



# TURBO EXPO

Turbomachinery Technical Conference & Exposition

*Presented by the ASME International Gas Turbine Institute*

CONFERENCE

June 26 - 30, 2017

EXHIBITION

June 27 - 29, 2017

Charlotte Convention Center, Charlotte, NC USA

## ONE EXCITER PER SECTOR TEST BENCH FOR BLADED WHEELS HARMONIC RESPONSE ANALYSIS



**L. Bertini, P. Neri, C. Santus, A. Guglielmo**

Paolo Neri\*, PhD

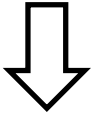
\*University of Pisa – Department of Civil and Industrial engineering  
Largo Lucio Lazzarino 1, 56126 Pisa. e-mail: [paolo.neri@dici.unipi.it](mailto:paolo.neri@dici.unipi.it)

# Introduction

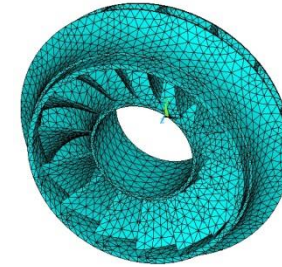
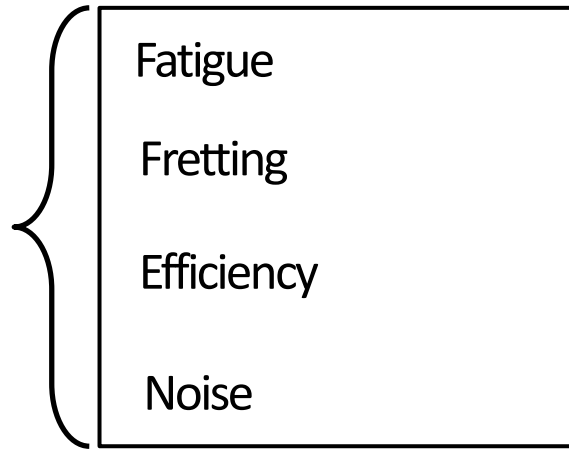


BLADED WHEELS:

Cyclic load



VIBRATIONS



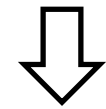
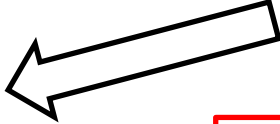
Analytical/numerical  
(FEM)

Experimental

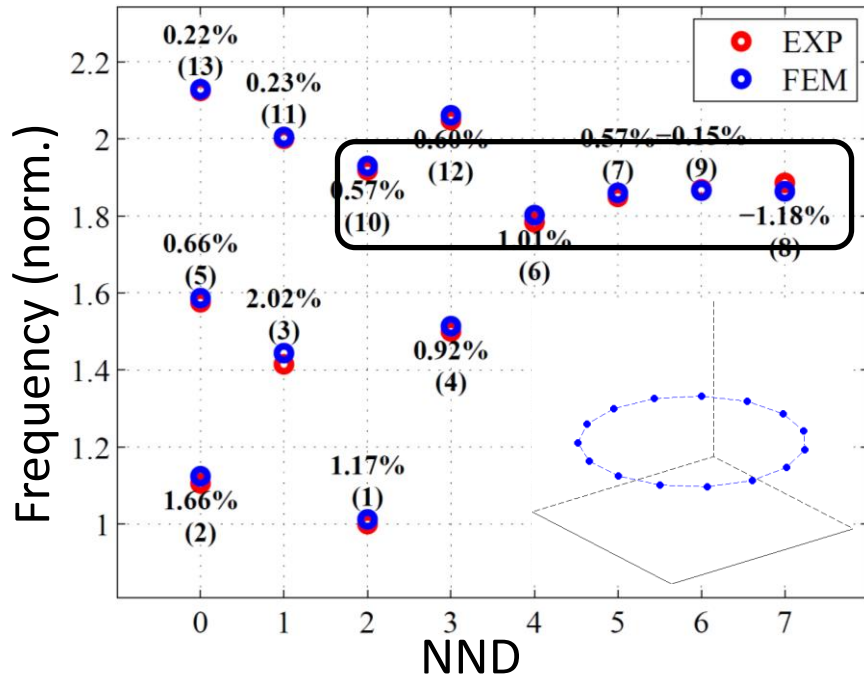


Harmonic Response  
Analysis (HRA)

Experimental Modal  
Analysis (EMA)



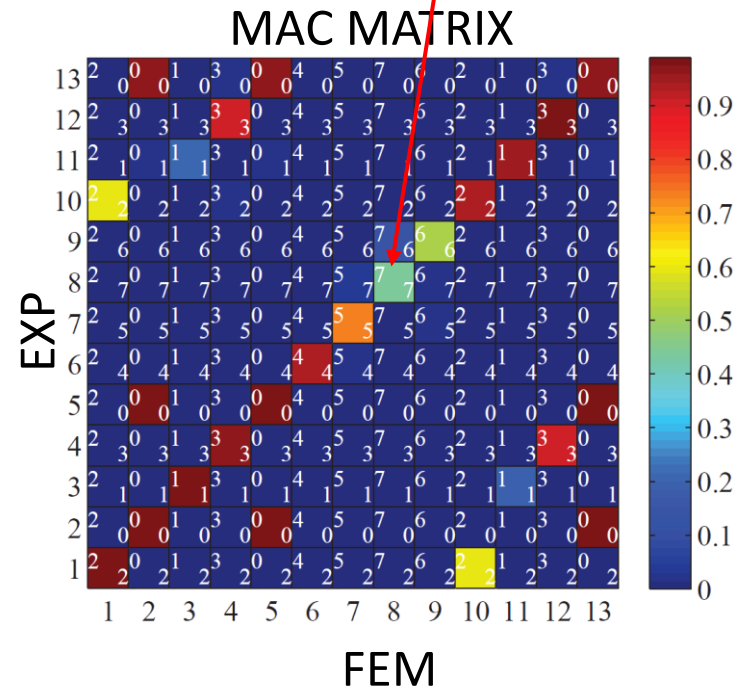
# Introduction



High density of modes



Complex reconstruction of high NND modes



- 1) Specific load distribution
- 2) Simulation of operational condition
- 3) SAFE diagram validation

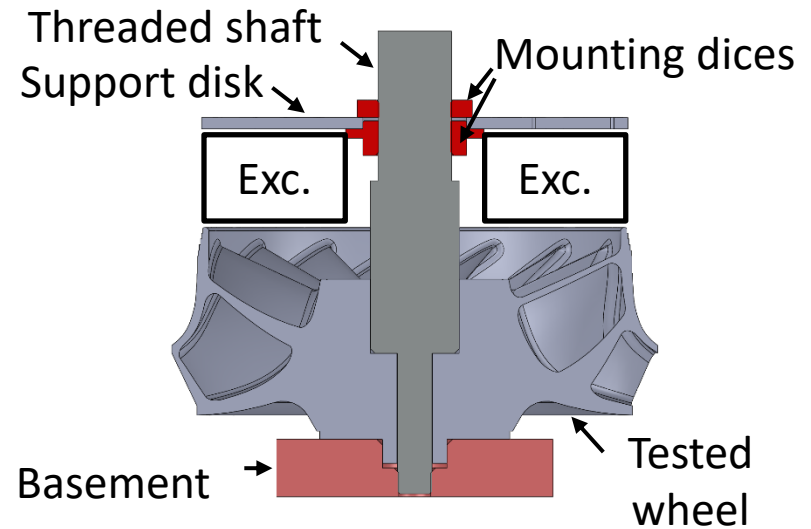


HRA with one exciter per blade

# Test bench overview



| Quantity        | Value | Unit |
|-----------------|-------|------|
| Freq. range     | 1-10  | kHz  |
| Peak force      | 0.1   | N    |
| Max exc. Number | 20    | --   |



