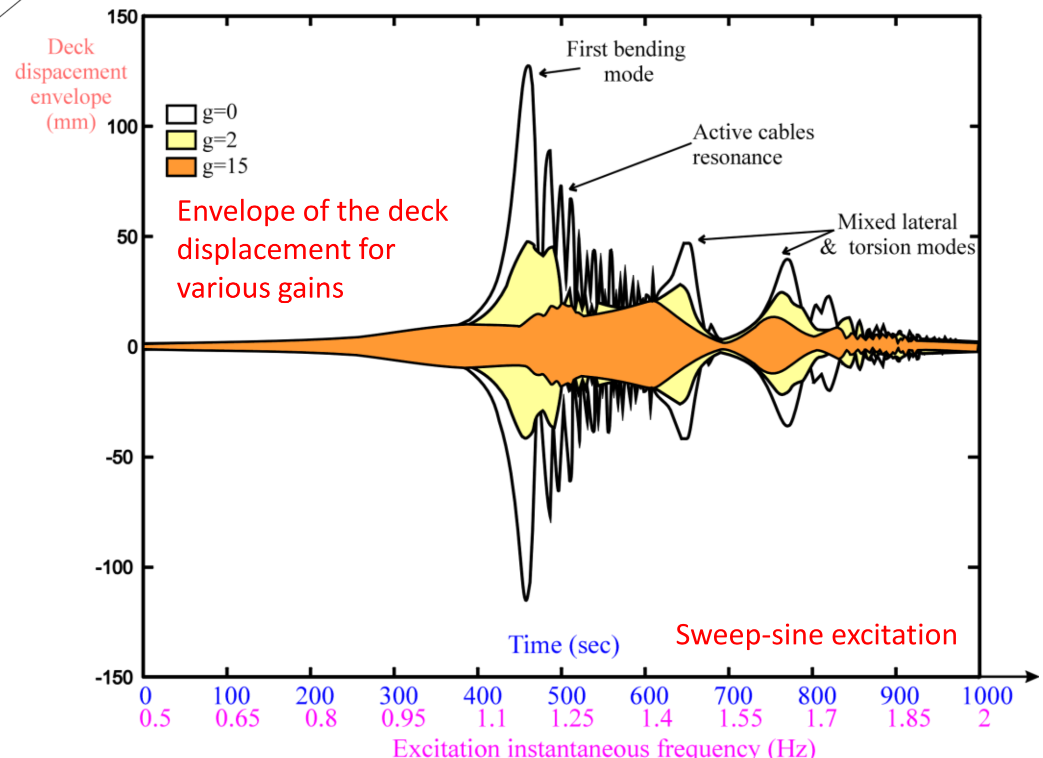
Cable-stayed bridge
« ACE » project (2000)
Large scale test (JRC-ELSA)







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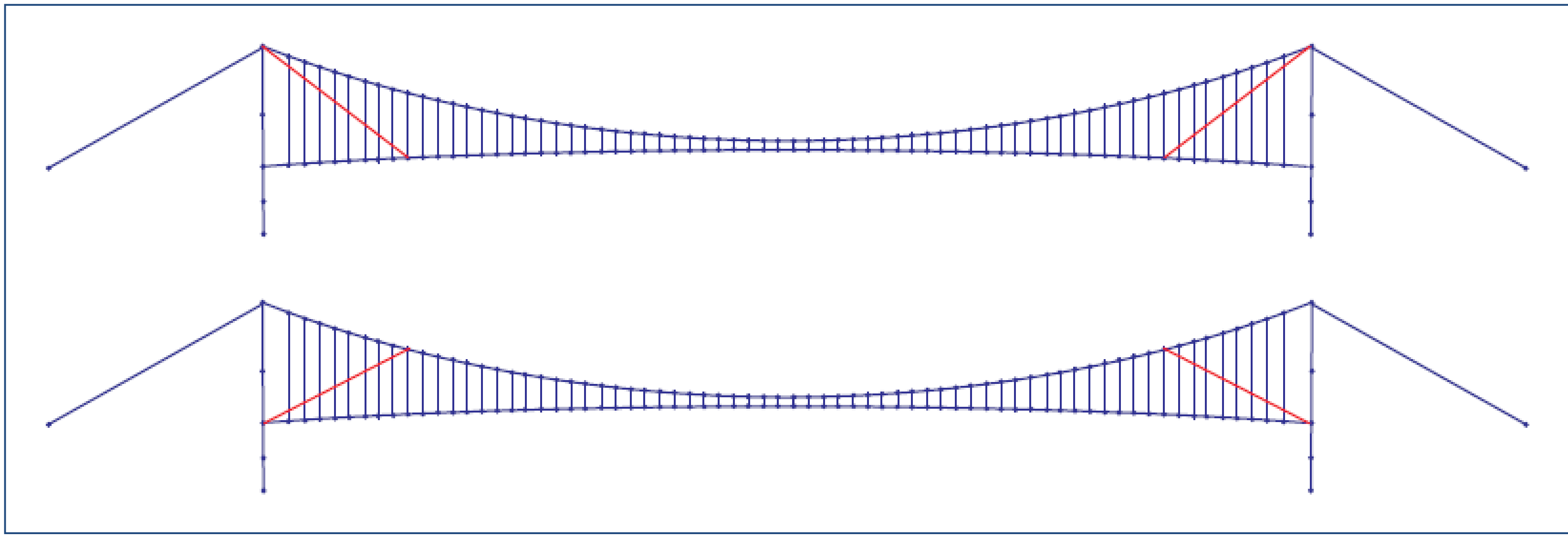
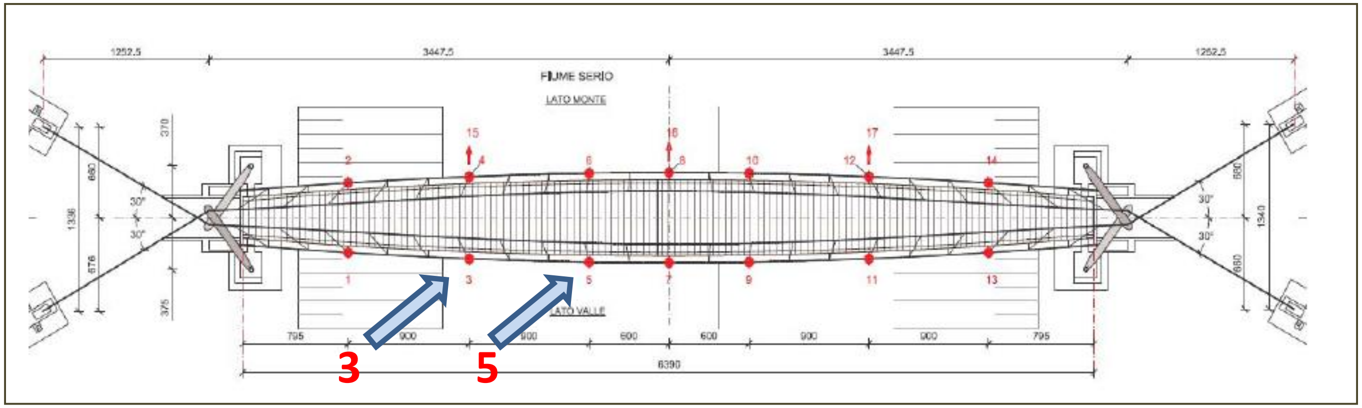
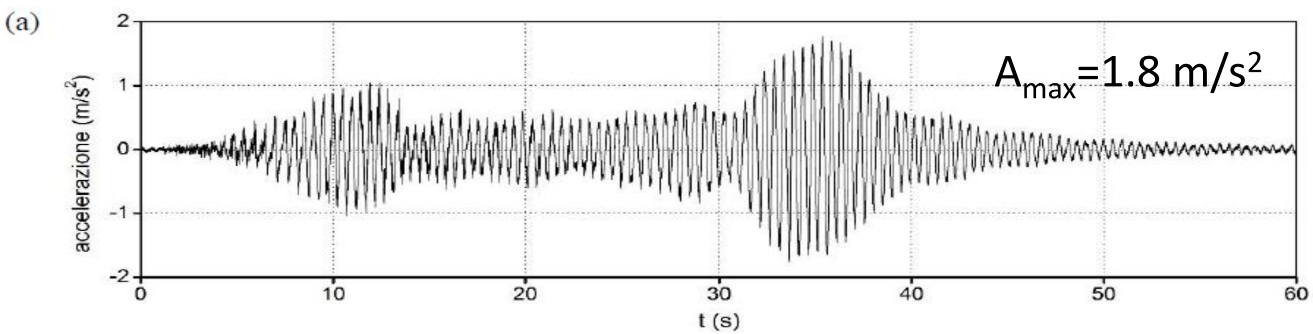
Suspension bridge



