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Structural Dynamics with Coincident Eigenvalues

test bench and ideas for aerodynamic structures

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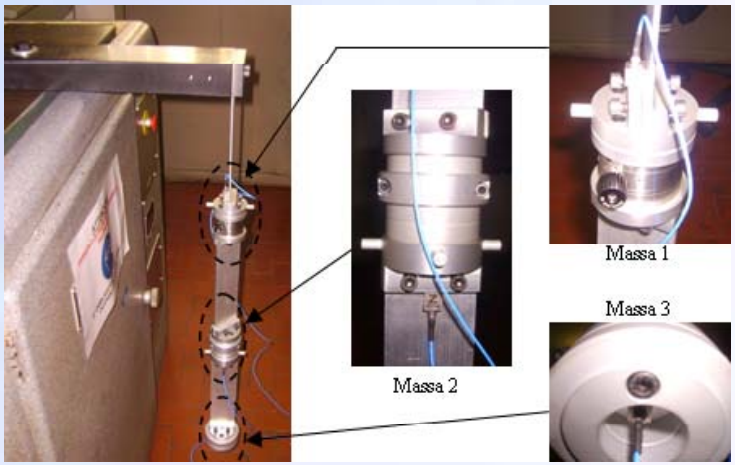
Introduction

Aim: **Design of an experimental test rig that exhibits dynamics with coincident or close eigenvalues**
(without symmetry or cyclic properties)

Sensitivity of dynamic properties

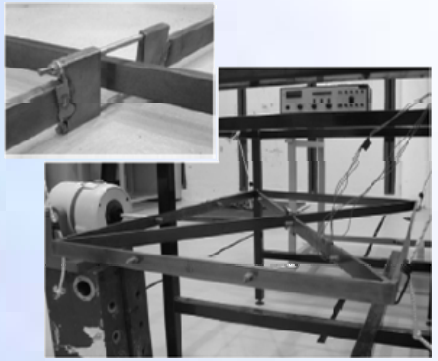
Reasons:

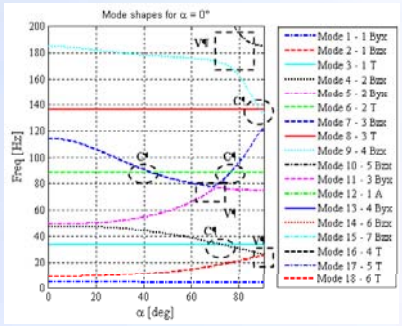
- Crossing and veering phenomena
- Energetic path transfer related to different eigenspaces
- Applications on aerodynamic structures (i.e. flutter instability)
- Experimental test rig on dynamic uncertainty and variability

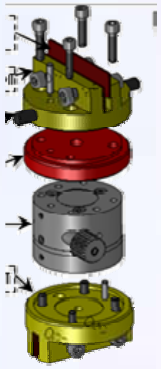


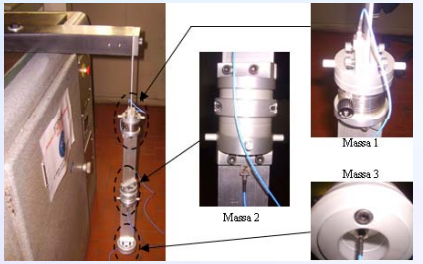
Summary

- Literature review
  - Symmetric, cyclic, uncoupled ideas
  - Experimental point of view
- Case test on lumped examples
  - Dynamic behaviour and eigenspaces
  - Crossing and veering phenomena
  - MAC index and tools for detection
- Models results
  - Numerical tool and dynamic properties
  - Proposed dynamic system and expected behaviour
- Experimental test rig and preliminary results
  - Design of the test bench
  - Experimental results and comparison
- Conclusions and future work …





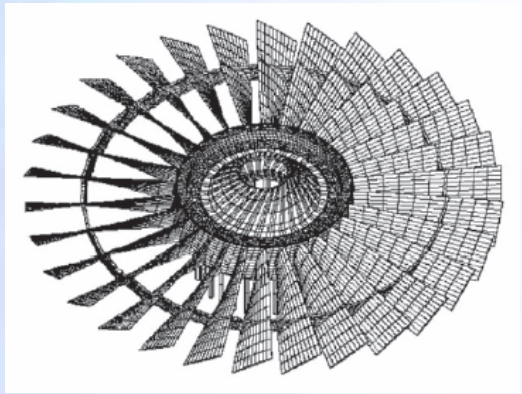




State of the art

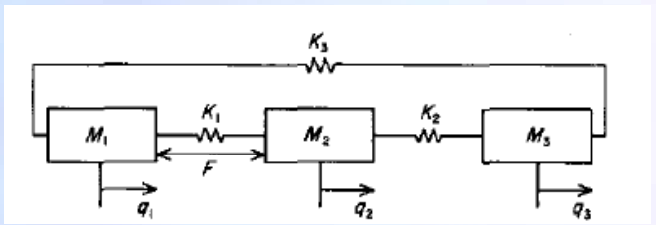
- Coincident or close modes structures:
  - **Symmetric structures**

    symmetric shells, bells, bladed disk, …



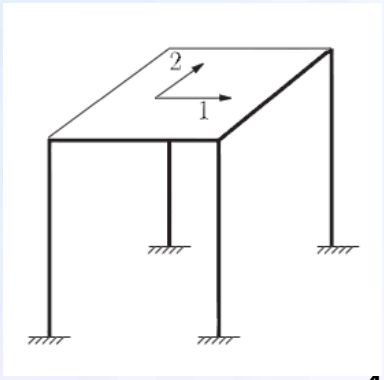
  - **Cyclic structures**

    lumped systems, bladed disk (again), …



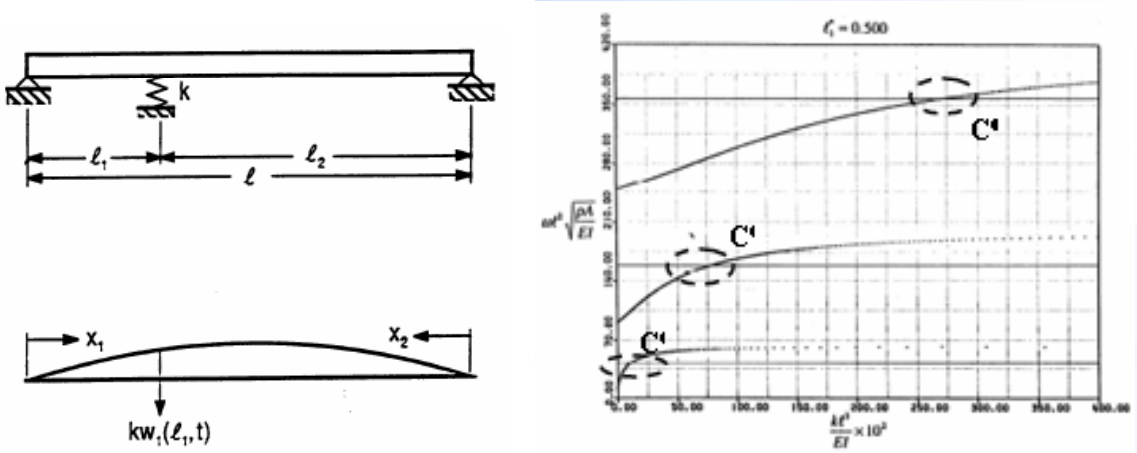
  - **Uncoupled or slightly coupled systems**

    symmetric beams, bladed disk (again), …

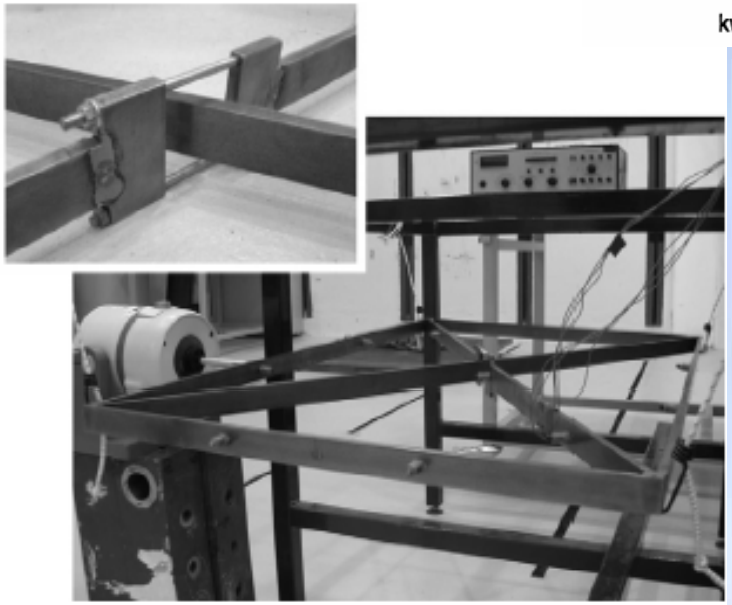


State of the art

Many references on theoretical dynamic systems with coincident or close eigenvalues