## Excitation device

Non-contact: electromagnets

No influence on structure response

Low precision force measurement

Low peak forces

Ferromagnetic materials

Poor harmonic content control

Contact: electrodynamic shaker

Direct force measurement

High peak force

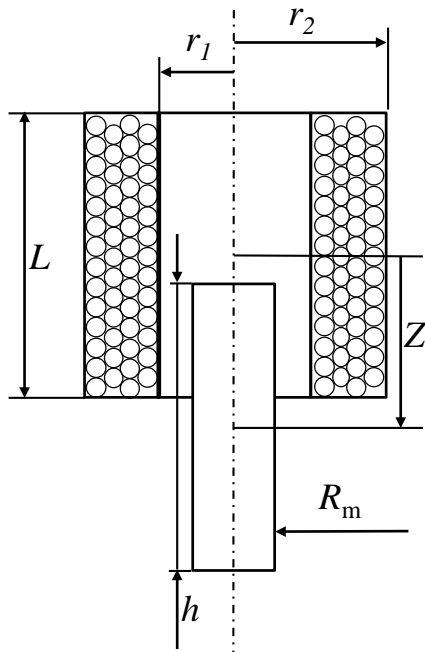
Any material

High precision load control

Possible influence on structure response

# Excitation device

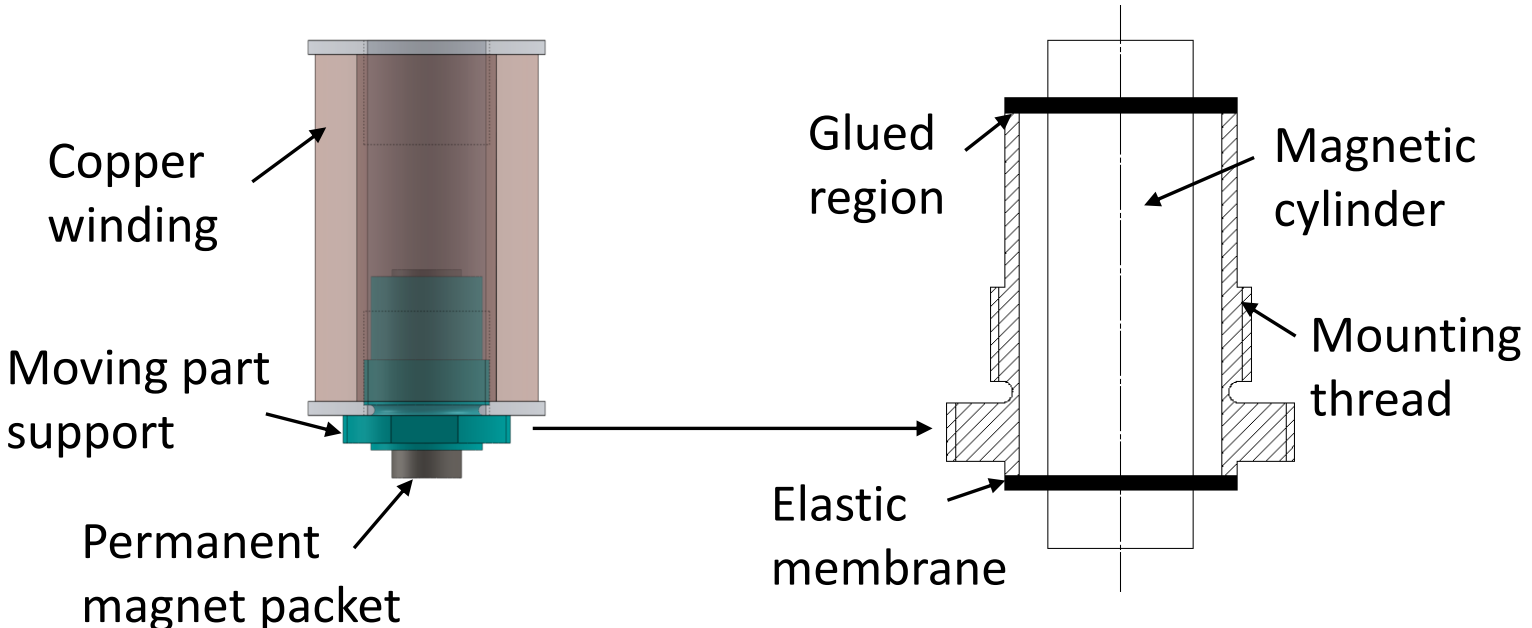
| Quantity    | Value | Unit |
|-------------|-------|------|
| Freq. range | 1-10  | kHz  |
| Peak force  | 0.1   | N    |
| Max Radius  | 17    | mm   |



Biot-Savart  
Shell-model  
→  
Optimization

| Quantity   | Value | Unit |
|------------|-------|------|
| $r_1$      | 10    | mm   |
| $r_2$      | 15    | mm   |
| L          | 50    | mm   |
| Wire diam. | 1.2   | mm   |
| $N_s$      | 150   | --   |
| h          | 30    | mm   |
| $R_m$      | 5     | mm   |

# Moving part support

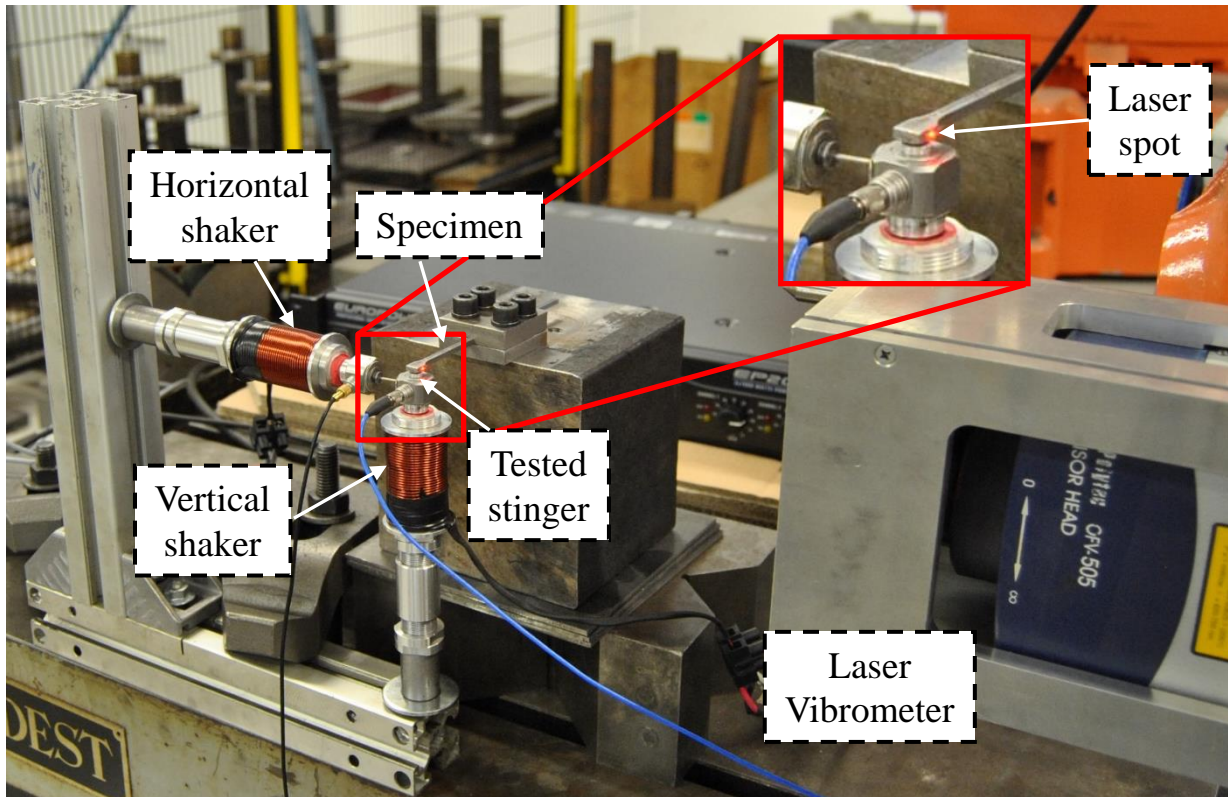


# Stingers comparison



Contact: electrodynamic shaker

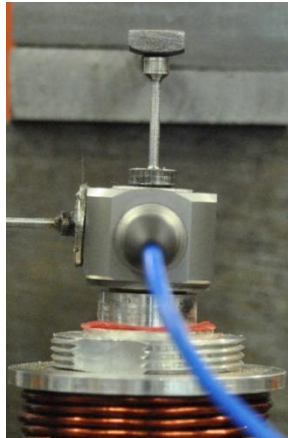
Possible influence on structure response



