

# **L'analisi vibratoria come strumento per l'ottimizzazione dinamica e la diagnostica sperimentale di sistemi meccanici**

**Emiliano Mucchi**

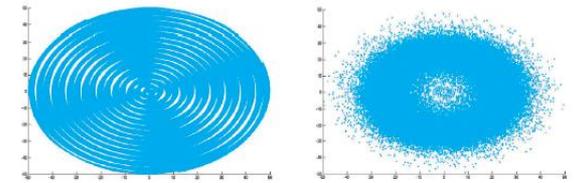
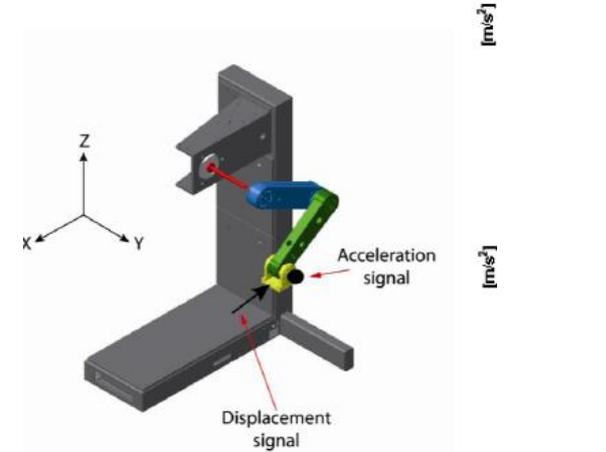
Gruppo di Vibrazioni e Meccanica Applicata alle Macchine

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**1. Ottimizzazione vibro-acustica di sistemi meccanici mediante modellazione ed analisi sperimentale**

**2. Controllo qualità e diagnostica di difetti mediante analisi vibratoria**

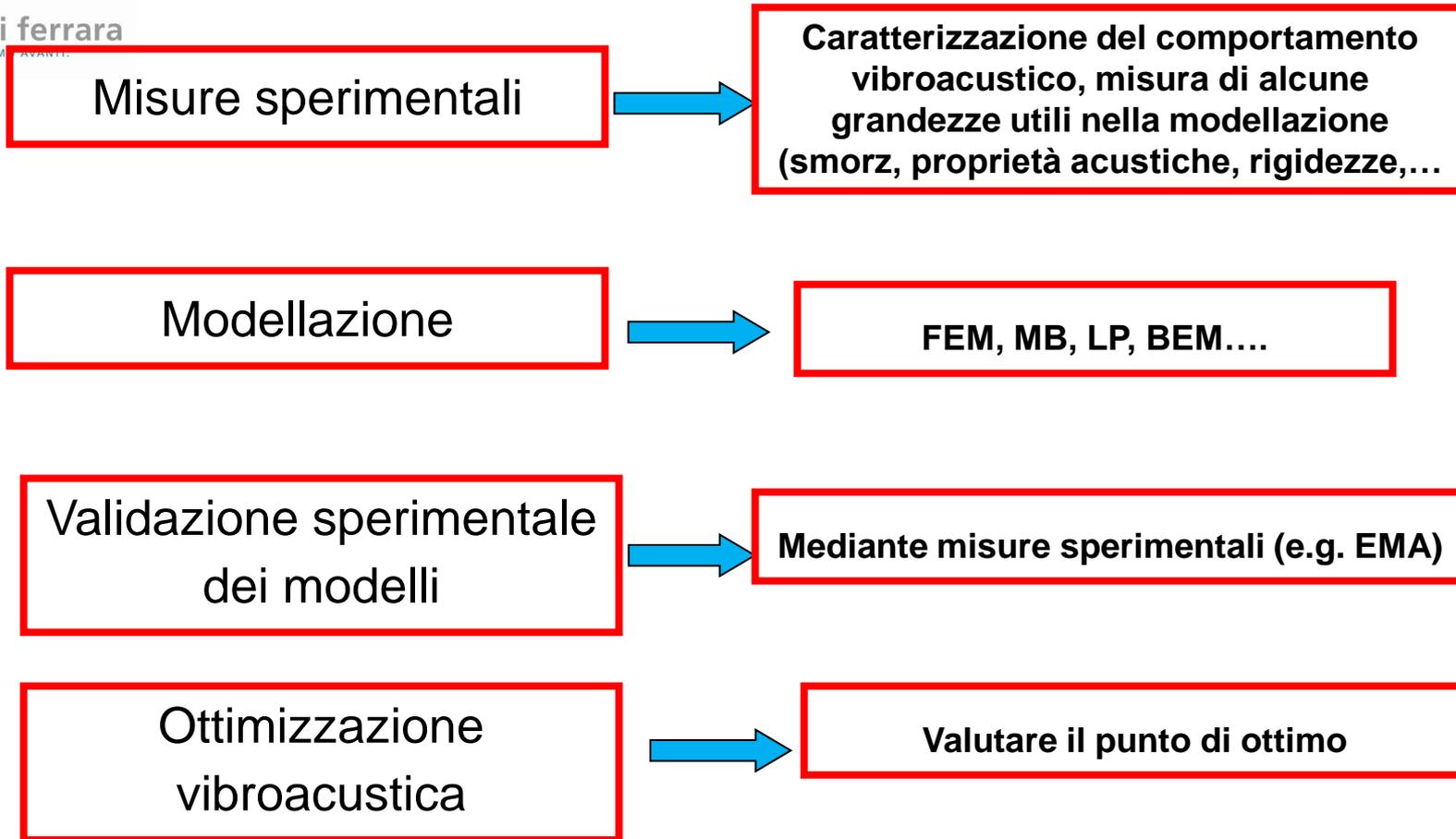
**3. Progettazione ed analisi di meccanismi/sistemi meccanici ( co-progettazione, analisi di movimento, cinematica)**