Young, Hwang, Chinese Proceed. 2007



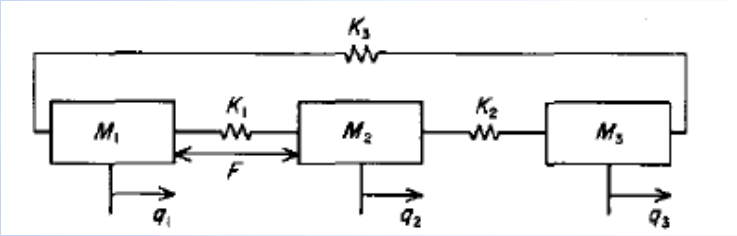
Adhikari, duBois, Lieven, JSV 2009

Few references on experimental test-rigs

No experimental test-rigs with NO-SYMMETRY or NO-CYCLIC, with structures “near” to wing-shape

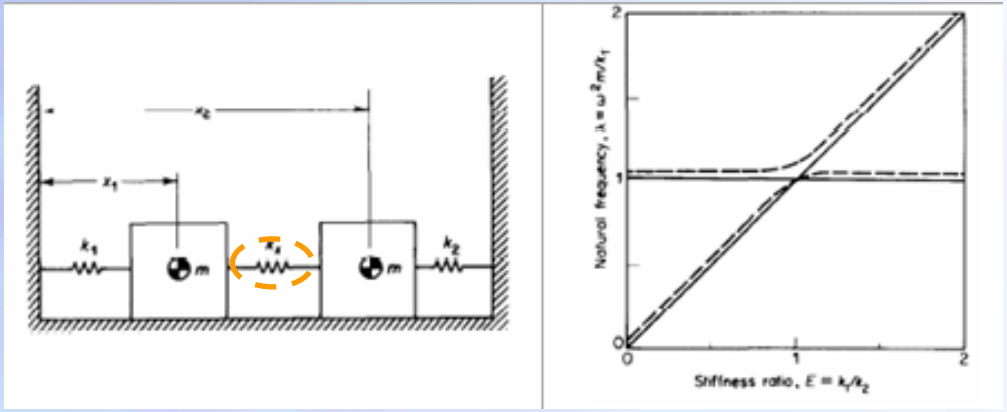
State of the art

Most of them presents SYMMETRY and/or CYCLIC characteristics, or some UNCOUPLING parameter

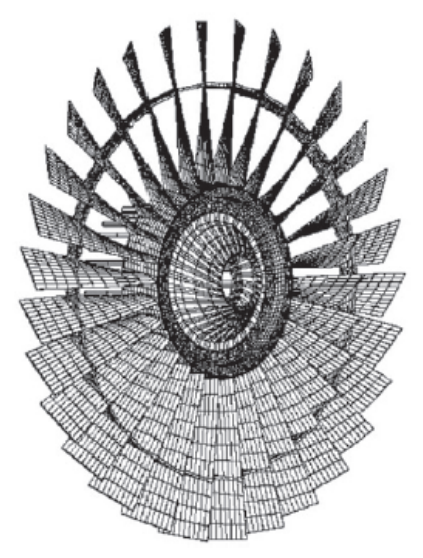


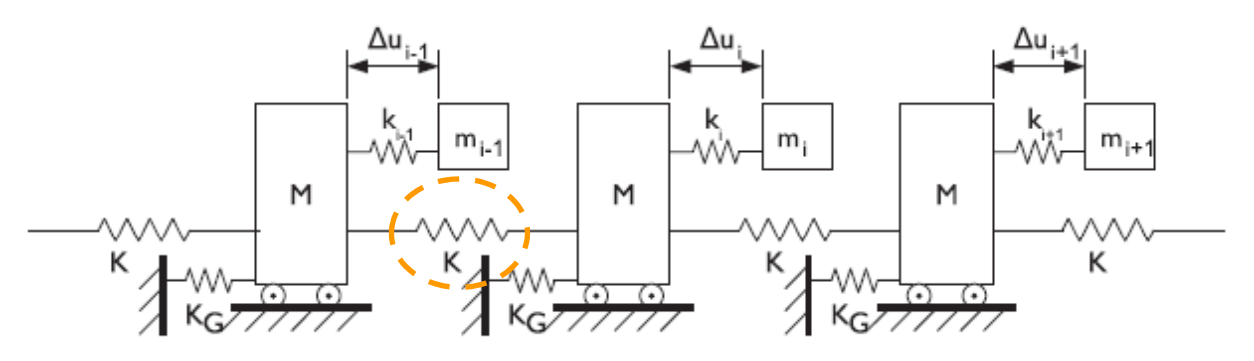
Balmes, JSV 1993

Perkins, Mote, JSV 1986



Chan, Ewins, MSSP 2010

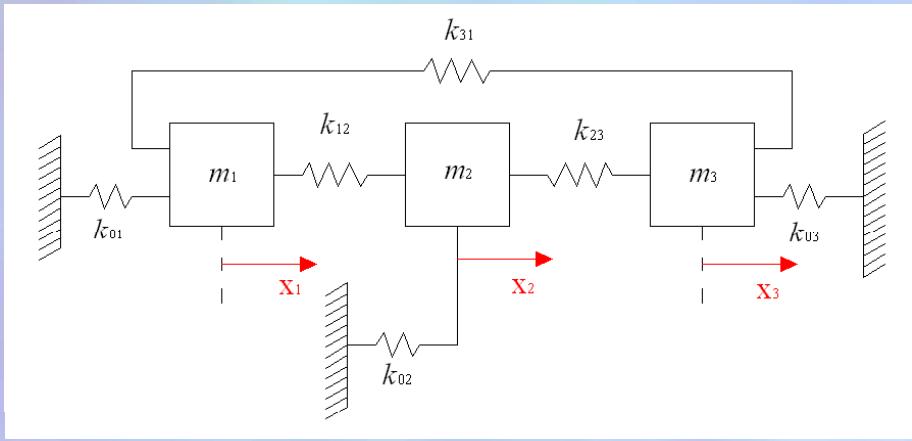


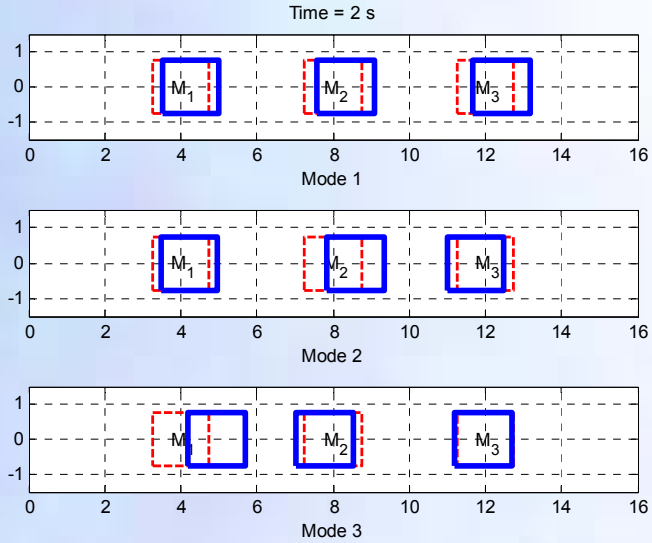


Starting point …

- Reliability of analytical models
  - Development of Matlab FE tools
  - Improvement of specific index (MAC, orthogonality, …)
- Reliability of CAD/CAE models and parametric tools
  - From simple lumped system to real structures
  - Tools for designing structures with coincident eigenvalues
- Analysis on uncertainty and variability
  - Rate of change and sensitivity of modal properties
  - Effects on uncertainty and variability
  - Dynamic properties (crossing and veering behaviour)
- Design of experimental test rigs
  - Experimental results
- Comparison between numerical and experimental results