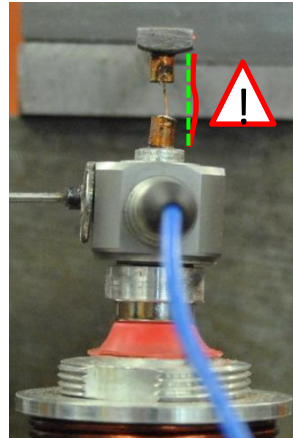
# Stingers comparison



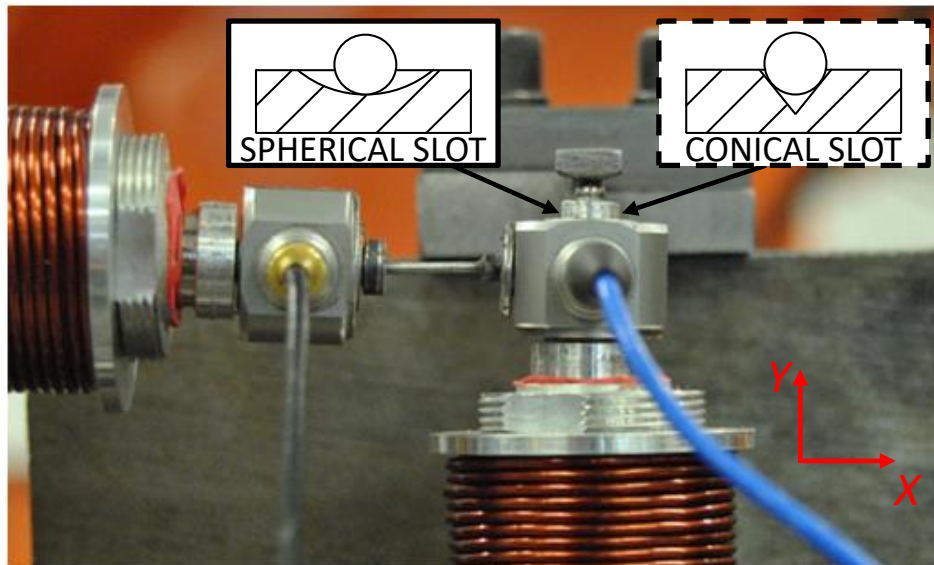
Glue  
No preload



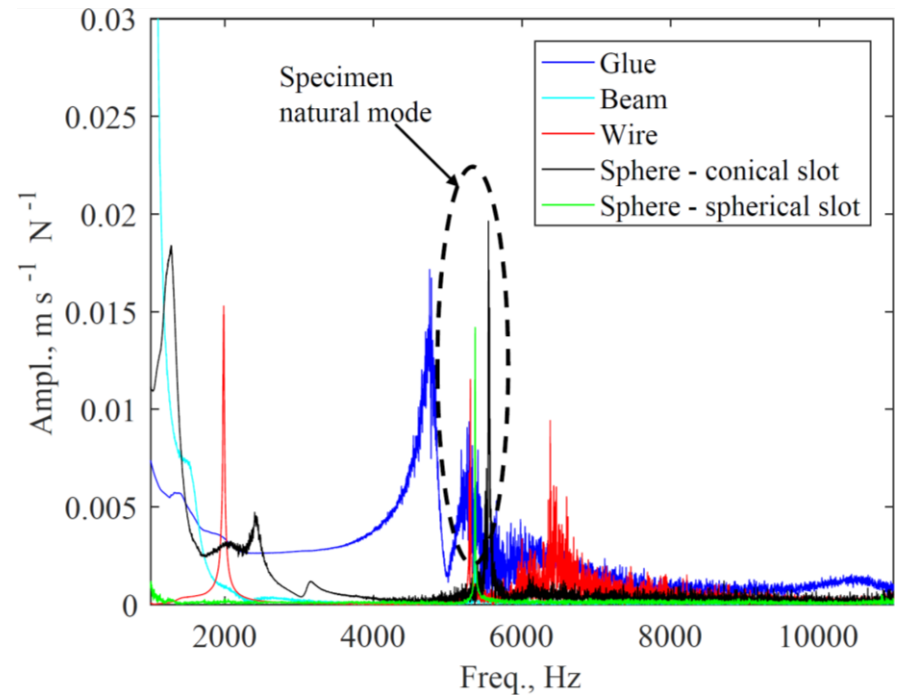
Beam stinger  
No preload



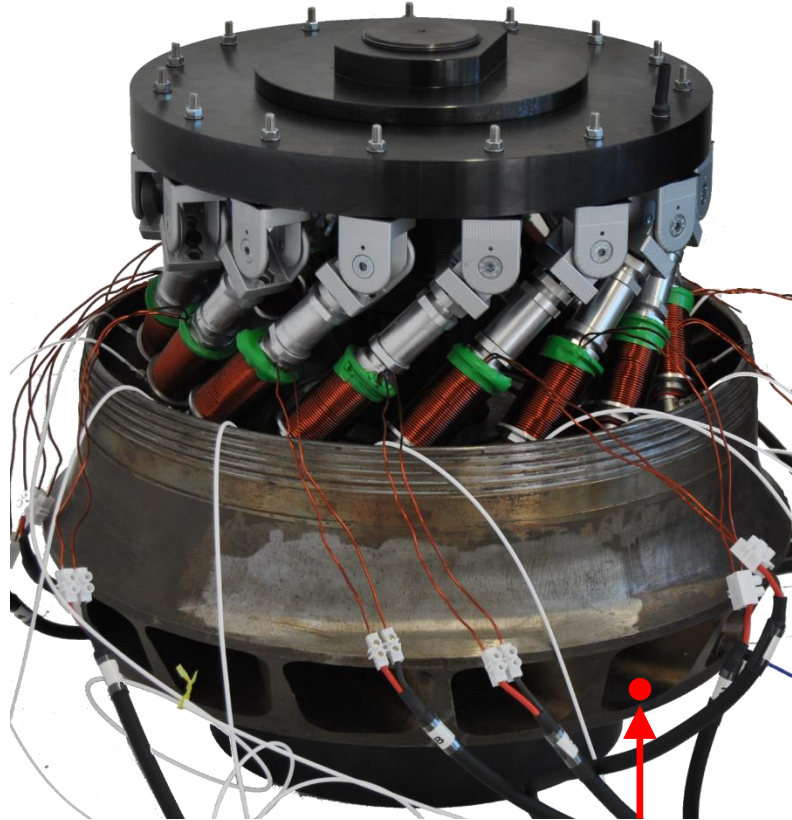
Wire stinger  
Tensile preload



FRF along horizontal direction (X)



# Final test bench



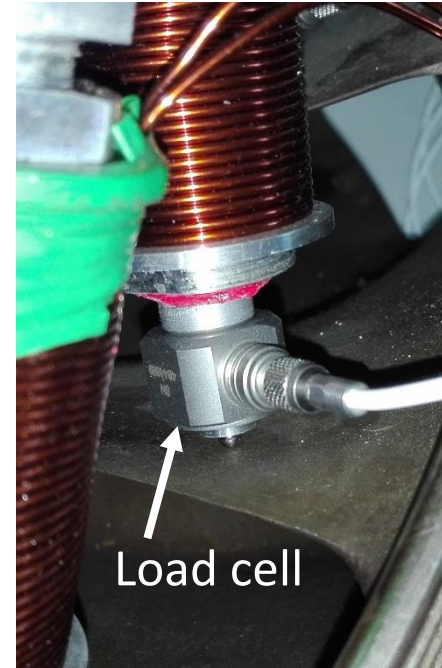
Response

15 shakers

Ball stinger

Compression preload

Response measurement: accelerometer

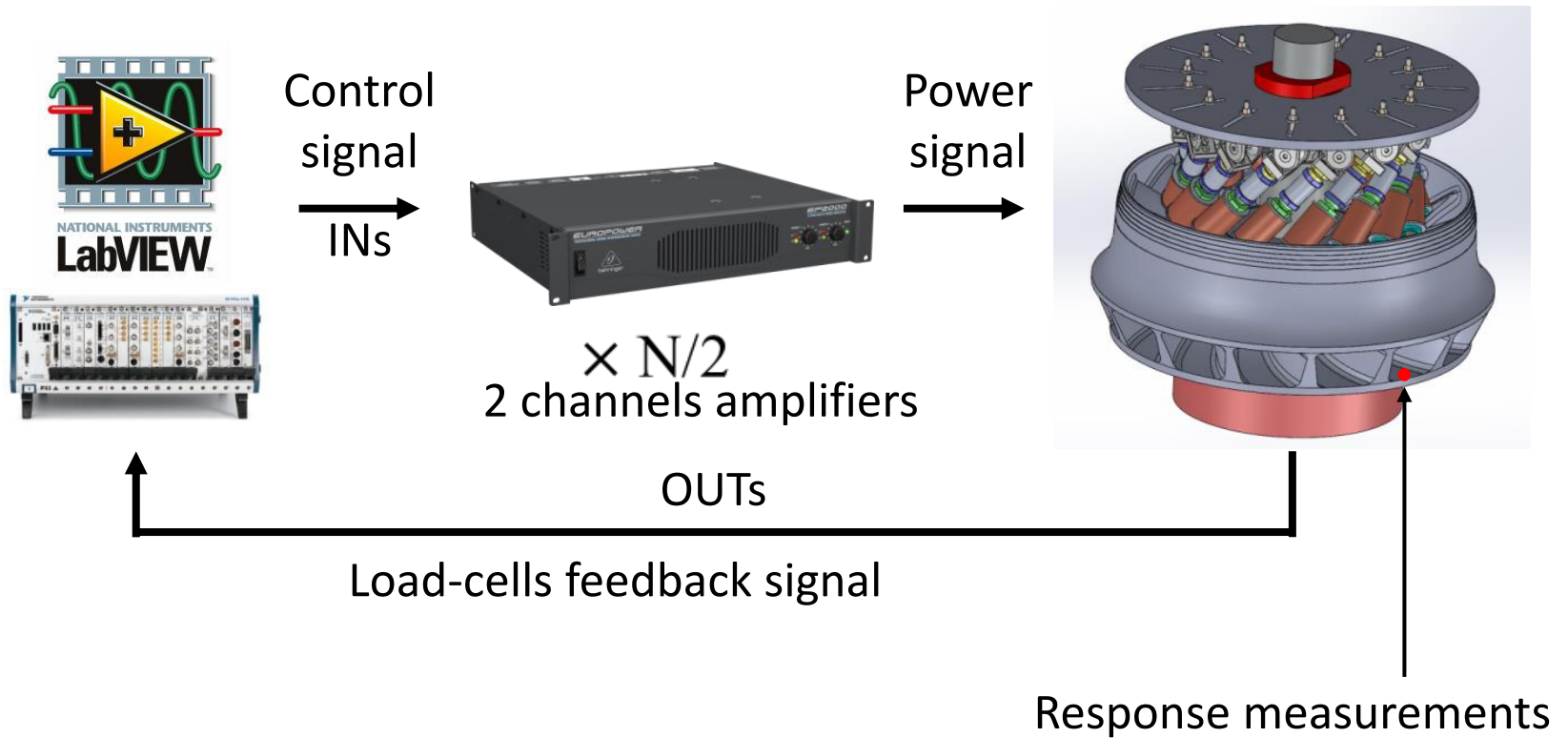


Load cell



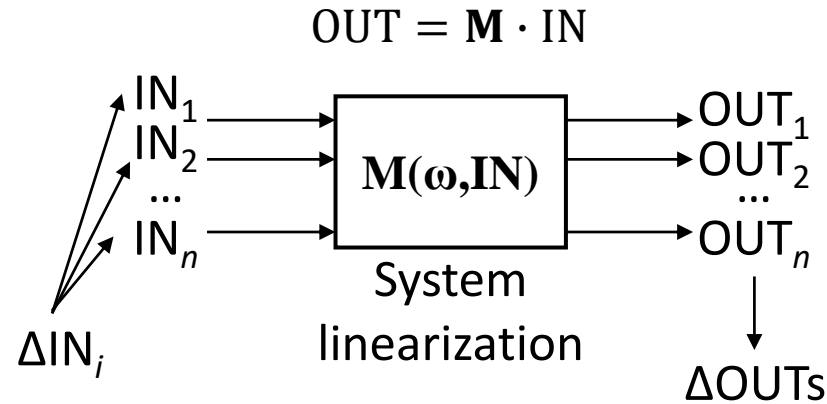
Ball stinger

# Control loop



INs and OUTs result coupled through the vibrating structure

# Control matrix

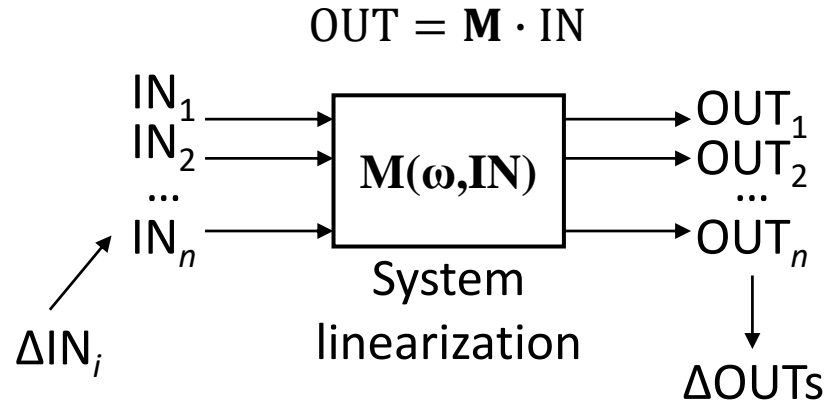


$$\begin{bmatrix} OUT_{1,1} \\ OUT_{2,1} \\ \vdots \\ OUT_{n,1} \end{bmatrix} = \begin{bmatrix} OUT_{1,1} & 0 & \cdots & 0 \\ OUT_{2,1} & 0 & \cdots & 0 \\ \vdots & \vdots & \ddots & \vdots \\ OUT_{n,1} & 0 & \cdots & 0 \end{bmatrix} \cdot \begin{bmatrix} 1 \\ 0 \\ \vdots \\ 0 \end{bmatrix}$$

MEASURED FAR FROM THE  
ACTUAL WORKING POINT!