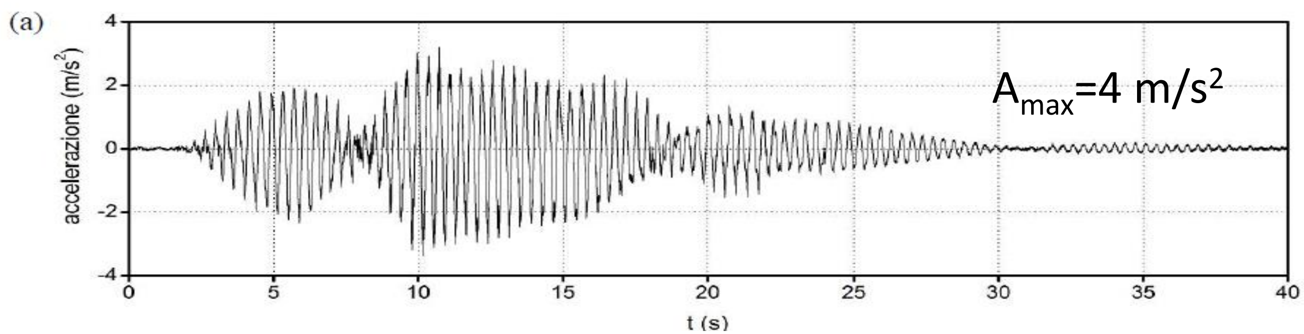
Auperin, M., Dumoulin, C., Proc. 3rd Int. Workshop on Structural Control (Paris 6-8 July 2000)

Suspension bridge: Seriate footbridge (45°40'18.5"N 9°43'45.2"E)





8 pedestrians walking on the bridge (measurement point 3)



4 joggers on the bridge (measurement point 5)

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F.E. model of the Seriate bridge

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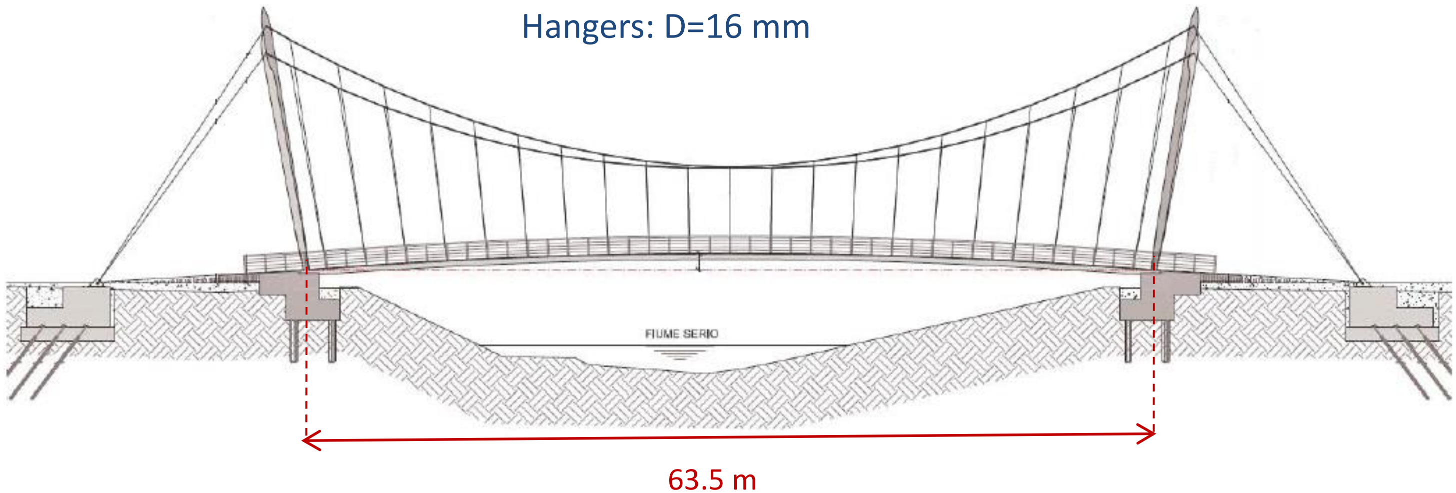
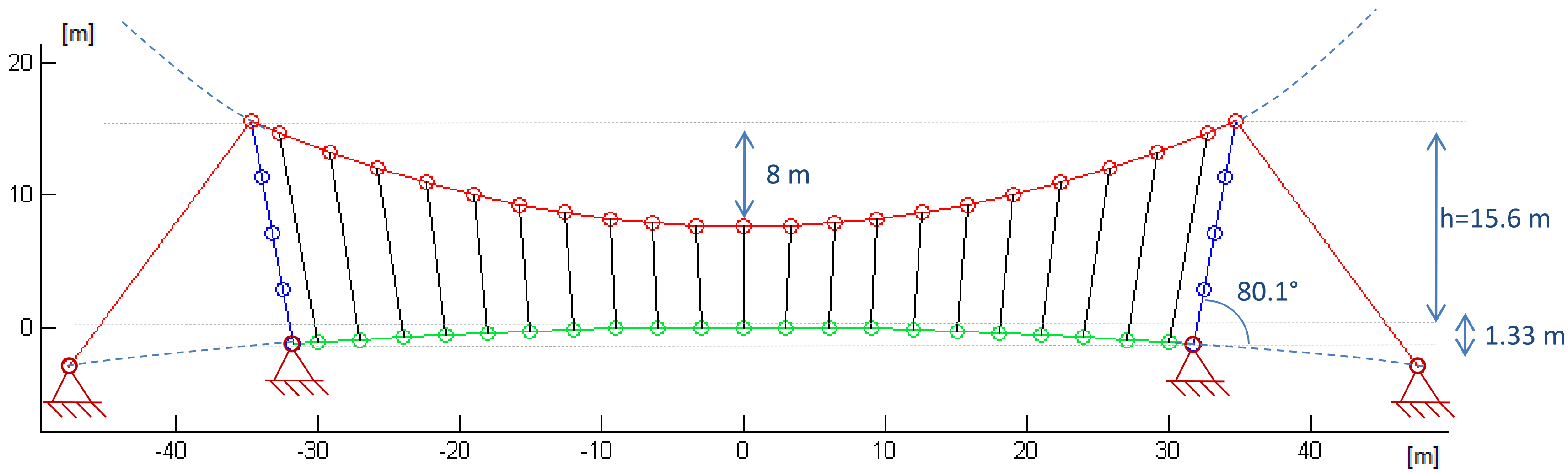
Main cables: D=60 mm
Hangers: D=16 mm