Cyclic structures





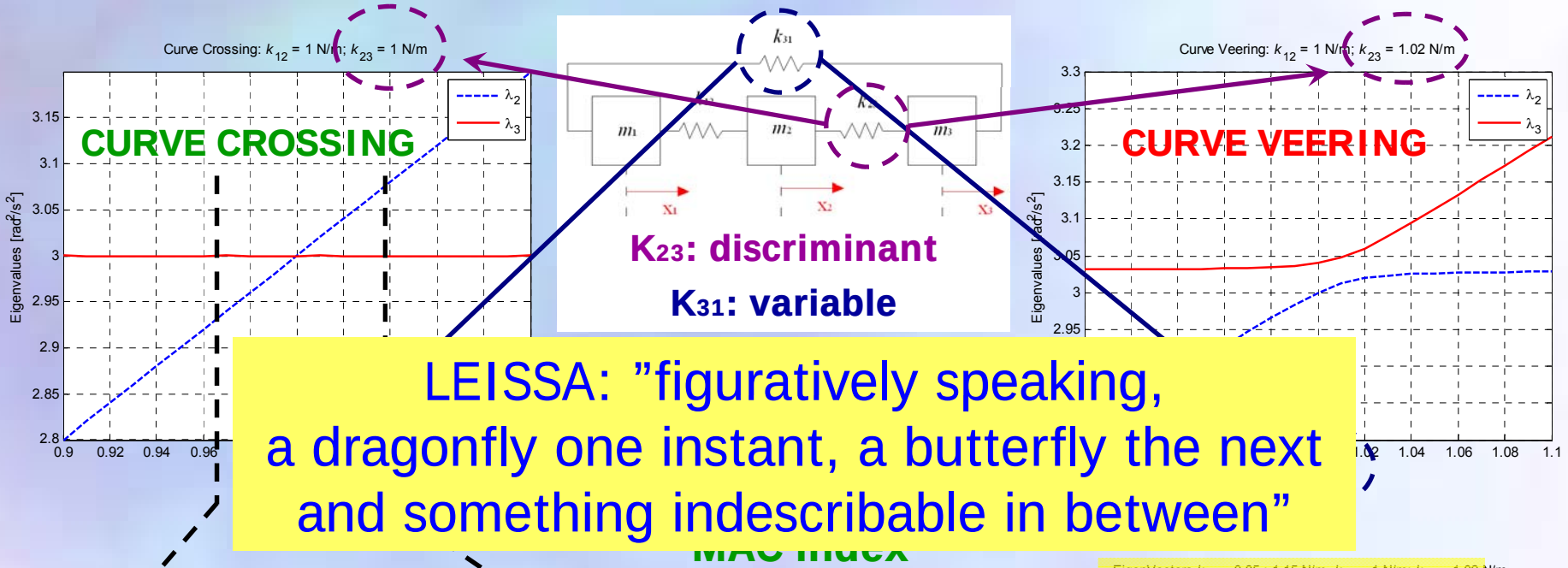
Deterministic analysis of crossing and veering phenomena:

- Crossing $k_{12} = k_{23}$; $k_{31} = 90\% \div 110\%\ k_{12}$
- Veering $k_{23} = 102\ \%\ k_{12}$; $k_{31} = 90\% \div 110\%\ k_{12}$

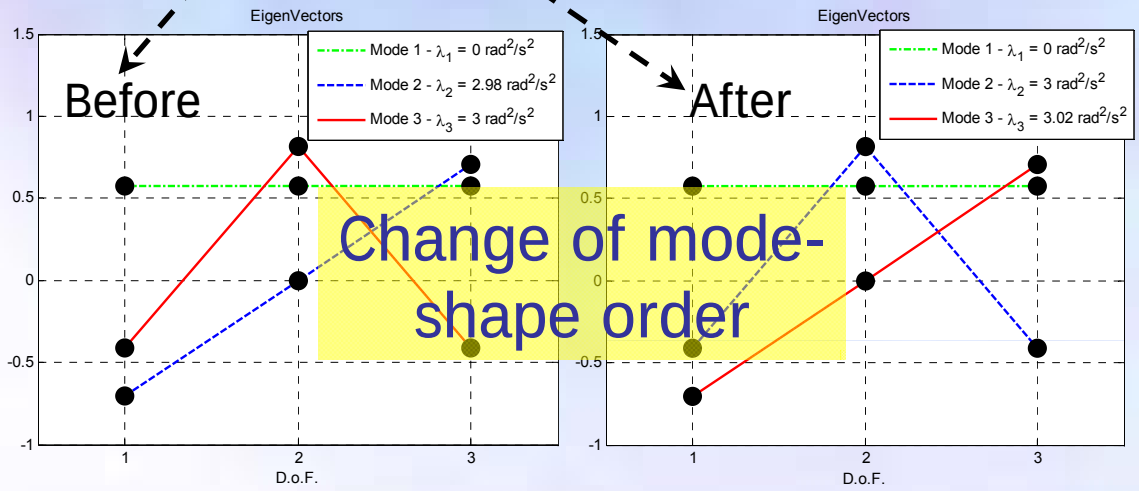
Sensitivity to uncertainly and variability

- Choice of index to discriminate crossing and veering → MAC
- Orthogonality properties
- Sensitivity to eigenvalues AND eigenvectors changes

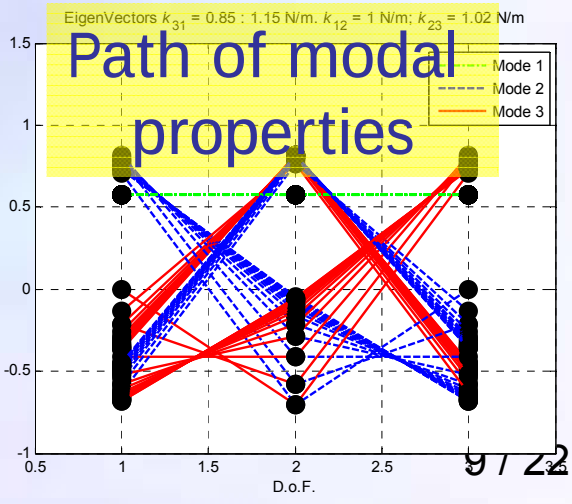
Curve Crossing and Curve Veering



LEISSA: ”figuratively speaking,
a dragonfly one instant, a butterfly the next
and something indescribable in between”