$$\begin{bmatrix} OUT_{1,2} \\ OUT_{2,2} \\ \vdots \\ OUT_{n,2} \end{bmatrix} = \begin{bmatrix} OUT_{1,1} & OUT_{1,2} & \cdots & 0 \\ OUT_{2,1} & OUT_{2,2} & \cdots & 0 \\ \vdots & \vdots & \ddots & \vdots \\ OUT_{n,1} & OUT_{n,2} & \cdots & 0 \end{bmatrix} \cdot \begin{bmatrix} 0 \\ 1 \\ \vdots \\ 0 \end{bmatrix}$$

# Control matrix



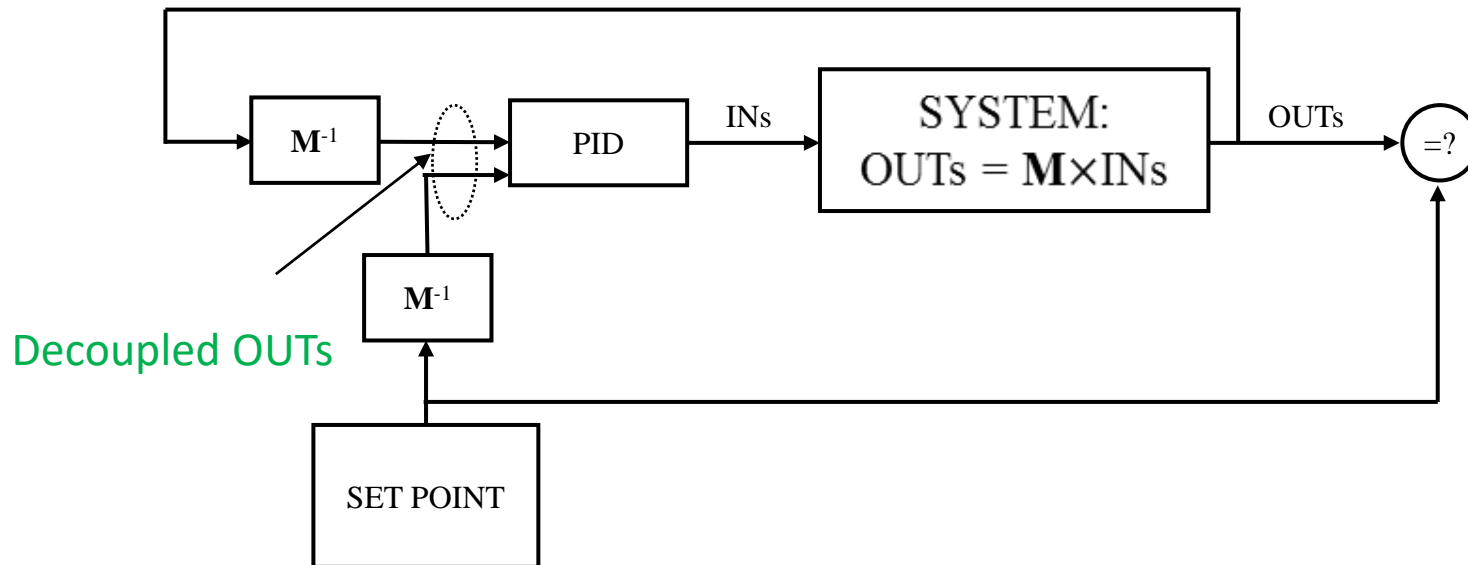
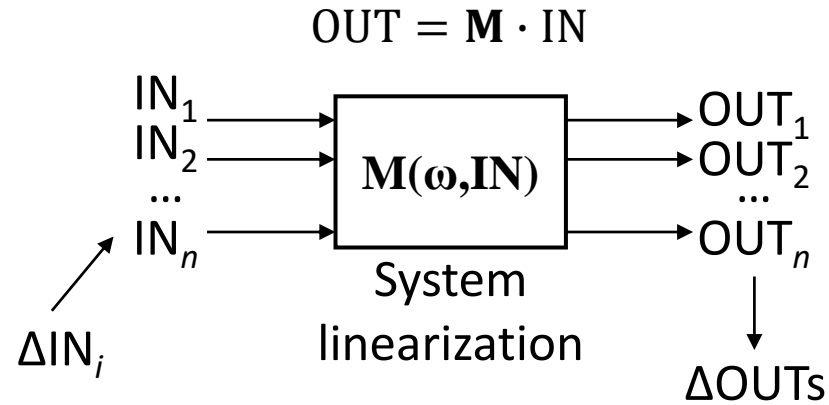
$$OUT = M \cdot IN \longrightarrow M \cdot (IN + \Delta IN) = M \cdot IN + M \cdot \Delta IN = OUT + \underbrace{M \cdot \Delta IN}_{\Delta OUT = M \cdot \Delta IN}$$

$$\begin{bmatrix} \Delta OUT_{1,1} \\ \Delta OUT_{2,1} \\ \vdots \\ \Delta OUT_{n,1} \end{bmatrix} = \frac{1}{\Delta IN} \begin{bmatrix} \Delta OUT_{1,1} & 0 & \cdots & 0 \\ \Delta OUT_{2,1} & 0 & \cdots & 0 \\ \vdots & \vdots & \ddots & \vdots \\ \Delta OUT_{n,1} & 0 & \cdots & 0 \end{bmatrix} \cdot \begin{bmatrix} \Delta IN \\ 0 \\ \vdots \\ 0 \end{bmatrix}$$

MEASURED CLOSE TO THE  
ACTUAL WORKING POINT!

$$\begin{bmatrix} \Delta OUT_{1,2} \\ \Delta OUT_{2,2} \\ \vdots \\ \Delta OUT_{n,2} \end{bmatrix} = \frac{1}{\Delta IN} \begin{bmatrix} \Delta OUT_{1,1} & \Delta OUT_{1,2} & \cdots & 0 \\ \Delta OUT_{2,1} & \Delta OUT_{2,2} & \cdots & 0 \\ \vdots & \vdots & \ddots & \vdots \\ \Delta OUT_{n,1} & \Delta OUT_{n,2} & \cdots & 0 \end{bmatrix} \cdot \begin{bmatrix} 0 \\ \Delta IN \\ \vdots \\ 0 \end{bmatrix}$$

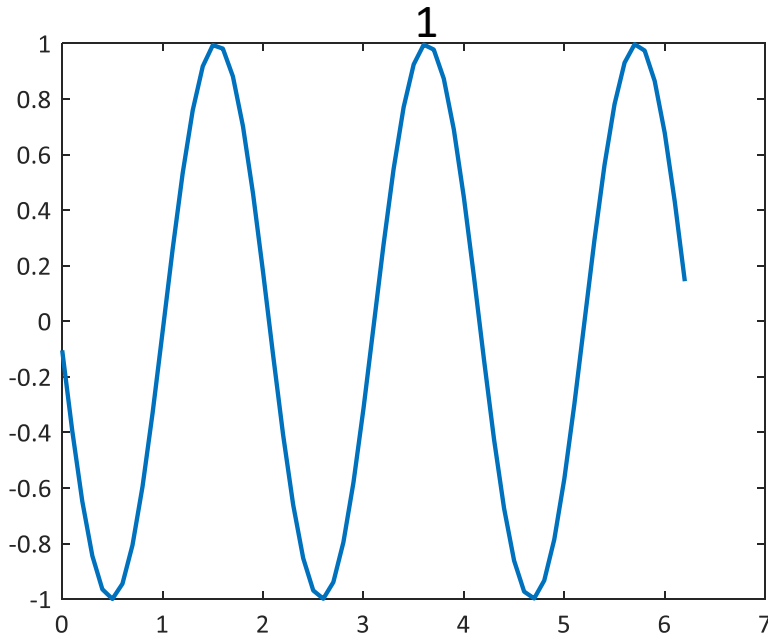
# Control matrix



# Operation example

$$F_i = A_i \cos(\omega t + \varphi_i)$$

Set point, rotating load:  $A_i = \bar{A}$ ,  $\varphi_i = i \frac{360\text{NND}}{N_B}$  ( $i = 1 \dots N_B$ )

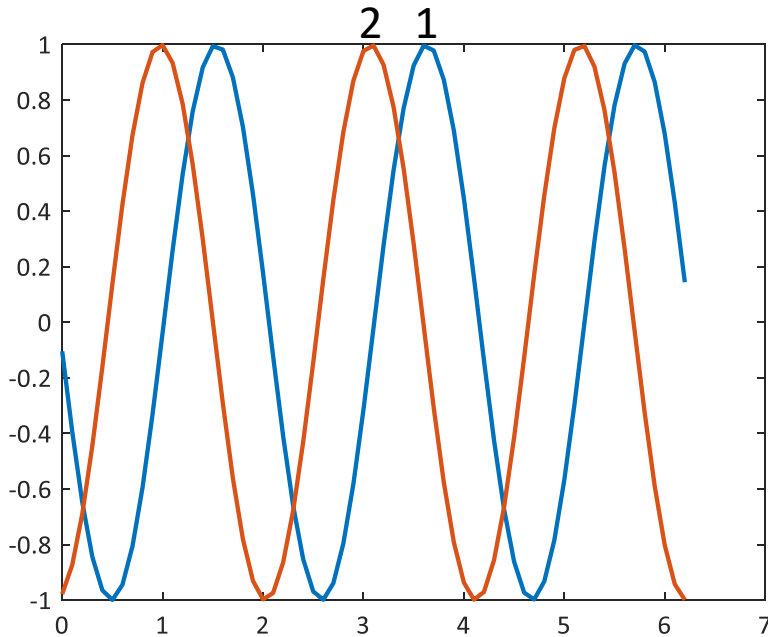


# Operation example



$$F_i = A_i \cos(\omega t + \varphi_i)$$

Set point, rotating load:  $A_i = \bar{A}$ ,  $\varphi_i = i \frac{360\text{NND}}{N_B}$  ( $i = 1 \dots N_B$ )