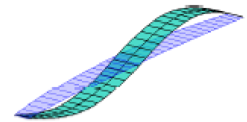
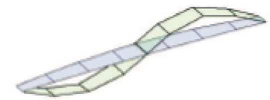
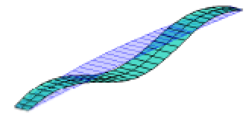
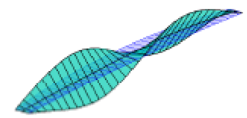
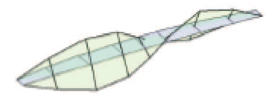
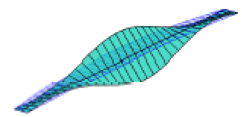
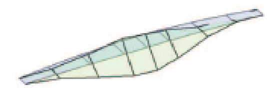
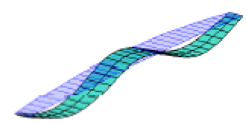
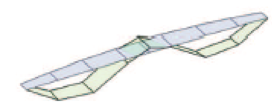
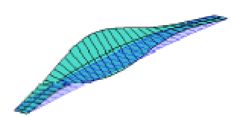
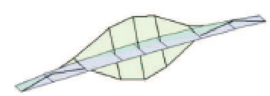
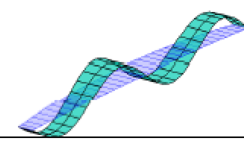
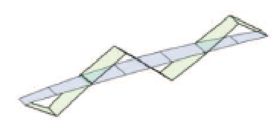
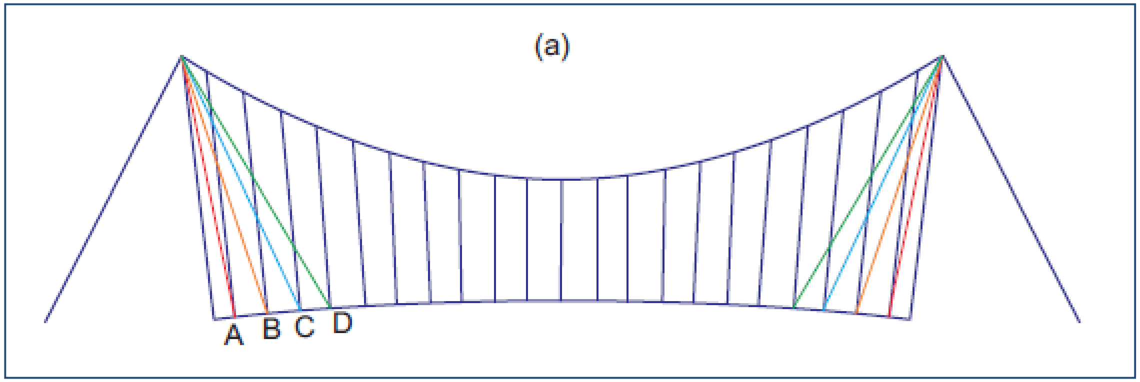
Mode N.	2D Numerical (Hz)	3D Numerical (Hz)	Experimental (Hz)	Numerical Mode Shape	Experimental Mode Shape
1^{st} B.	1.03	1.02	1.03 $\xi_1 = 2.77$ %		
2^{nd} B.	1.39	1.48	1.48 $\xi_2 = 1.34$ %		
1^{st} T.	/	1.79	1.92		
2^{nd} T.	/	2.1	1.94		
3^{rd} B.	**2.22**	**2.20**	**2.17** $\xi_3 = 1.48$ %		
3^{rd} T.	/	2.65	2.75		
4^{th} B.	**2.81**	**2.78**	**2.86** $\xi_4 = 1.50$ %		

Table 1: Natural frequencies and mode shapes of the Seriate footbridge, comparison of the 3D model and 2D model with experiments [18]. The two critical modes are **3B** and **4B**.

Option 1: Four active steel cables of diameter 10 mm between the pylon and the deck

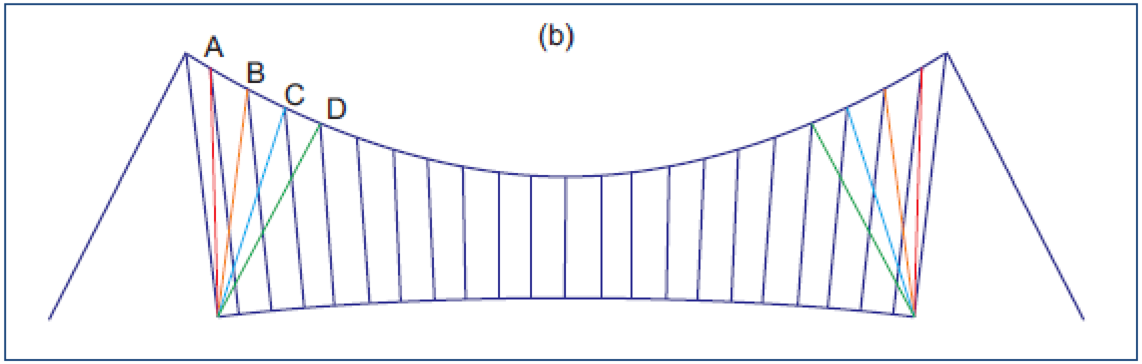
$$\xi_i^{max} = \frac{\Omega_i - \omega_i}{2\omega_i}$$