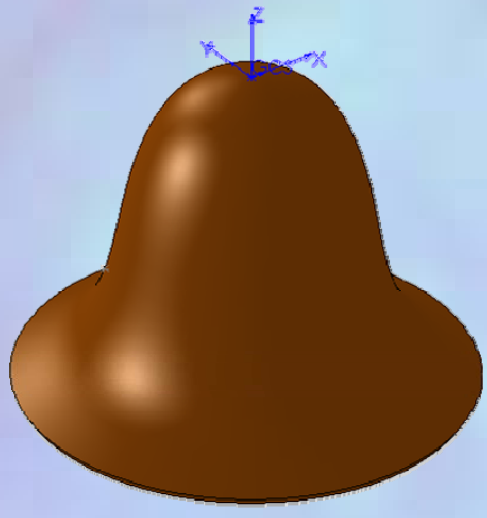


Change of mode-shape order

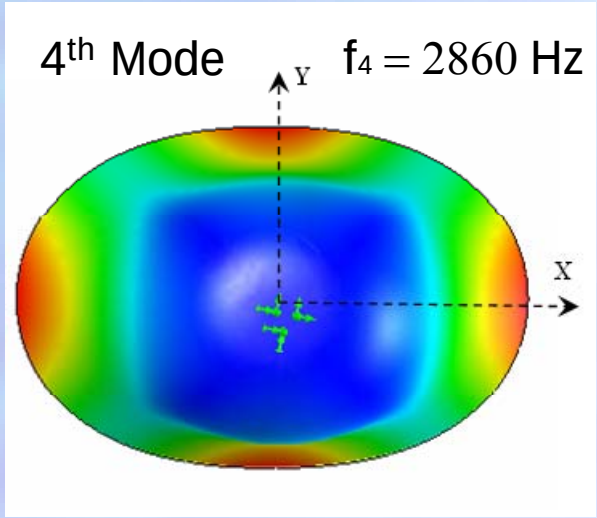


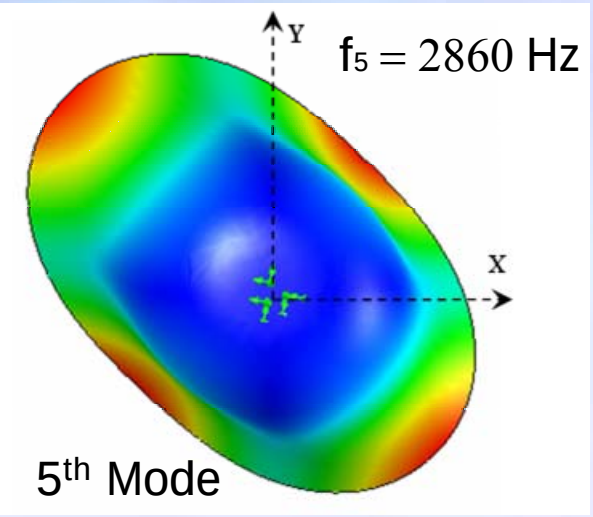
Path of modal properties

Coincident eigenvalues: bell

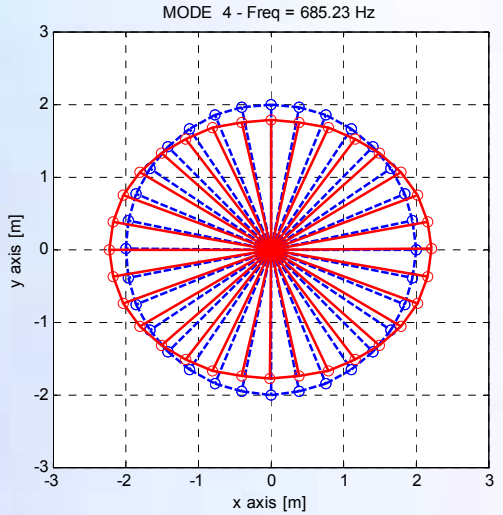


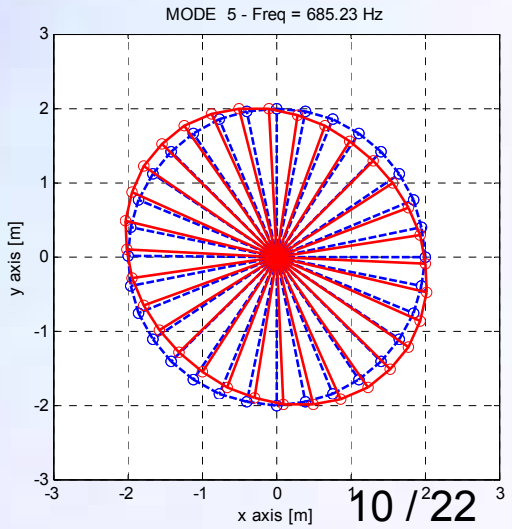
CosmosWorks





Matlab FEM





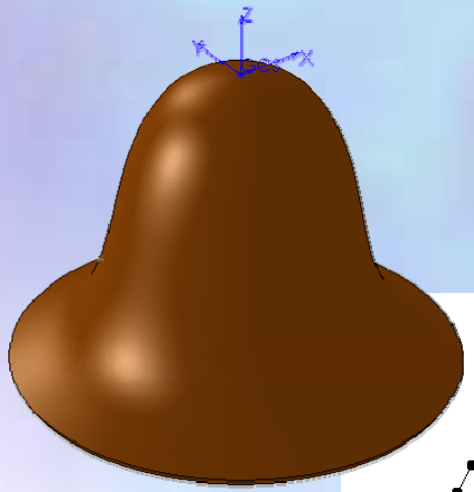
- couples of two modes with coincident eigenfrequencies ...
  ... but different (rotated) mode shapes

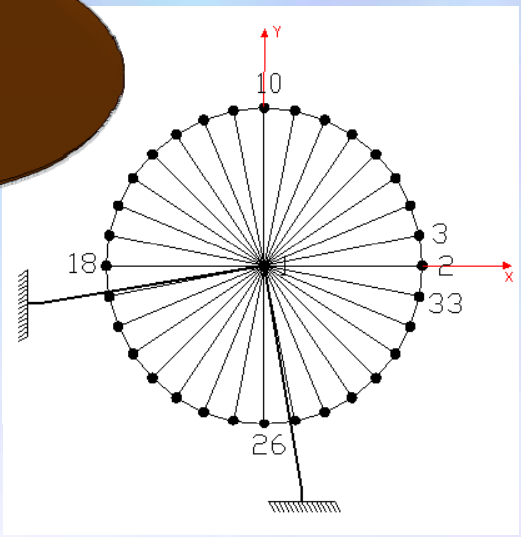
- energy path between coincident mode shapes ?

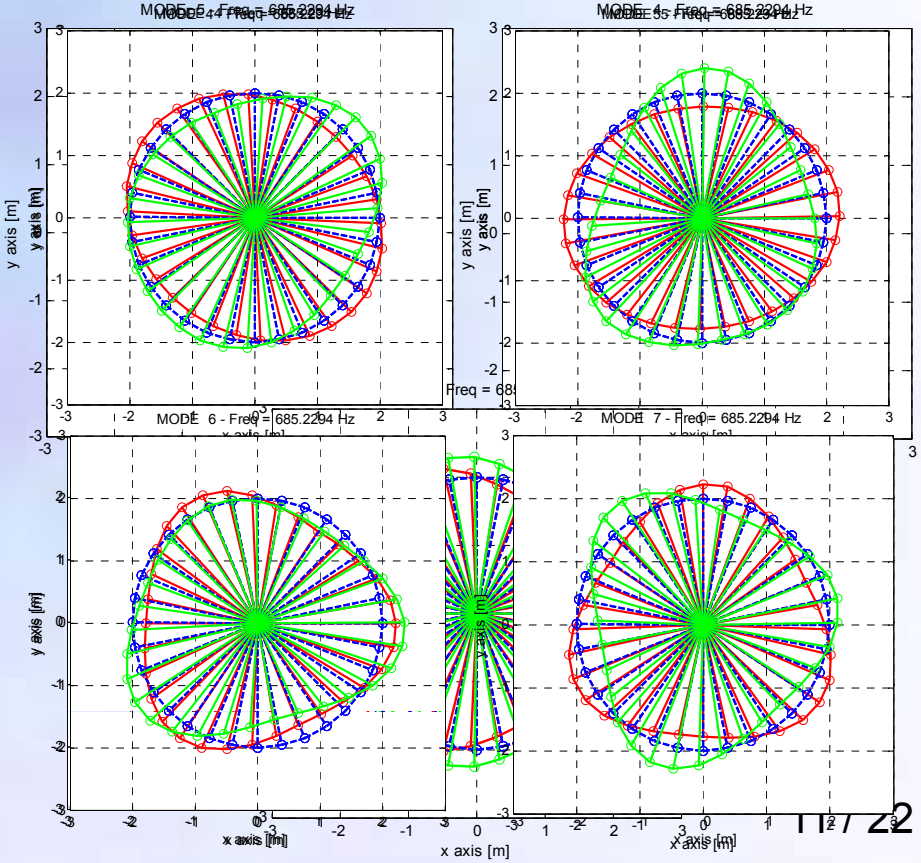
Coincident eigenvalues: bell

Structural modifications:

- Modify lumped elastic parameters on symmetric structures to enforce coincident mode shapes







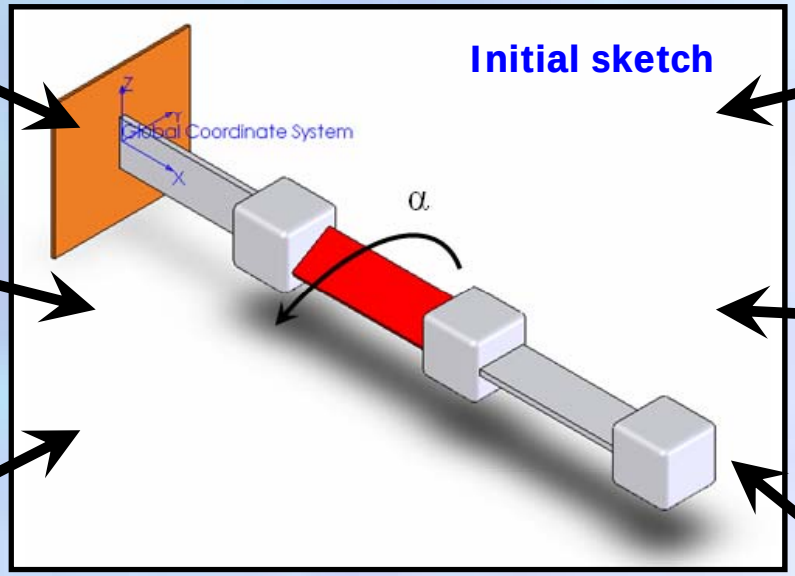
Main ideas of the test rig

Idea: modal coupling between bending and torsional mode-shapes
energy path between two mode-shapes ...

NO SYMMETRY
NO CYCLIC

SIMPLE TUNABLE PARAMETER: α

SIMPLE STRUCTURE (wing form ?)



COINCIDENT EIGENVALUES (Crossing)

CLOSE EIGENVALUES (Veering)

MODULAR and FLEXIBLE PROP.