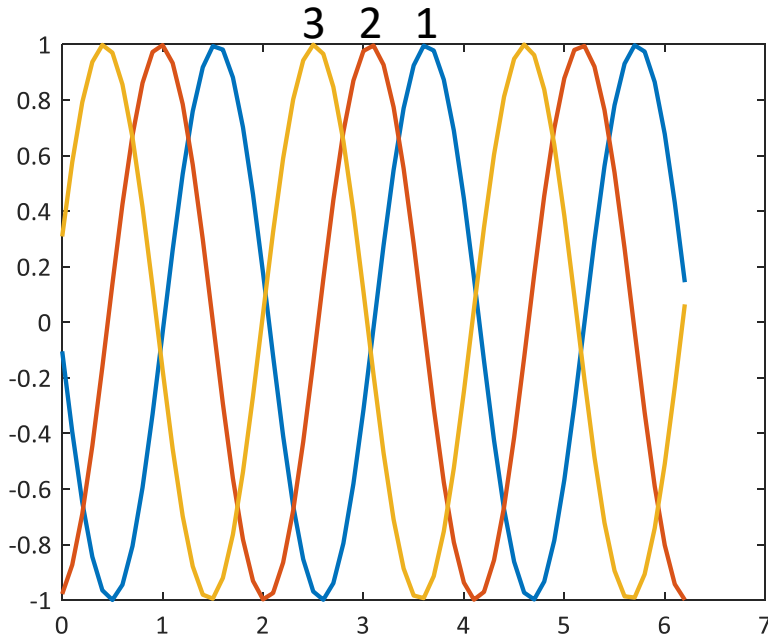


# Operation example



$$F_i = A_i \cos(\omega t + \varphi_i)$$

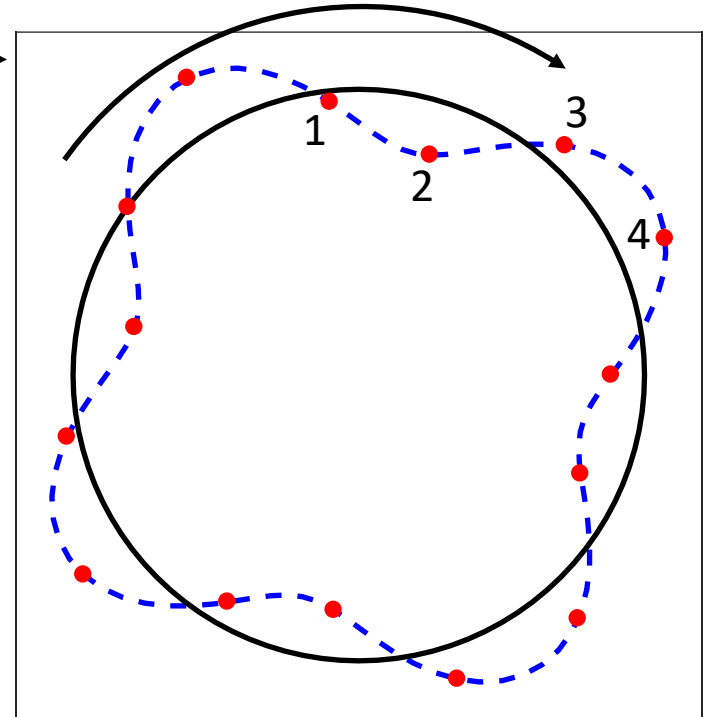
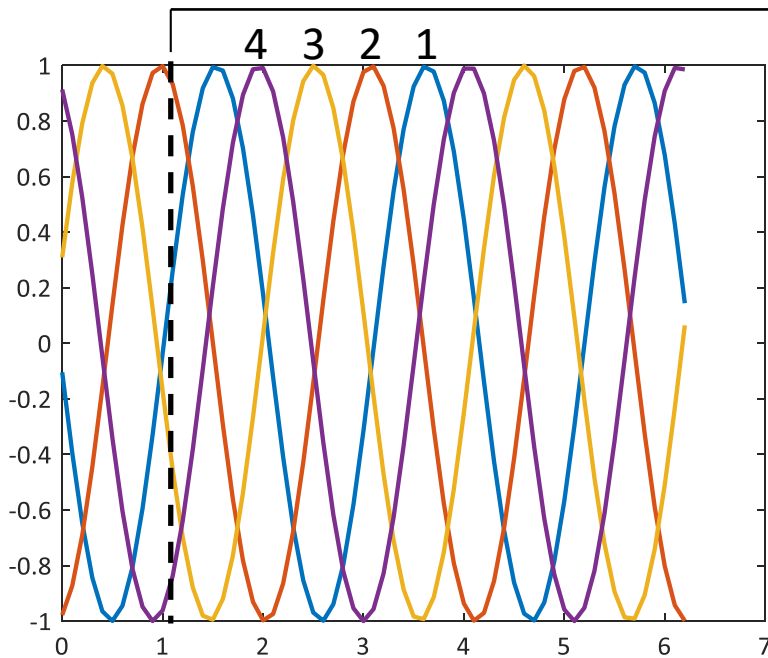
Set point, rotating load:  $A_i = \bar{A}$ ,  $\varphi_i = i \frac{360\text{NND}}{N_B}$  ( $i = 1 \dots N_B$ )



# Operation example

$$F_i = A_i \cos(\omega t + \varphi_i)$$

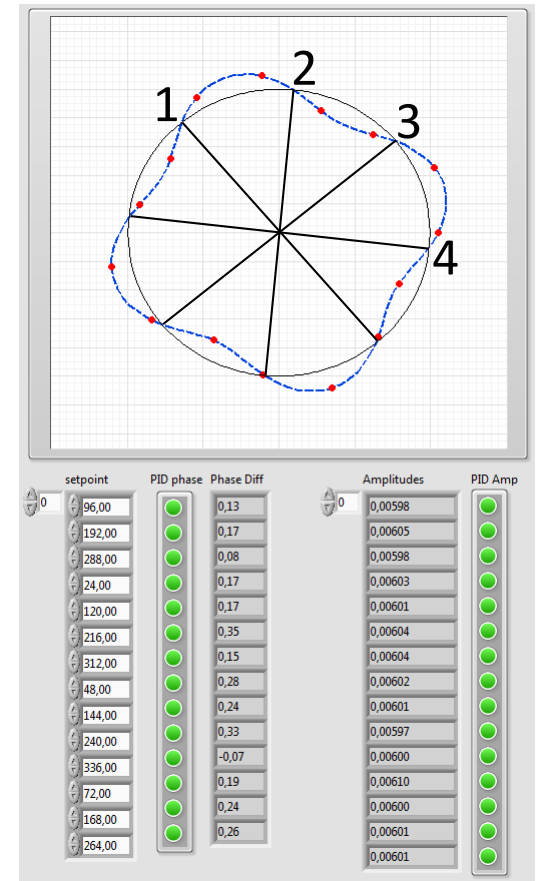
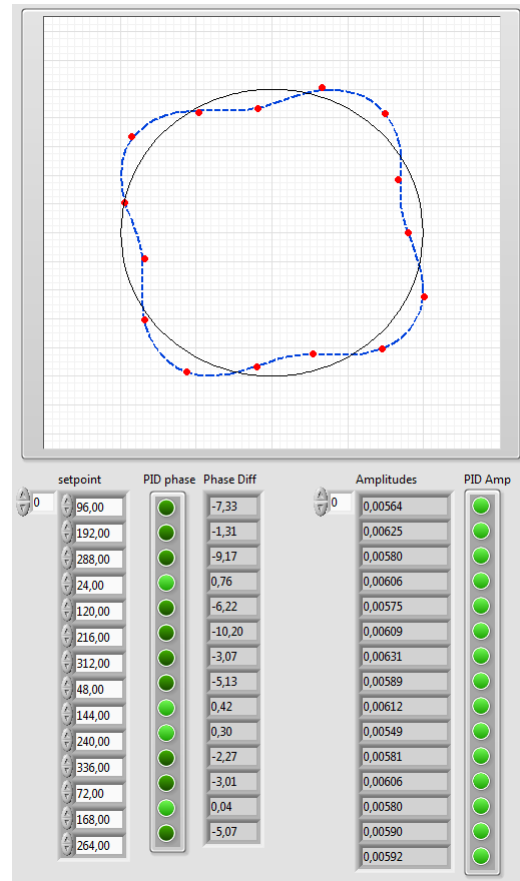
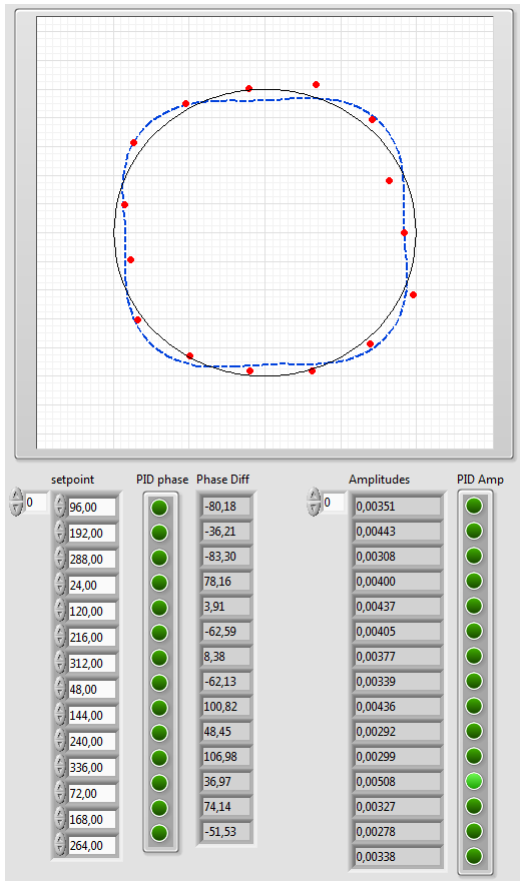
Set point, rotating load:  $A_i = \bar{A}$ ,  $\varphi_i = i \frac{360\text{NND}}{N_B}$  ( $i = 1 \dots N_B$ )