Mode #	ω_i (Hz)	Position A Ω_i (Hz)	Position A ξ_i^{max} (%)	Position B Ω_i (Hz)	Position B ξ_i^{max} (%)	Position C Ω_i (Hz)	Position C ξ_i^{max} (%)	Position D Ω_i (Hz)	Position D ξ_i^{max} (%)
1^{st} B	1.02	1.07	2.2	1.22	9.8	1.38	17.5	1.53	24.7
2^{nd} B	1.48	1.49	0.6	1.54	2.1	1.55	2.5	1.53	1.8
1^{st} T	1.79	1.81	0.6	1.91	3.3	2.04	6.9	2.12	9.0
2^{nd} T	2.10	2.10	0.2	2.13	6.2	2.13	0.8	2.18	2.0
3^{rd} B	2.20	2.23	**0.7**	2.36	**3.6**	2.54	**7.7**	2.64	**10.0**
3^{rd} T	2.65	2.65	0.0	2.65	0.0	2.65	0.0	2.65	0.0
4^{th} B	2.78	2.85	**6.3**	3.13	**6.3**	3.31	**9.6**	3.17	**7.1**
4^{th} T	3.26	3.28	1.7	3.37	1.7	3.52	3.9	3.66	6.1

Option 2: Active cables attached to the catenary

$$\xi_i^{max} = \frac{\Omega_i - \omega_i}{2\omega_i}$$



Mode #	ω_i (Hz)	Position A Ω_i (Hz)	Position A ξ_i^{max} (%)	Position B Ω_i (Hz)	Position B ξ_i^{max} (%)	Position C Ω_i (Hz)	Position C ξ_i^{max} (%)	Position D Ω_i (Hz)	Position D ξ_i^{max} (%)
1^{st} B	1.02	1.06	1.6	1.21	9.4	1.40	18.5	1.58	27.2
2^{nd} B	1.48	1.50	0.6	1.56	2.9	1.59	4	1.58	3.4
1^{st} T	1.79	1.81	0.5	1.93	3.7	2.12	9.1	2.36	15.7
2^{nd} T	2.10	2.11	0.3	2.16	1.5	2.18	1.9	2.16	1.5
3^{rd} B	2.20	2.21	**0.3**	2.30	**2.4**	2.42	<u>**5.1**</u>	2.90	<u>**15.9**</u>
3^{rd} T	2.65	2.65	0.0	2.66	0.0	2.66	0.1	2.66	0.1
4^{th} B	2.78	2.83	**1.0**	3.09	**5.7**	3.63	<u>**15.4**</u>	3.59	<u>**14.7**</u>
4^{th} T	3.26	3.27	0.1	3.35	1.3	3.54	4.3	3.81	8.3

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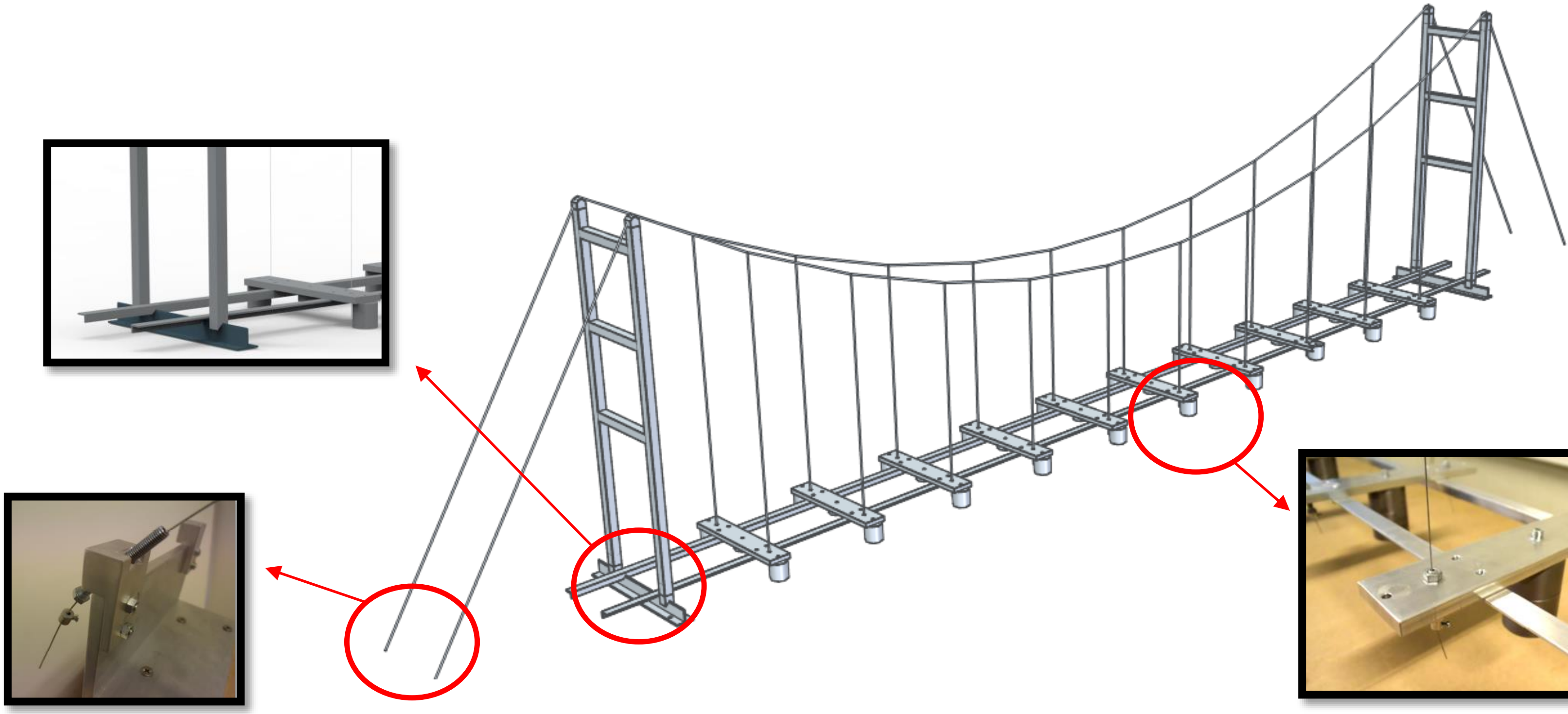
MSc students **Andrea Sangiovanni** and **Matteo Voltan**, from Politecnico di Milano (2015)

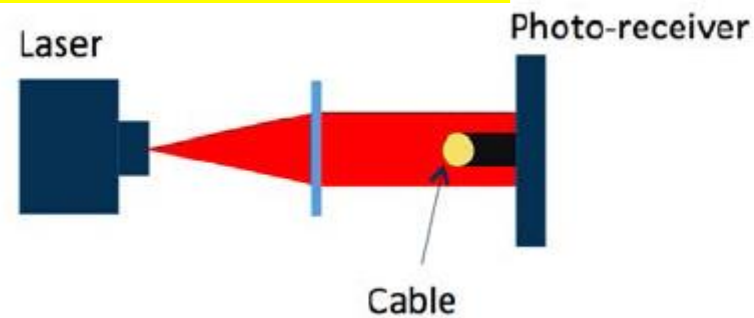
Schematic view of the laboratory mock-up