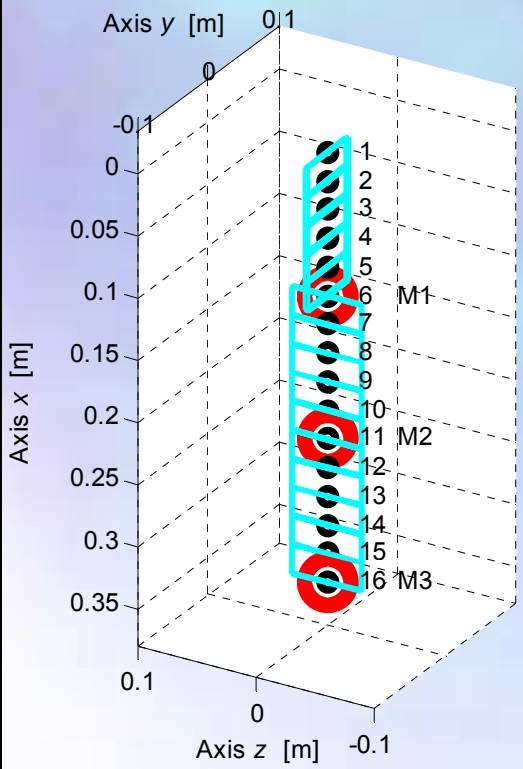
Parametric dynamic analysis by varying the angle α

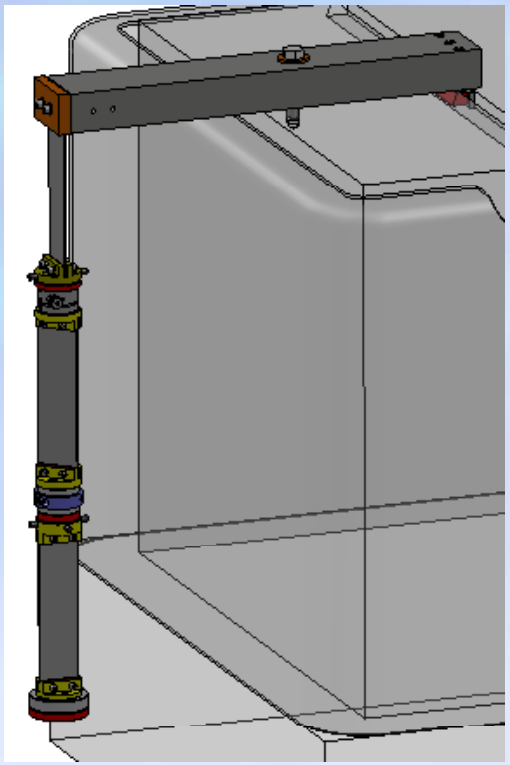
For each configuration α, modal approach (following modal changes):

$$[M]\{\ddot{x}\}+[K]\{x\}=\{0\} \rightarrow \left([K]-\omega^2[M]\right)\{\phi_0\}=0 \rightarrow \det\left([K]-\omega^2[M]\right)=0$$

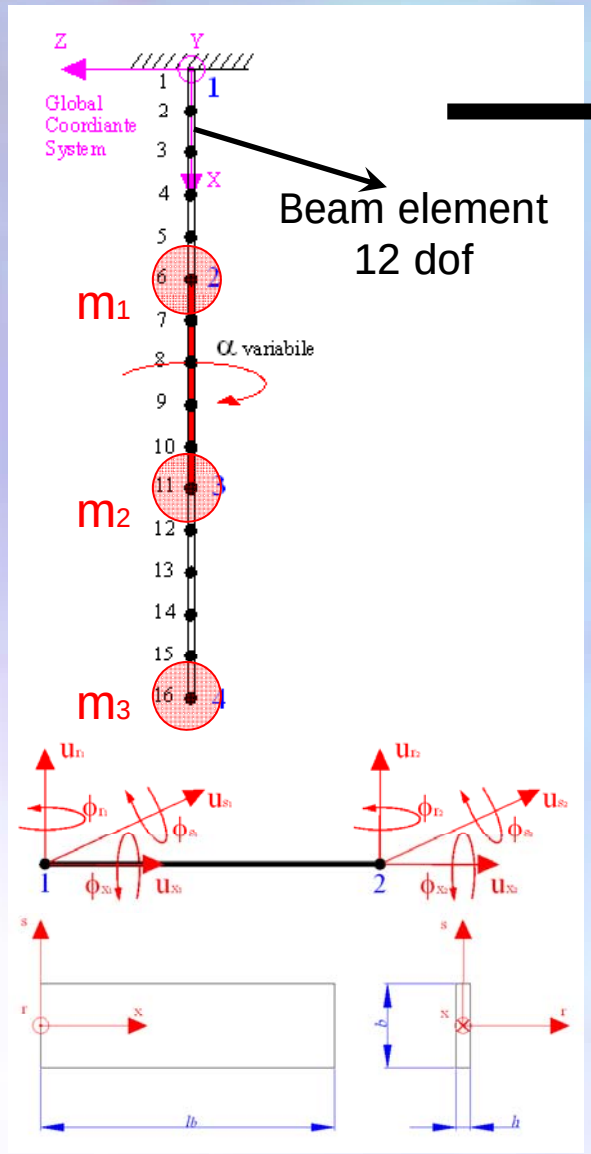
Design steps

Numerical tool (FE model) → **Design (CAD integration)** → **Experimental rig and tests**