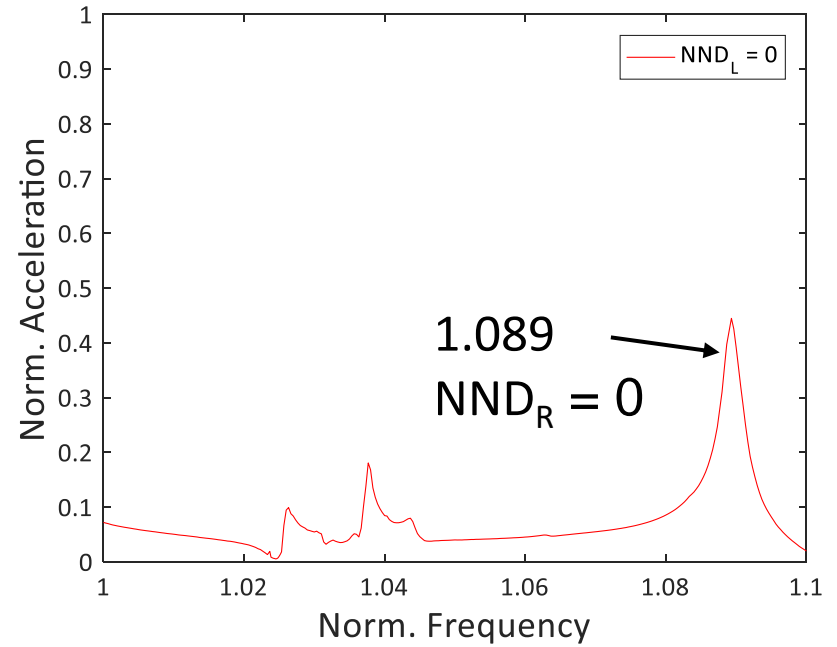
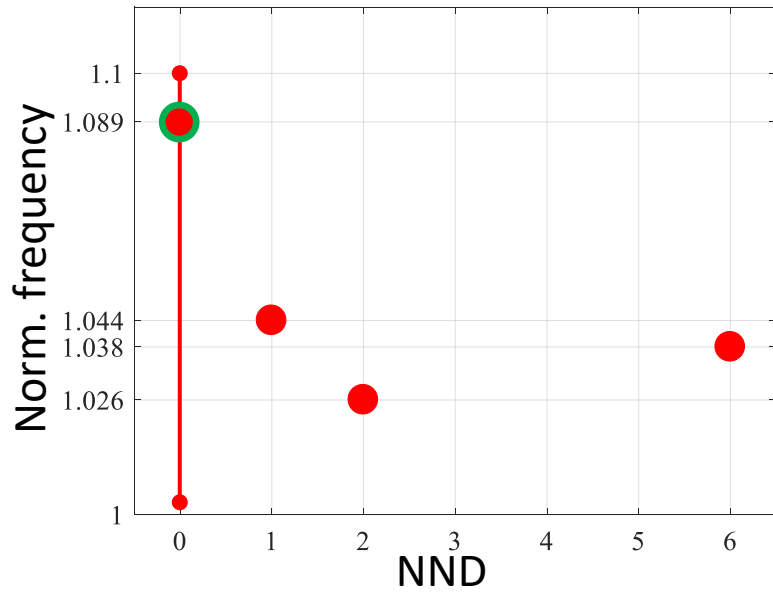
# Operation example

$$F_i = A_i \cos(\omega t + \varphi_i)$$

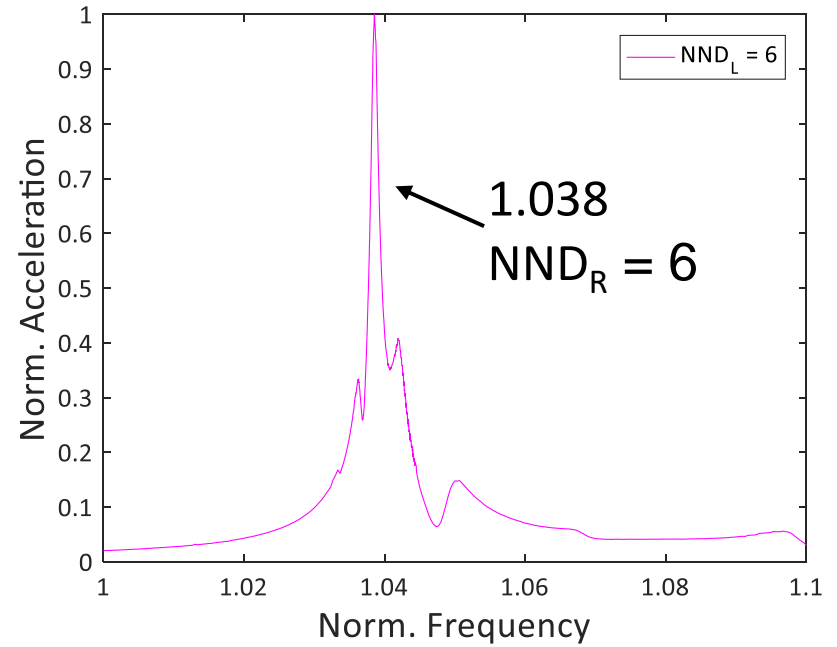
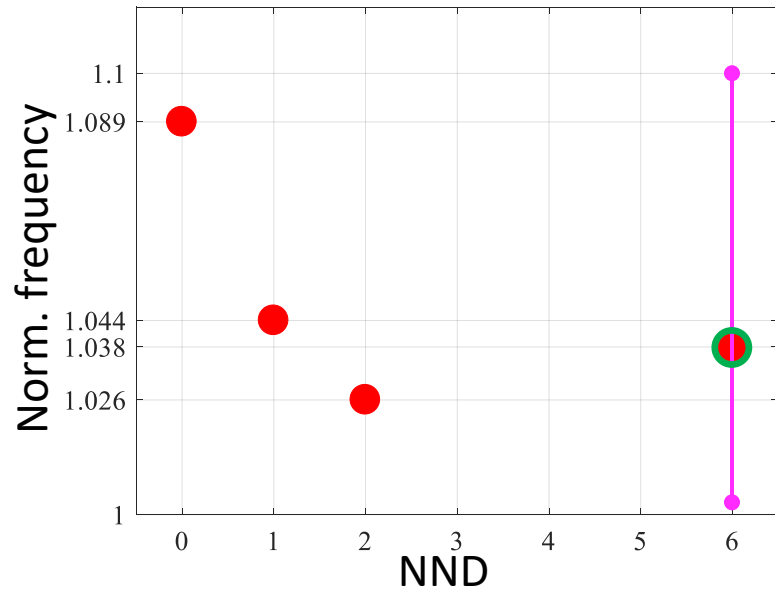
Set point, rotating load:  $A_i = \bar{A}$ ,  $\varphi_i = i \frac{360NND}{N_B}$  ( $i = 1 \dots N_B$ )



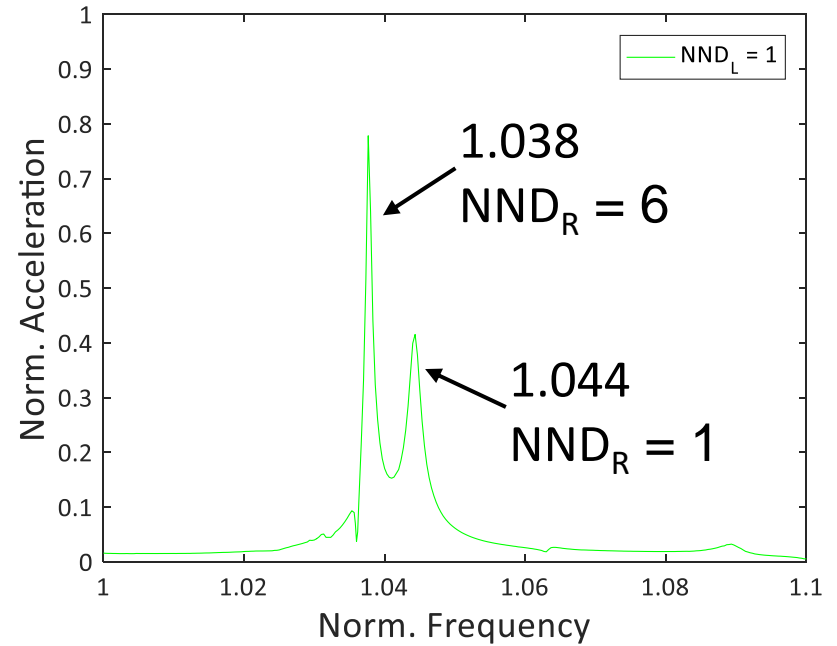
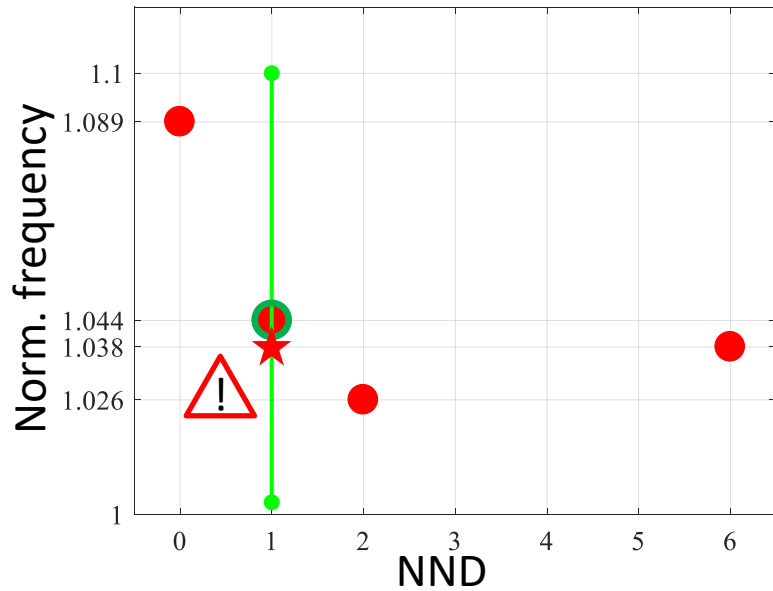
# Experimental results