The tension in the hanger is adjusted from the measured natural frequency:

$$f = \frac{1}{2L}\sqrt{\frac{T_0}{\varrho A}}$$

Optical device for measuring *f*



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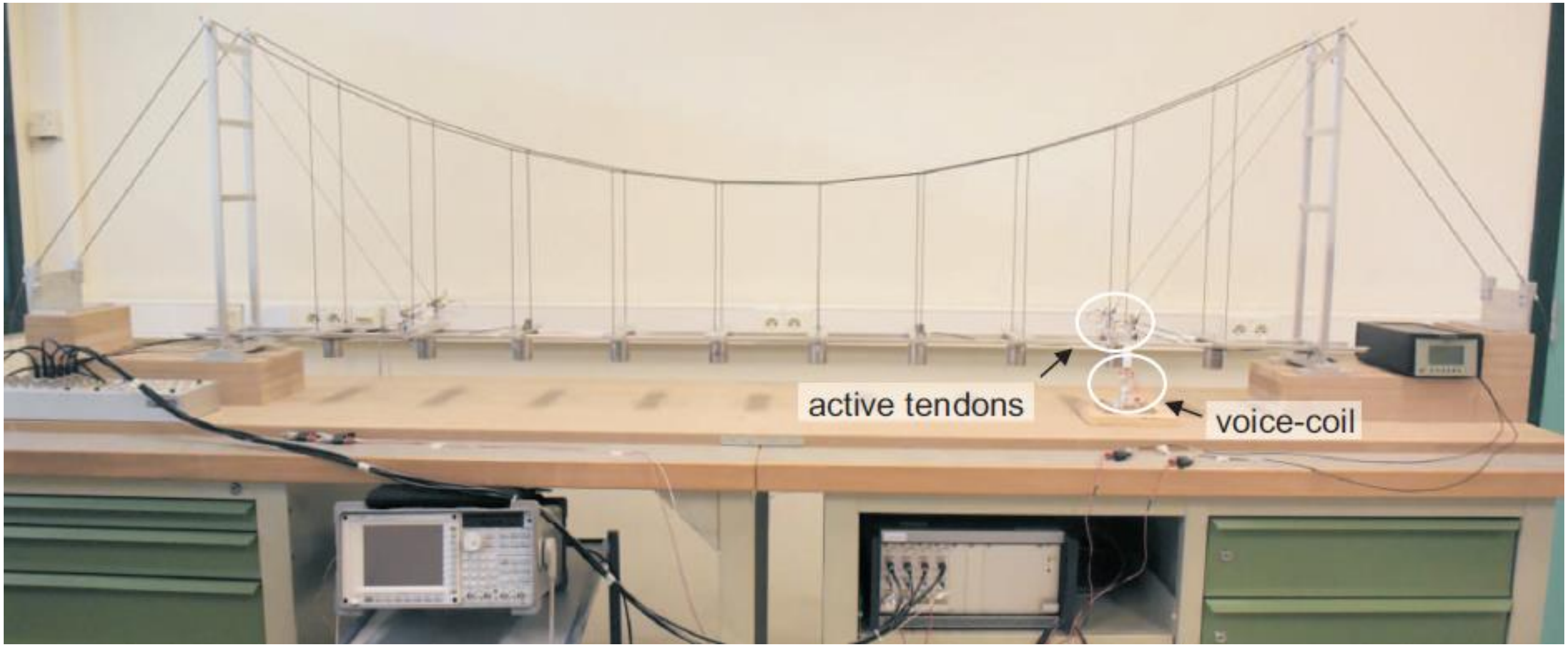
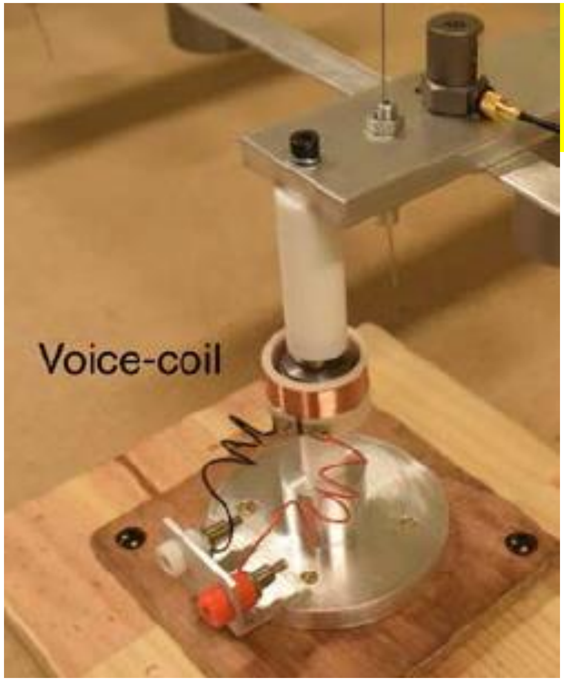
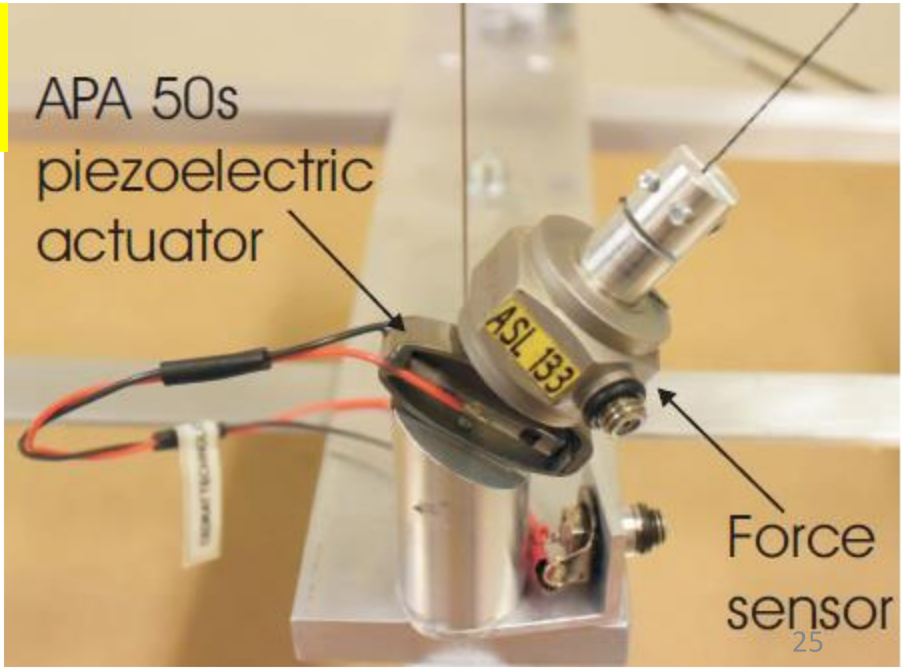
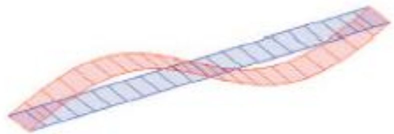
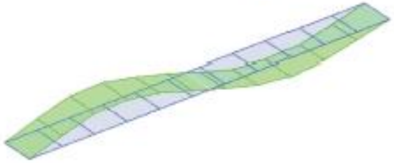
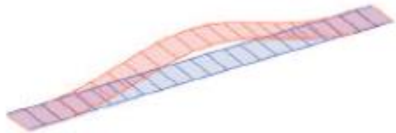
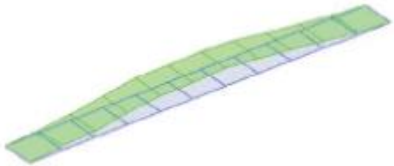
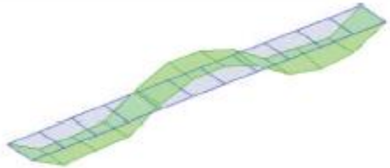
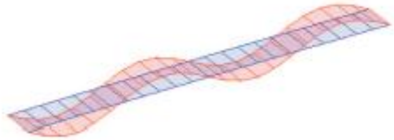
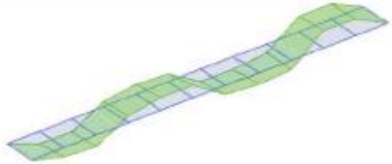
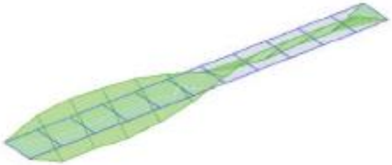
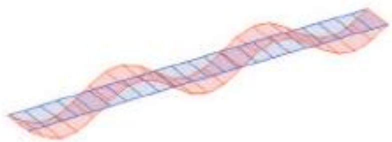
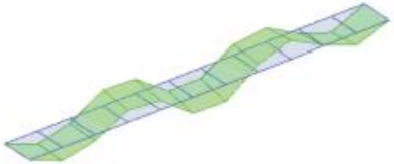