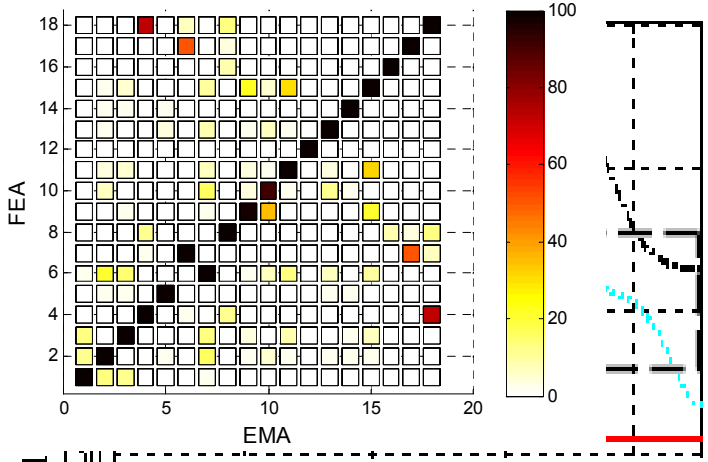


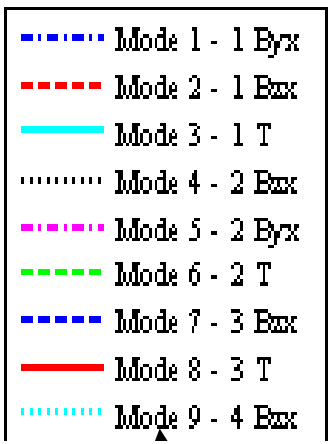
FE model



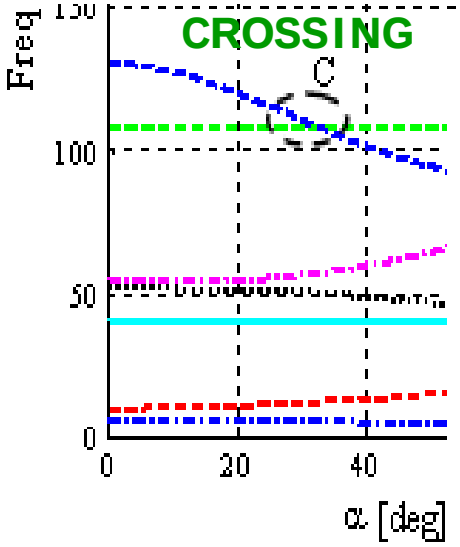
Parametric analysis

CROSSING

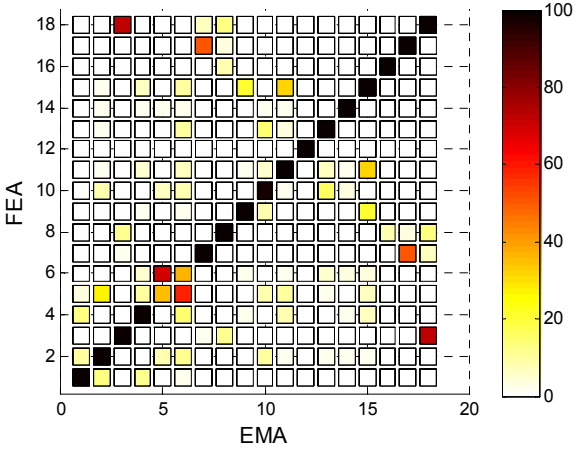




CROSSING

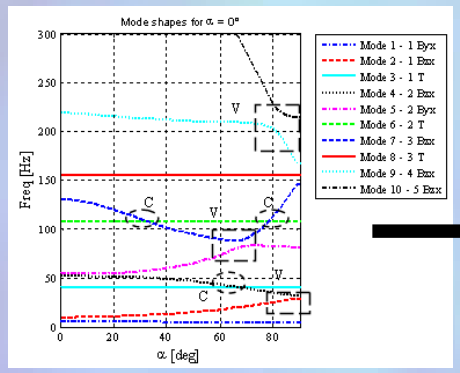


VEERING

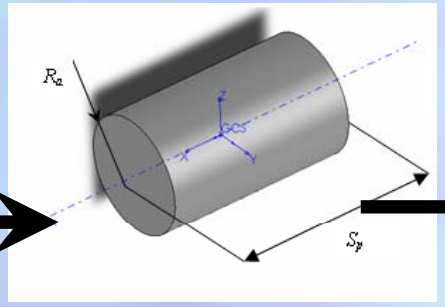


Design process

Theoretical parameters

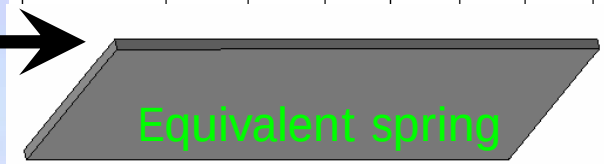


Equivalent parameters

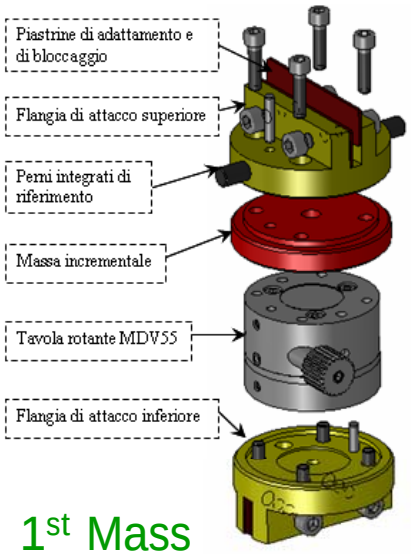


Equivalent mass

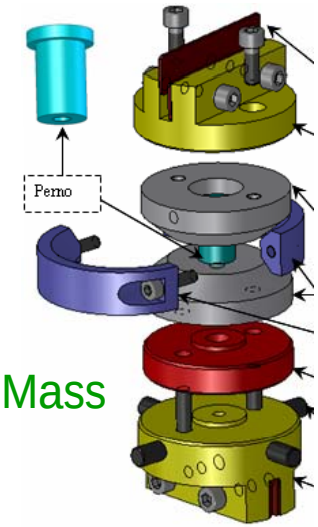
Parametri elasticità	L	b	h			
Descrizione	Lunghezza tratto	Larghezza sezione	Altezza sezione			
Parametri inerziali	R_{a1}	S_{p1}	R_{a2}	S_{p2}	R_{a3}	S_{p3}
Descrizione	Raggio 1°massa	Spessore 1°massa	Raggio 2°massa	Spessore 2°massa	Raggio 3°massa	Spessore 3°massa



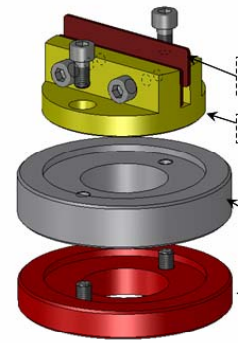
DESIGN PROCESS



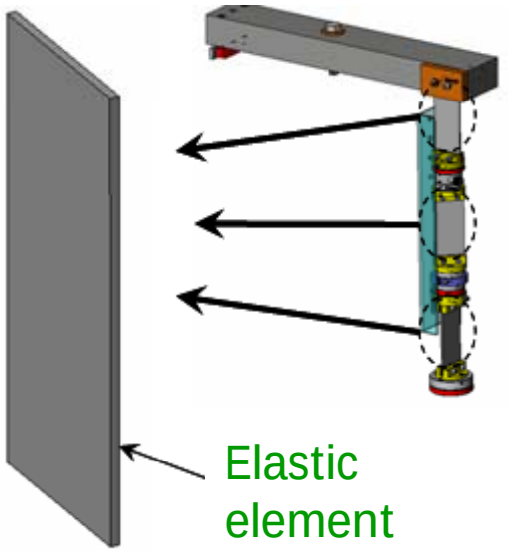
1st Mass



2nd Mass



3rd Mass



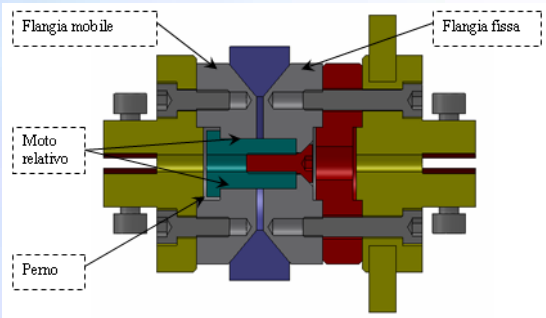
Elastic element

Design process

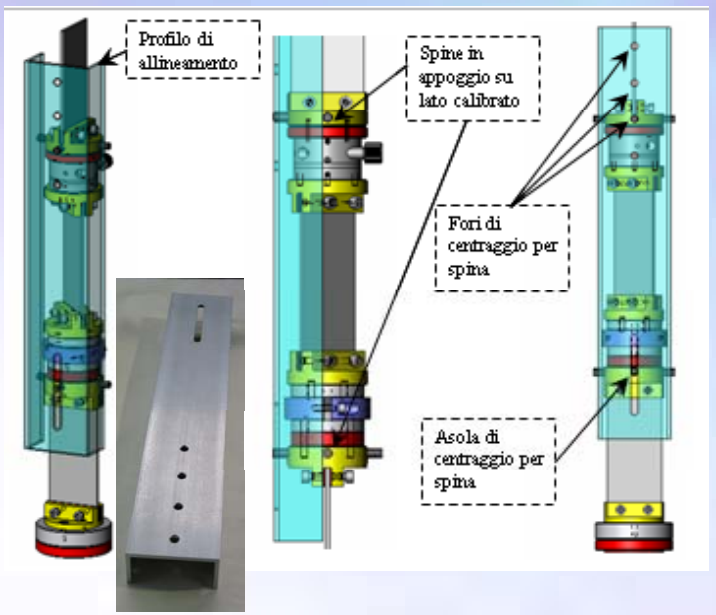
- Angle parameter α:

Manual rotary table

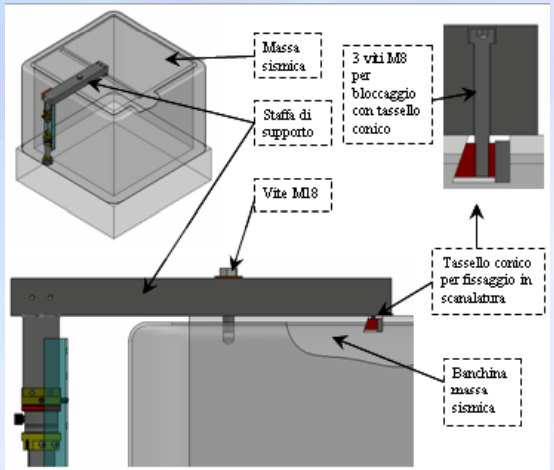
Rotation and locking



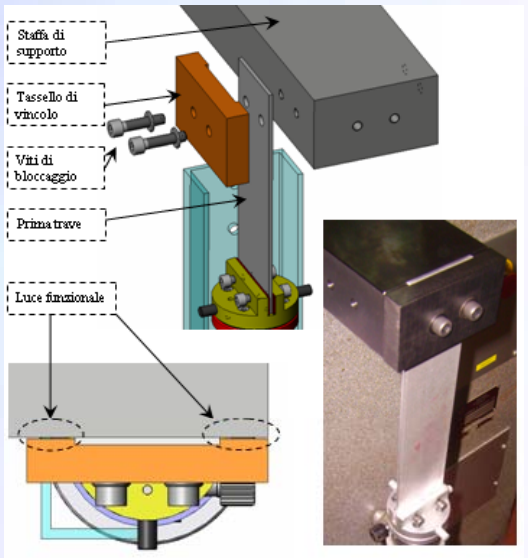
- Alignment device



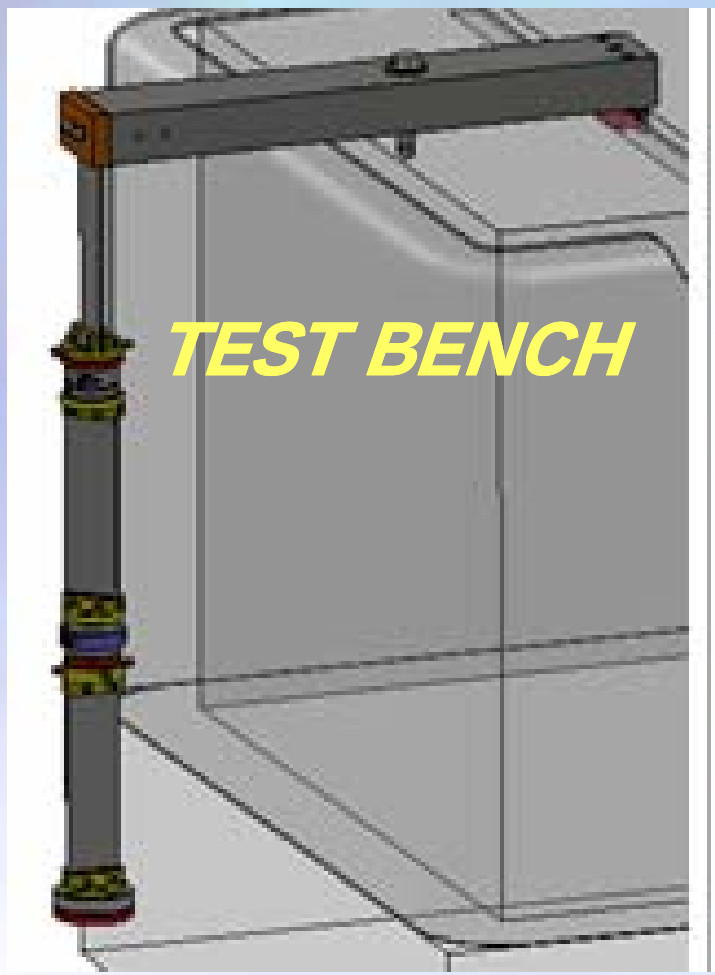
- Clamp beam



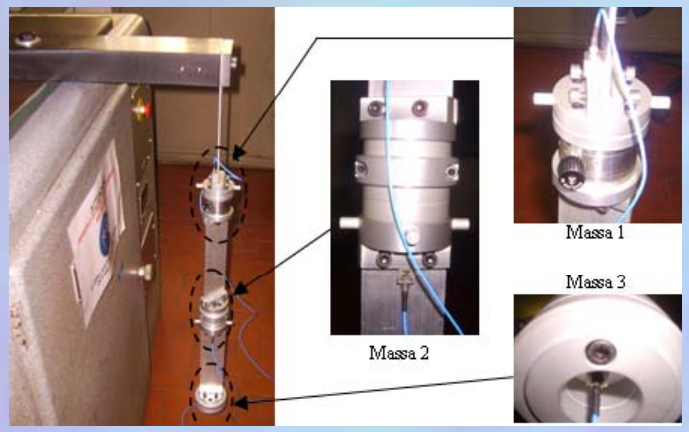
- Boundary conditions



Design process



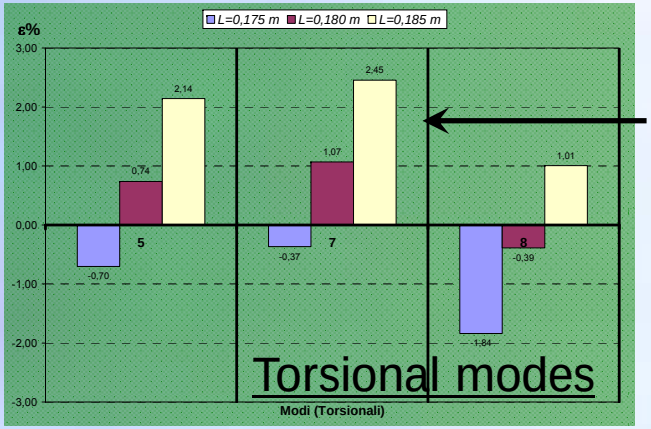
Experimental modal analysis



Experimental results

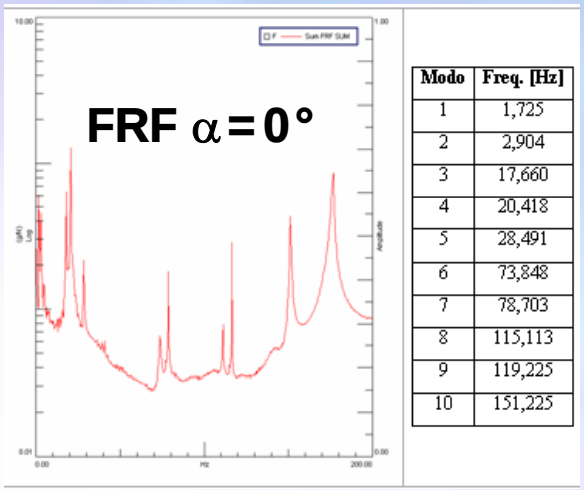
➢ Tuning of beam lengths based on FE Matlab:

ε %



3 lengths

➢ Model Updating: Experimental/CosmosWorks

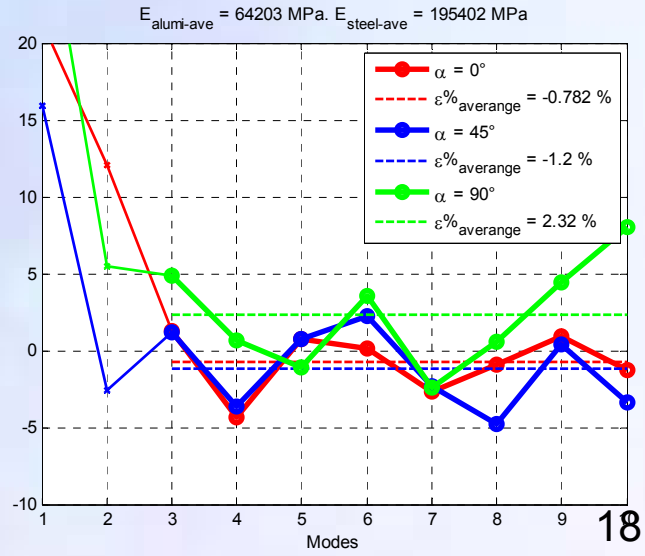


Modo	Freq. [Hz]
1	1,725
2	2,904
3	17,660
4	20,418
5	28,491
6	73,848
7	78,703
8	115,113
9	119,225
10	151,225