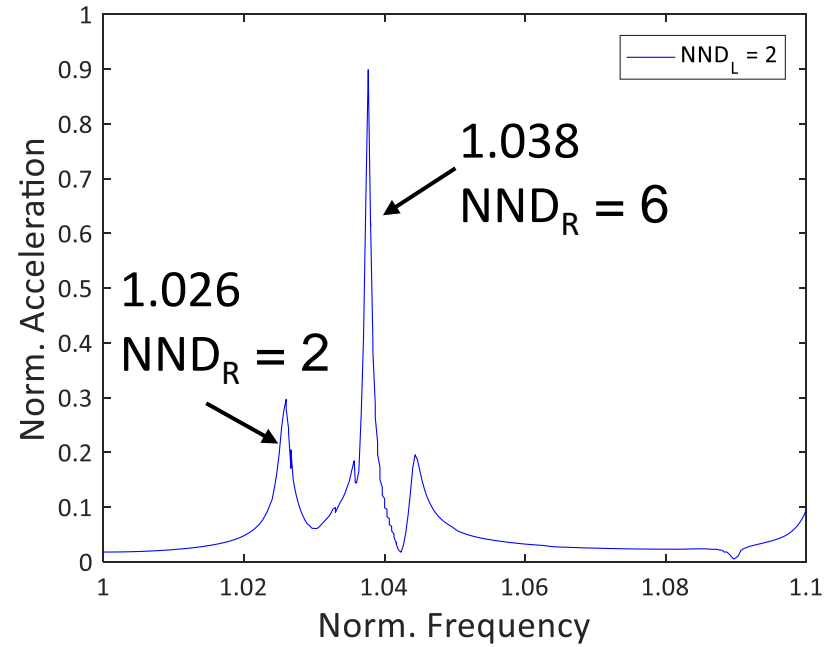
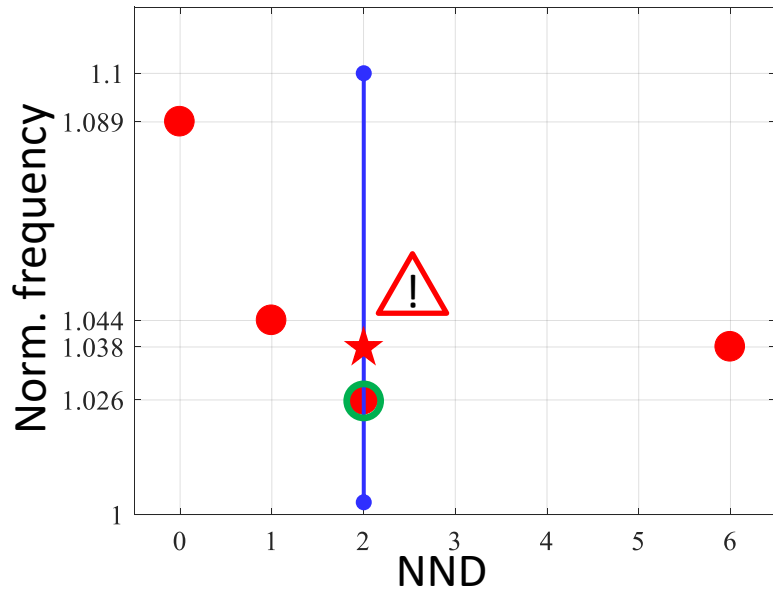
# Experimental results



# Experimental results



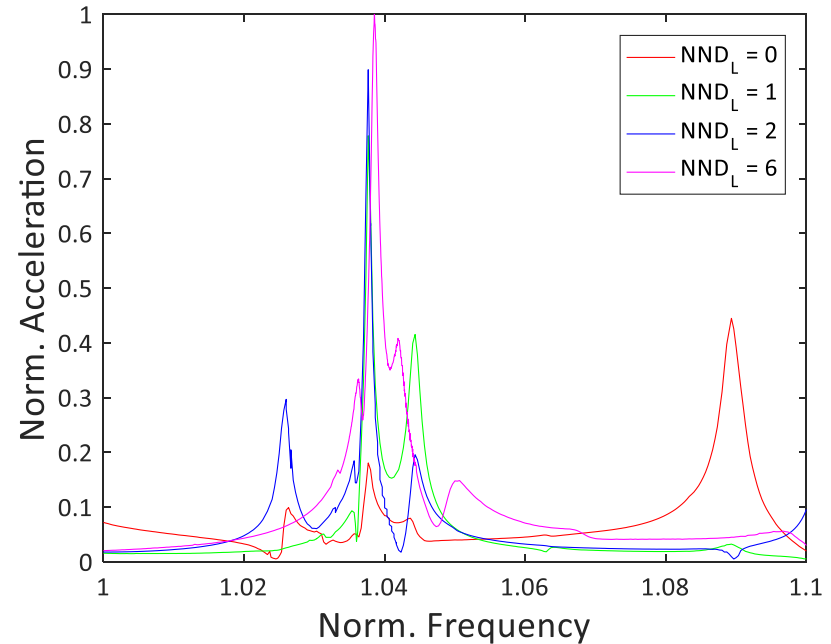
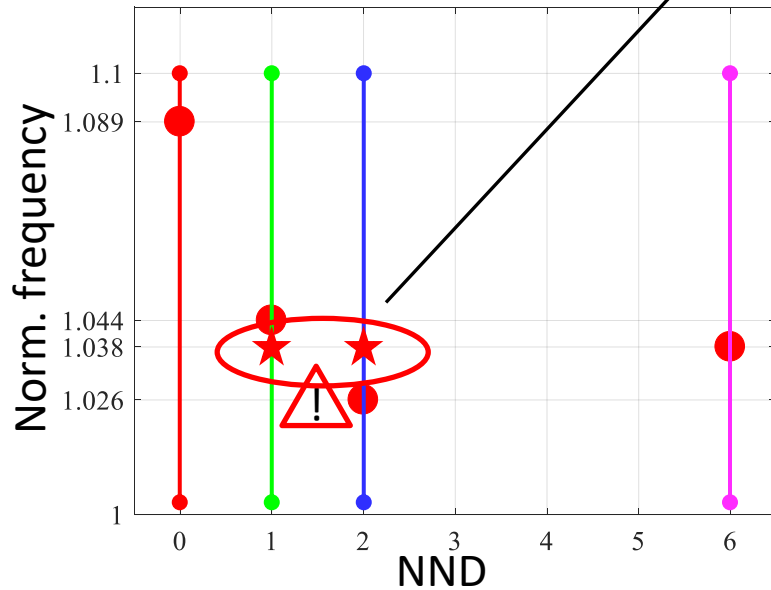
# Experimental results



# Experimental results



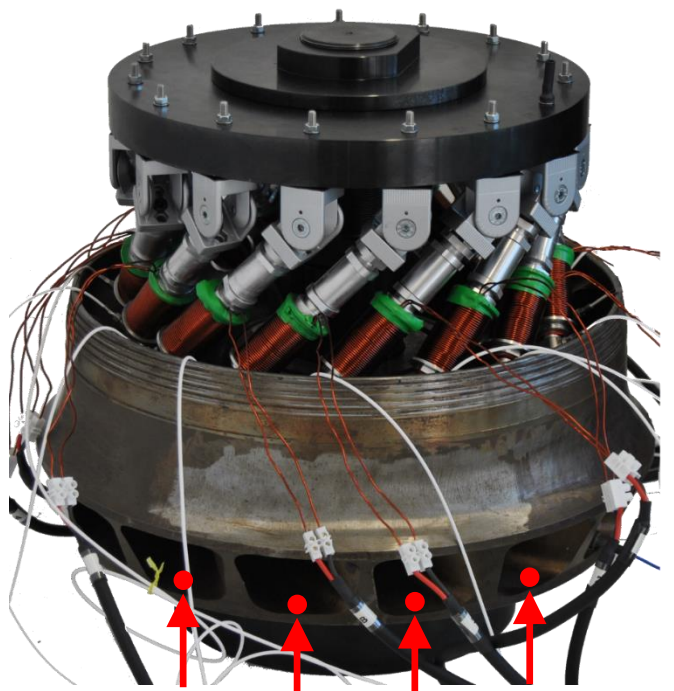
Deformed shape reconstruction: measurement  
of the response of all the sectors



Hypothesis:

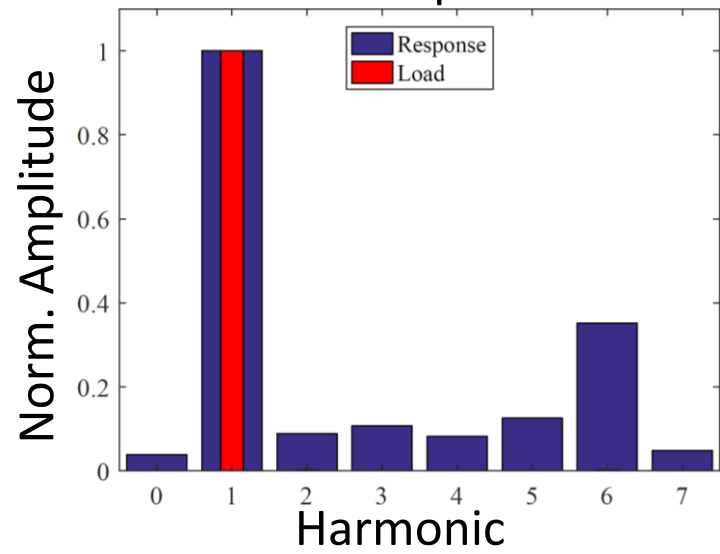
- Component mistuning
- Inaccurate force control
- Error in shaker positioning