Mock-up with 4 active tendons

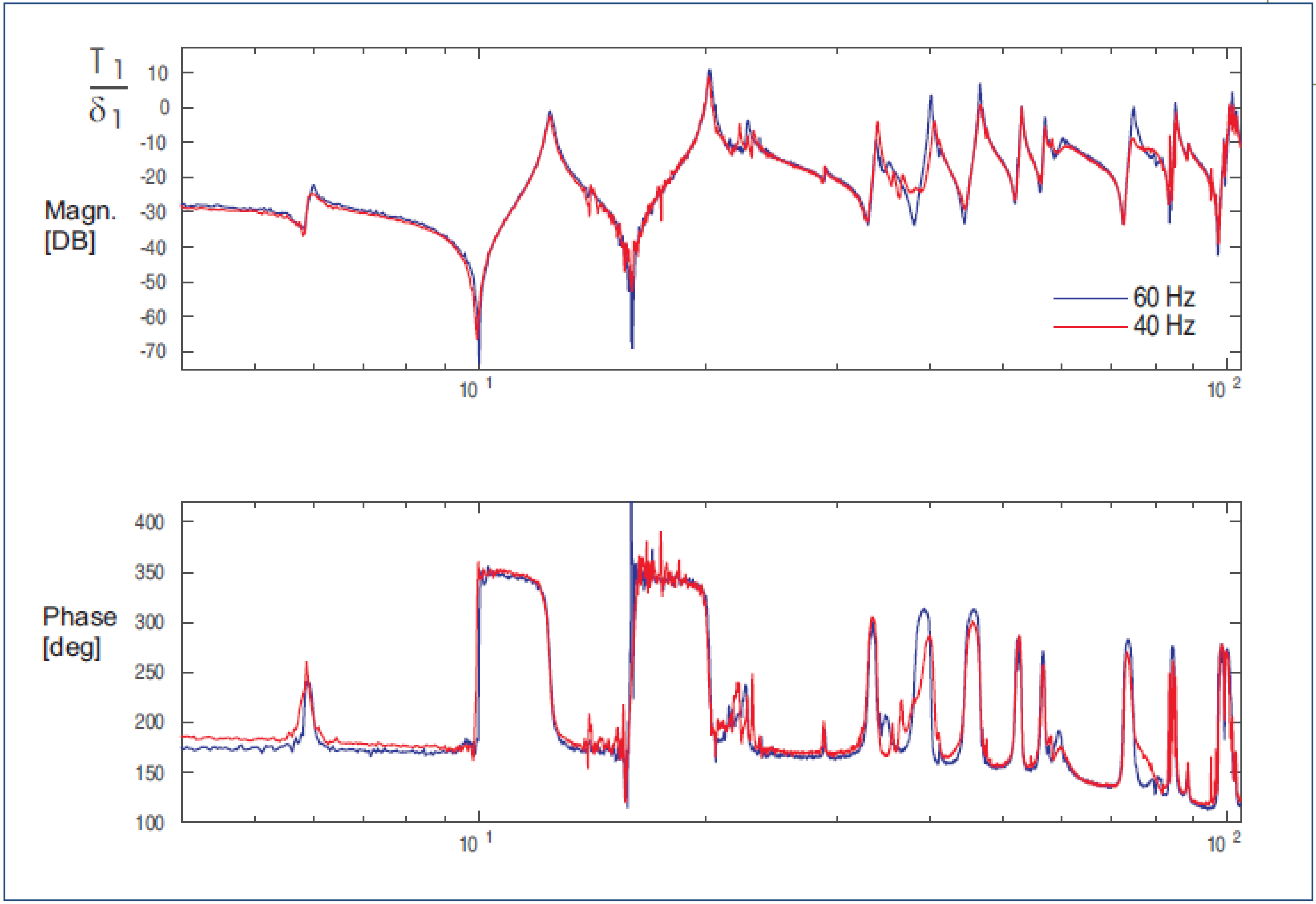


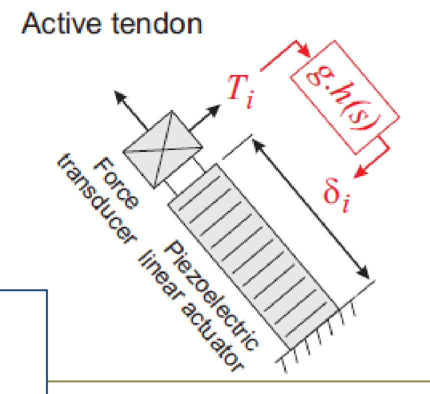
Laboratory demonstrator: comparison between numerical and experimental modes