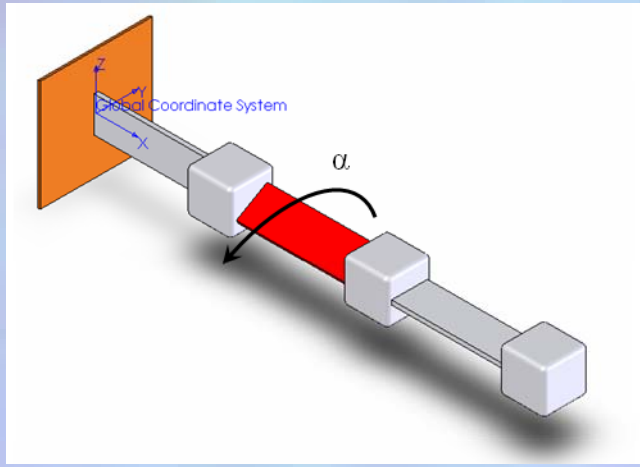
Material moduli E,G

Good correspondence of eigenvalues

ε %

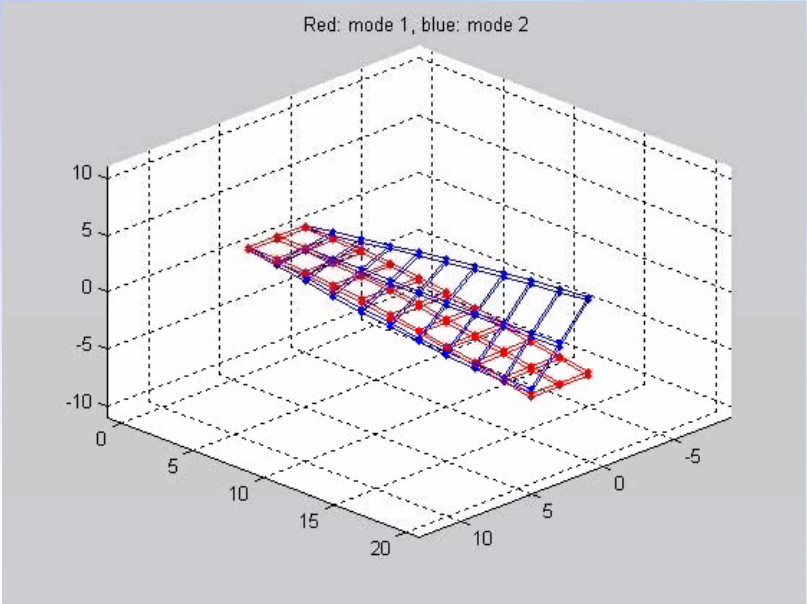


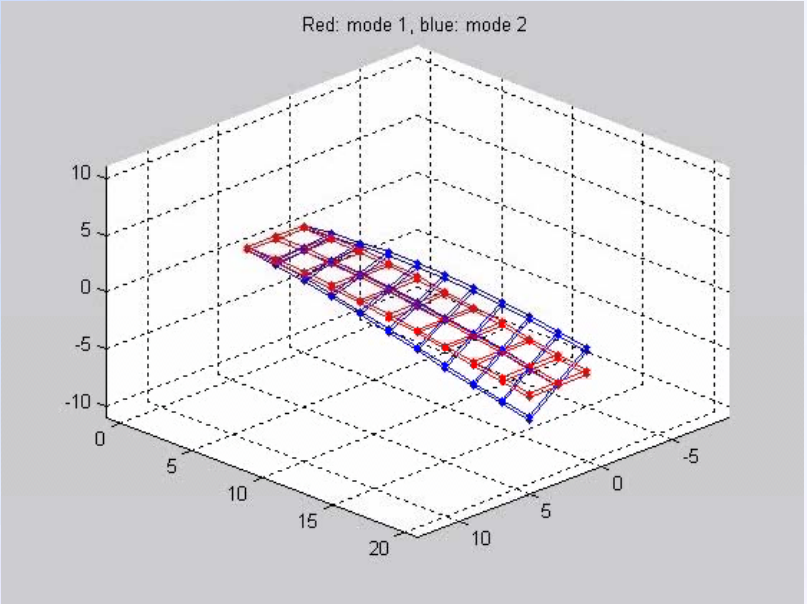
Main ideas of the test rig



Torsional and bending modes:

- independent, but coincident eigenvalues (crossing)
- coupled and veering eigenvalues (close modes)





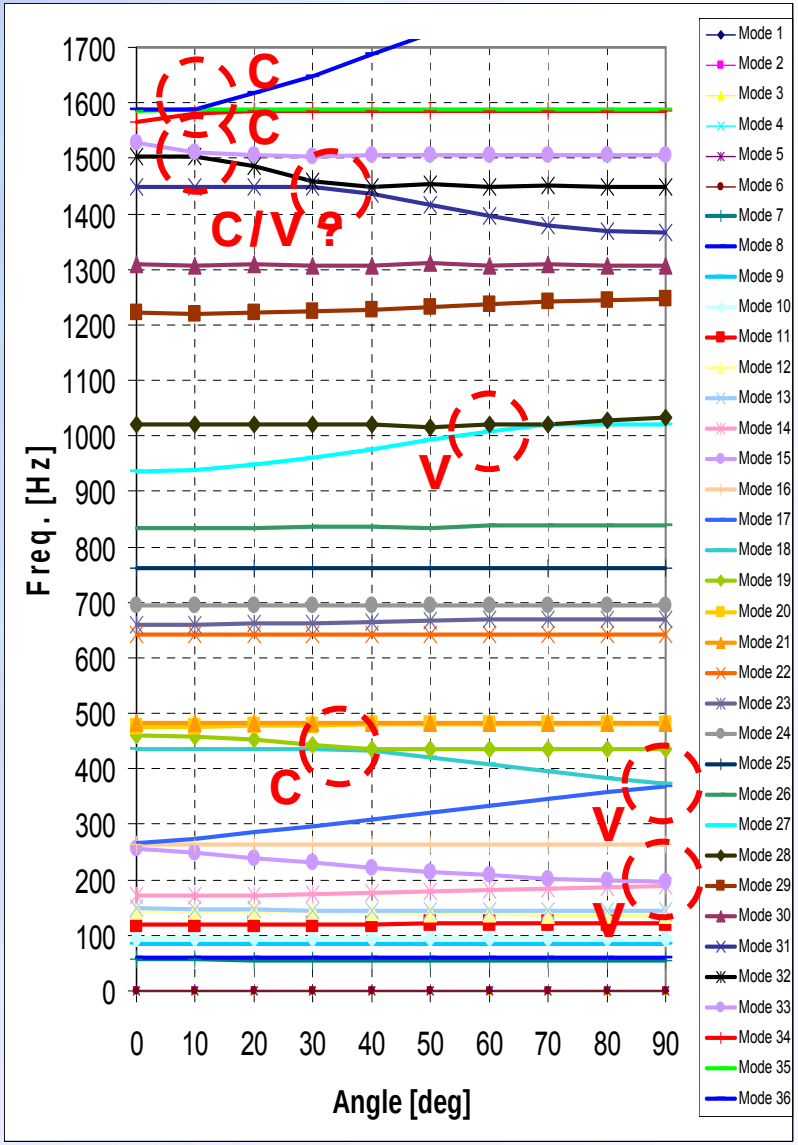
Structural modifications

Modular test rig:

- Choice of the parameter for obtaining coincident eigenvalues
- Uncertainty of configurations, modal properties, eigenvalues and mode shapes

Other mechanical structures:

- Parametric FE models (geometric properties and configurations) with uncertainty in simulations



Conclusions

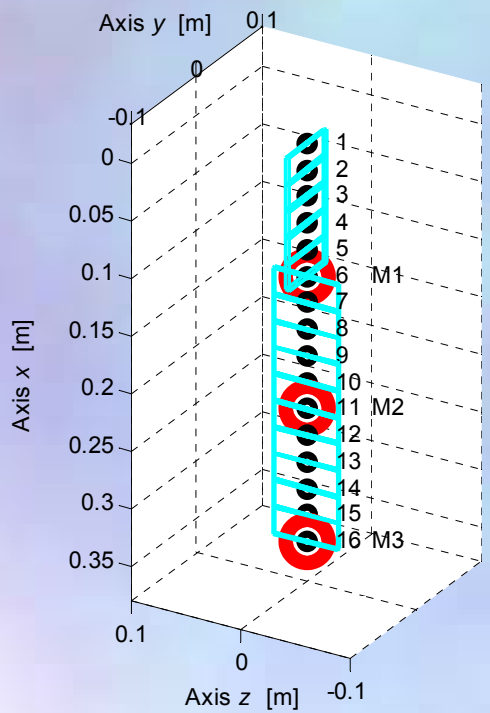
Aim: **Design of an experimental test rig that exhibits dynamics with coincident or close eigenvalues**

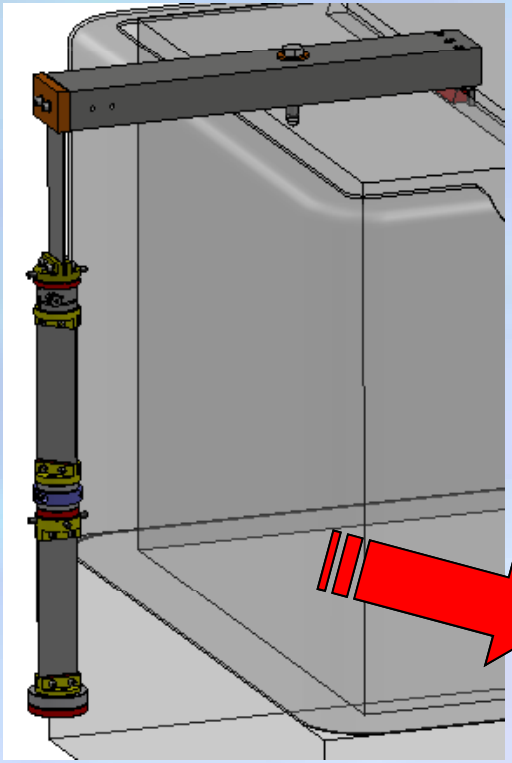
Sensitivity of dynamic properties

Next step ideas:

- Design of a not-symmetric and not-cyclic mechanical structure with coincident eigenvalues
- Experimental measures of crossing and veering phenomena taking into account uncertainty and variability
- Development of strategies for energy path between close or coincident eigenvalues

Thanks for your attention …





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