# Results discussion

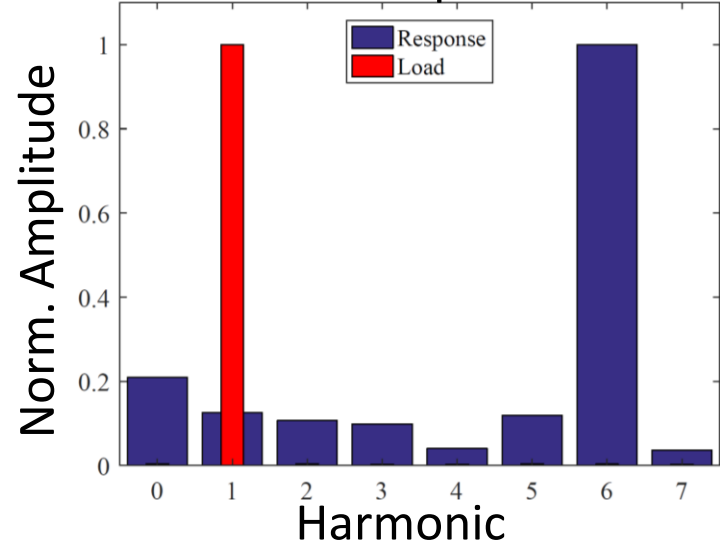


DFT  
→

Norm. freq. 1.044



Norm. freq. 1.038

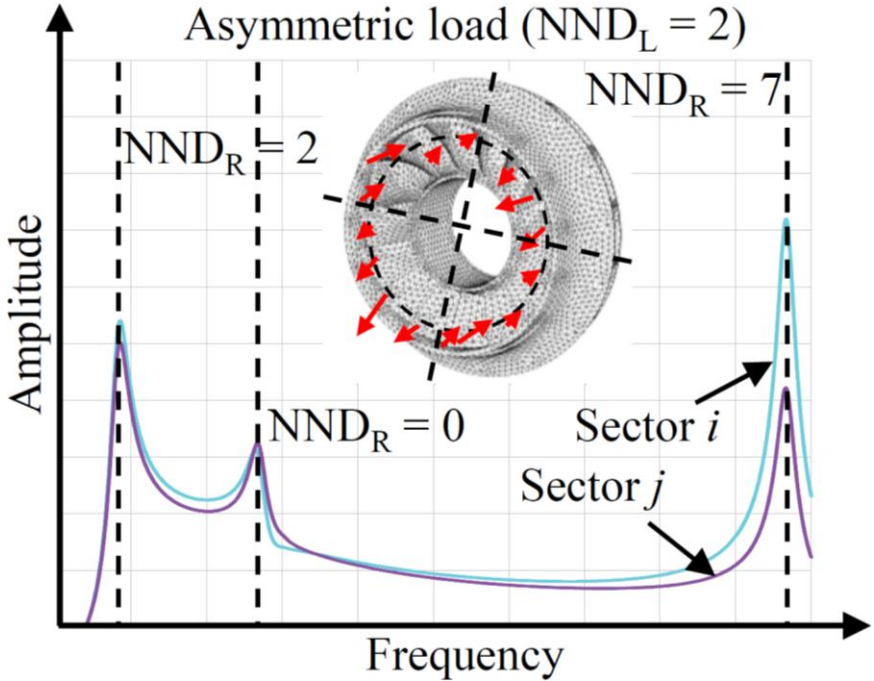
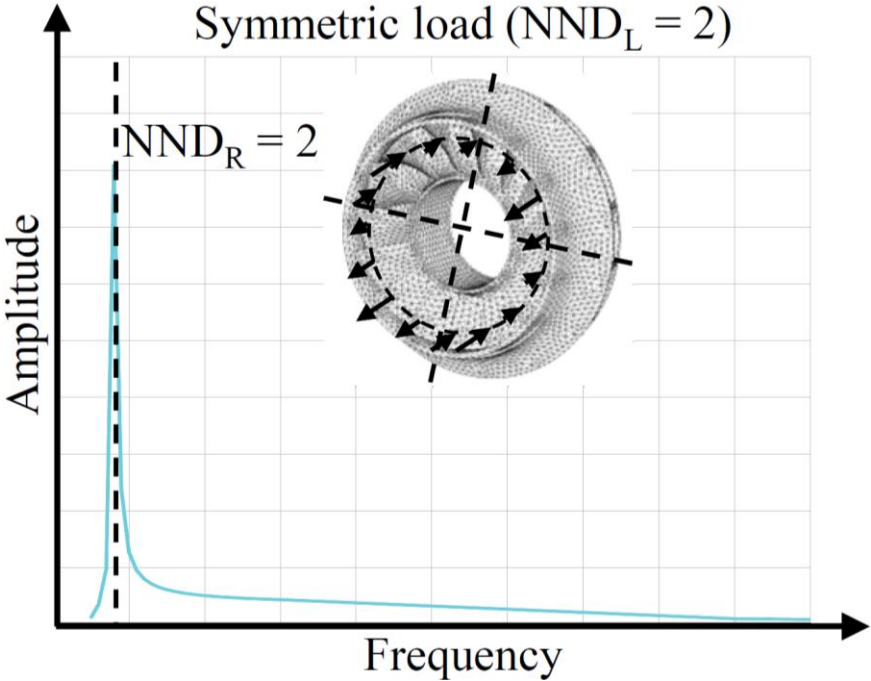


The phase of the response was referred to the a shaker signal to compare subsequent measurements

# Results discussion

Error in shaker positioning: FEM analysis

HRA, Damping ratio: 0.02 %



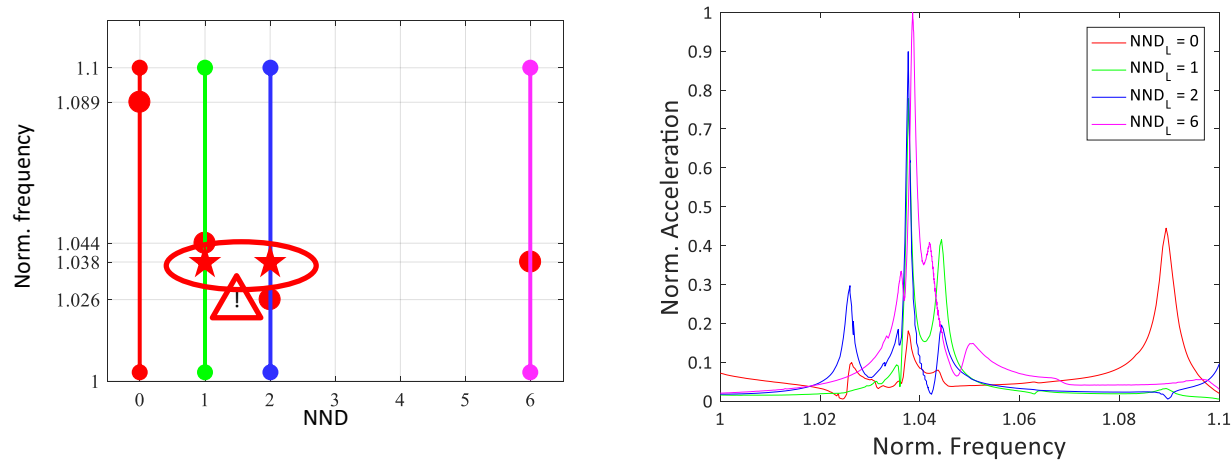
High sensitivity to shaker positioning!

# Conclusions

HRA test bench design: exciters, stinger solution and control software

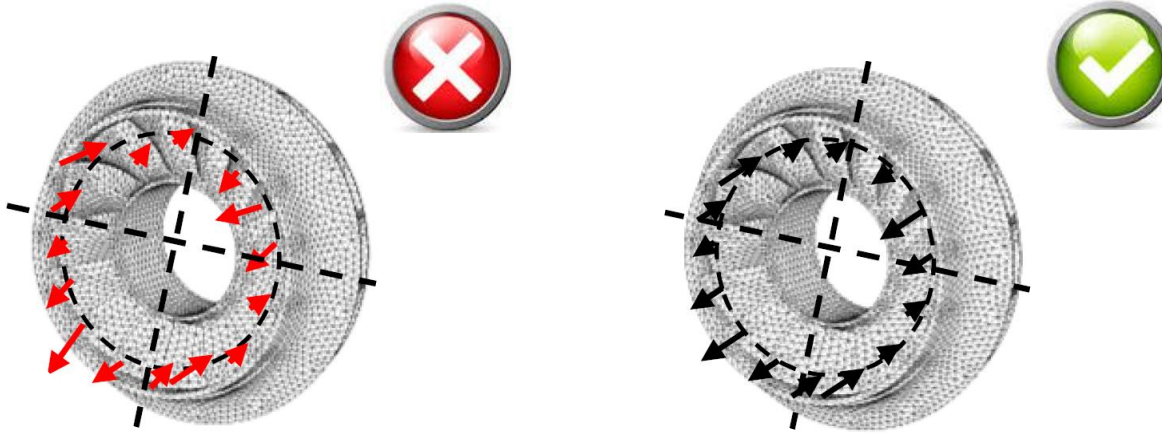


Preliminary results specification fulfillment, sensitivity to shaker positioning

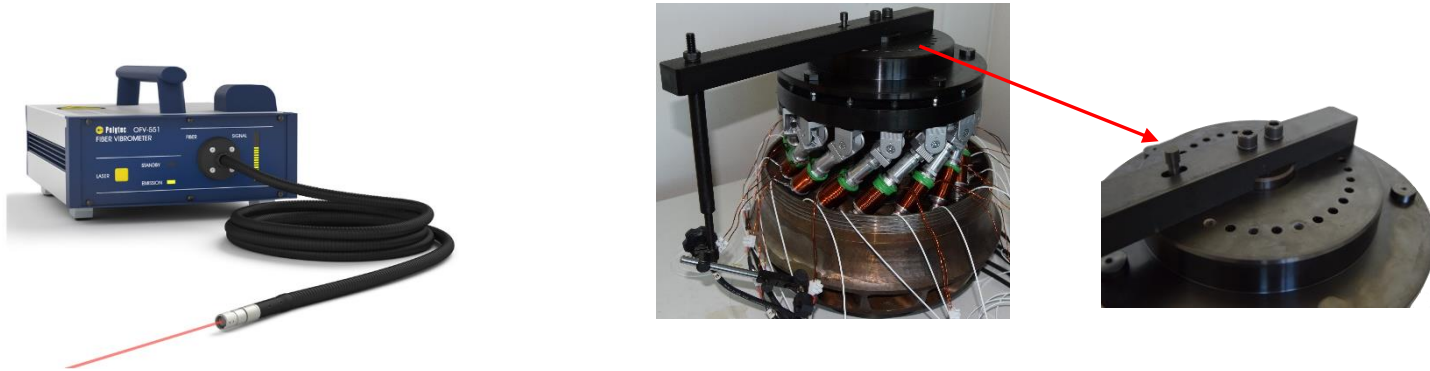


# Future developments

Improved shaker positioning to reduce spurious effects



Fiber optic laser to reduce the influence of accelerometer mass/position





# TURBO EXPO

Turbomachinery Technical Conference & Exposition

*Presented by the ASME International Gas Turbine Institute*

CONFERENCE

June 26 - 30, 2017

EXHIBITION

June 27 - 29, 2017

Charlotte Convention Center, Charlotte, NC USA

## THANK YOU



**L. Bertini, P. Neri, C. Santus, A. Guglielmo**

Paolo Neri\*, PhD

\*University of Pisa – Department of Civil and Industrial engineering  
Largo Lucio Lazzarino 1, 56126 Pisa. e-mail: [paolo.neri@dici.unipi.it](mailto:paolo.neri@dici.unipi.it)