Mode N.	Numerical (Hz)	Experimental (Hz)	Numerical Mode Shape	Experimental Mode Shape
1^{st} B.	4.84	4.81		
2^{nd} B.	7.68	5.59		
3^{rd} B.	11.33	10.82		
4^{th} B.	17.93	18.25		
3^{rd} T.	19.12	21.75		
5^{th} B.	28.01	28.84		

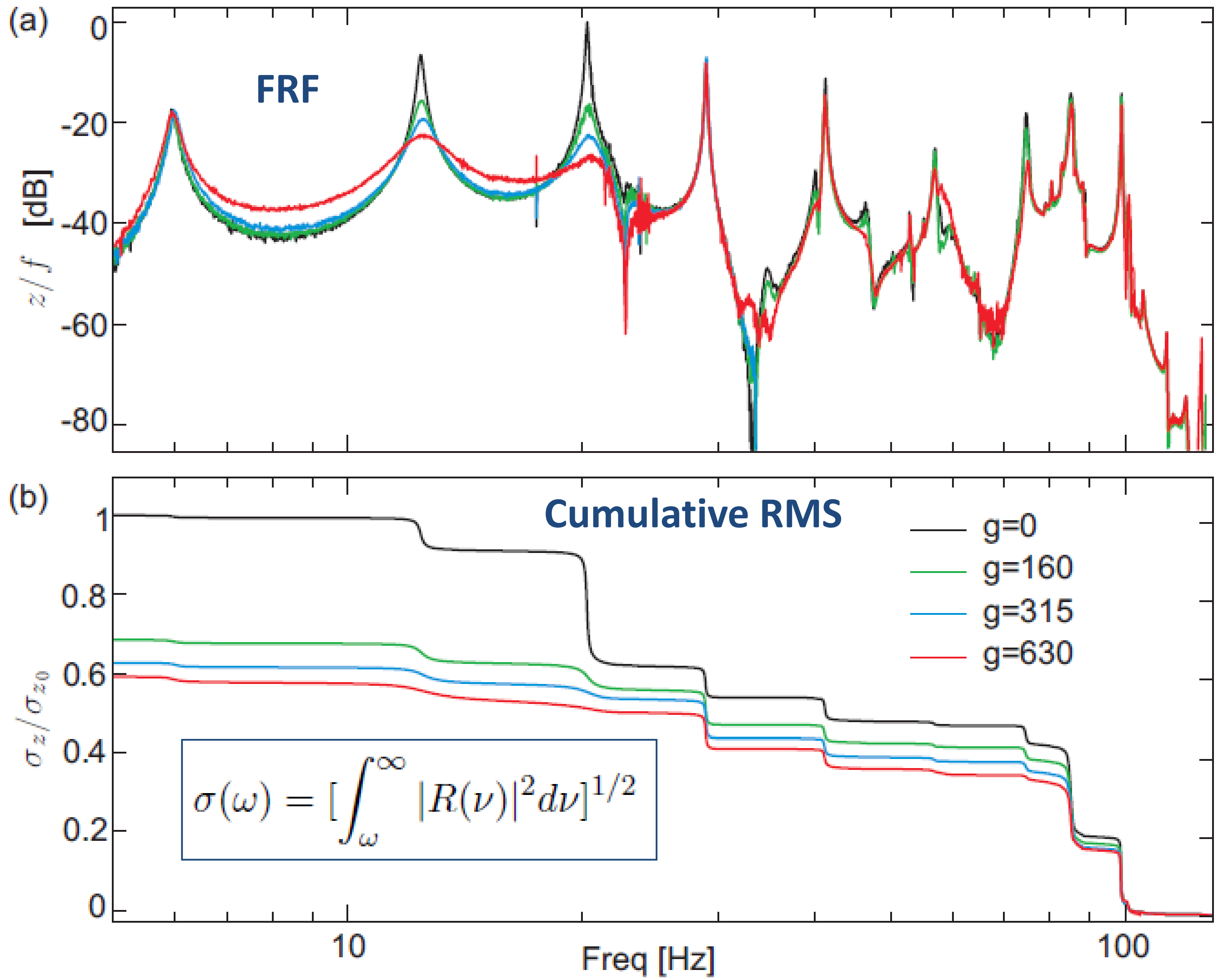
Open-loop Transfer Function

The two curves refer to different
Natural frequencies of the active cable

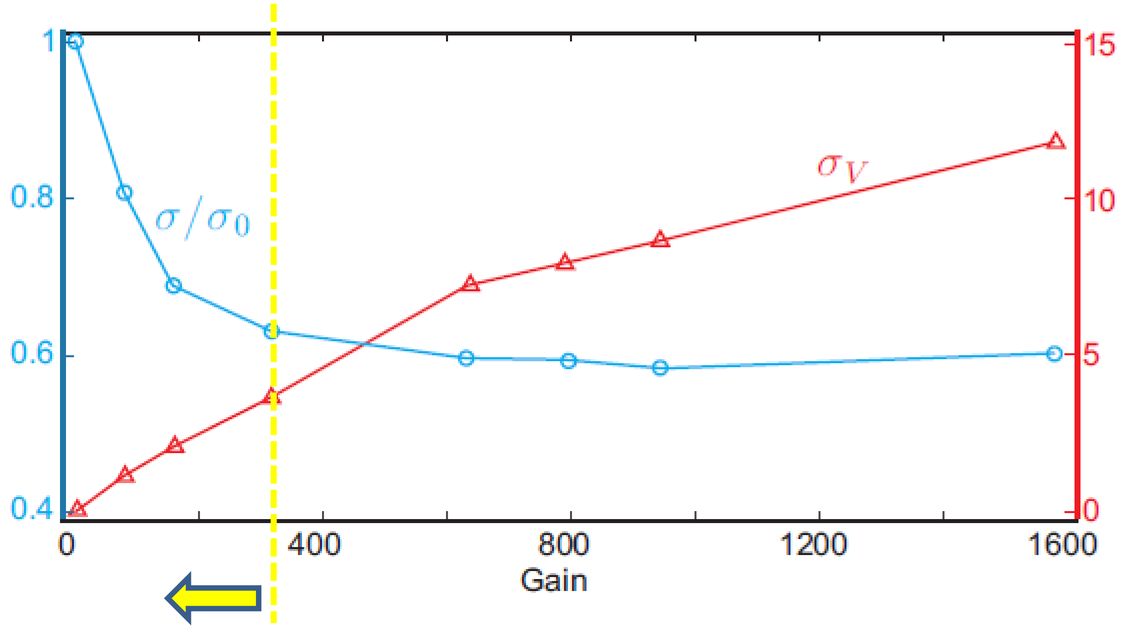




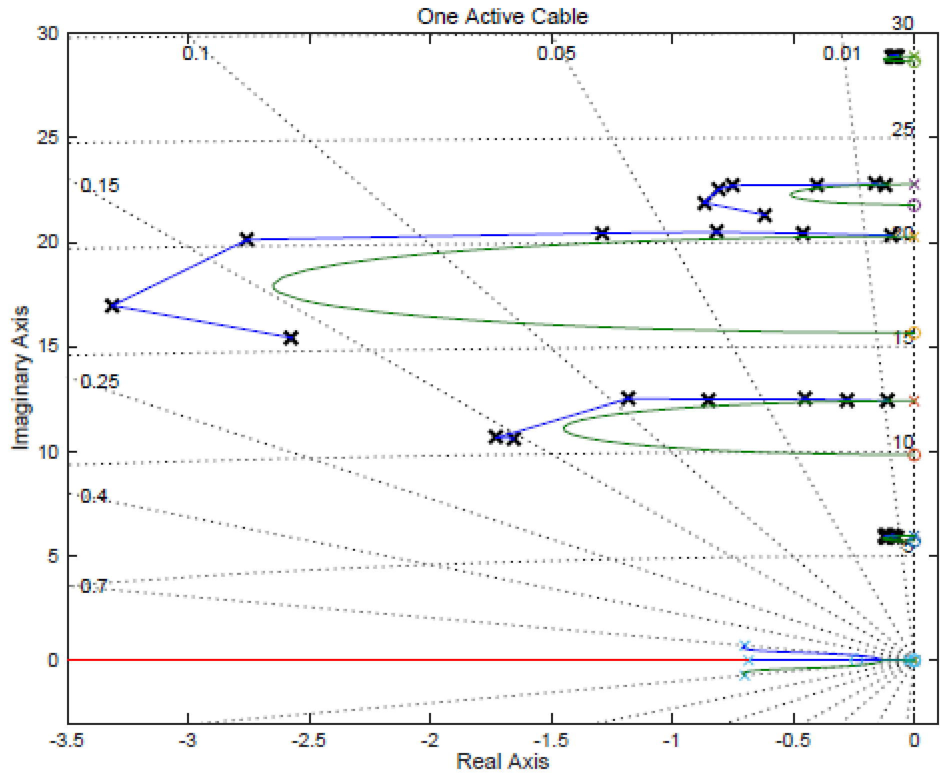
Response to disturbance, *z/f* with a single loop of control



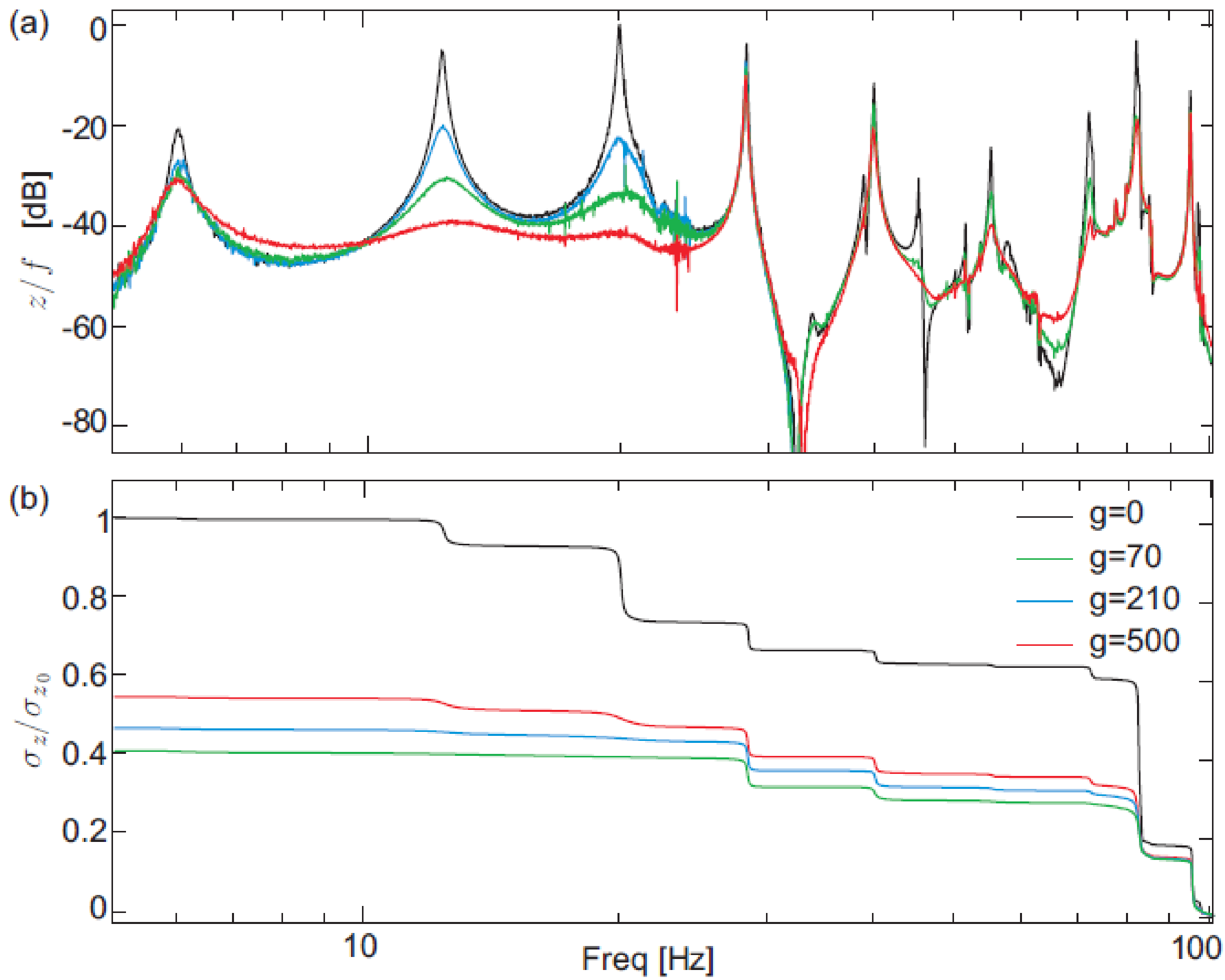
Response with a single control loop: Evolution of the RMS response (*z*) and the RMS control input (*v*) with the control gain *g*



Response with a single control loop: Root locus reconstruction and comparison with the approximate theory



Decentralized control with Four independent loops
Reponse to disturbance z/f (FRF and cumulative RMS)



No spillover !

Conclusions

- Decentralized active tendon control of cable-structures is possible.
- Simple prediction formulae based on linear models may be used for design.
- **The simple performance prediction formulae are supported by experiments**.
- The static stiffness deficiency of the IFF can be recovered by high –pass filtering.
- A highly effective control of a **suspension bridge** may be obtained with few and small active control cables which do not have to withstand the dead loads.

ULB

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