*Tecnica basata sulla correlazione di immagini, ottenute attraverso la simmetrizzazione del segnale accelerometrico, per la classificazione buono/scarto di motori a c.i. (attività con APicom).*



# 1. Ottimizzazione vibro-acustica: Metodo



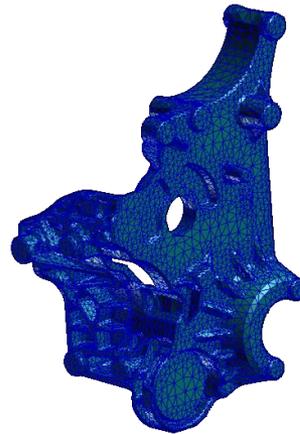
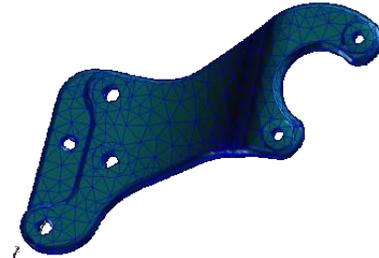
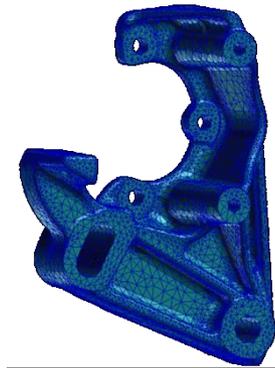
# Sviluppare un modello: perchè?

Identificare le cause di malfunzionamenti

Identificare le sorgenti di vibrazioni

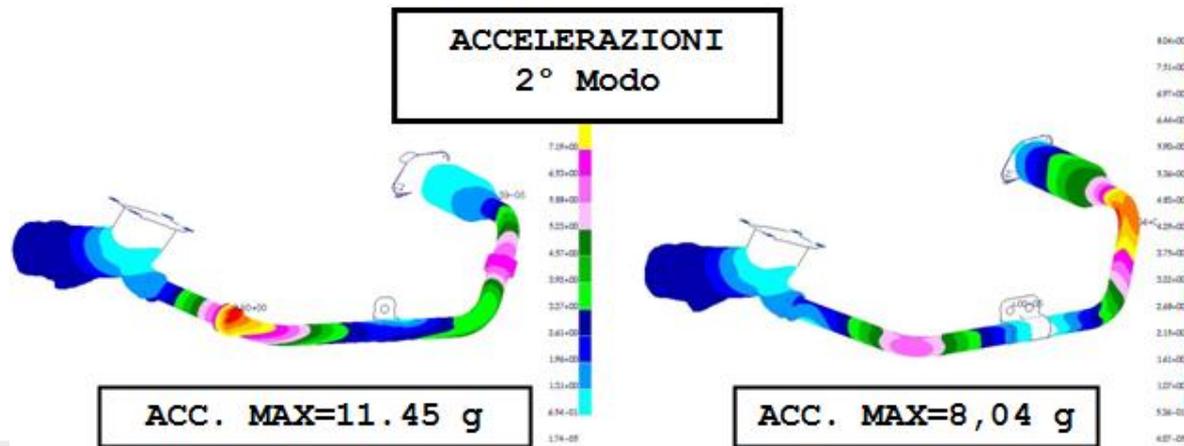
Prevedere gli effetti di modifiche progettuali

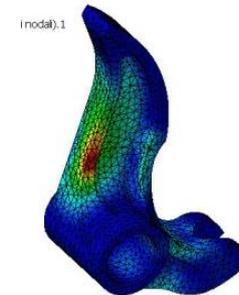
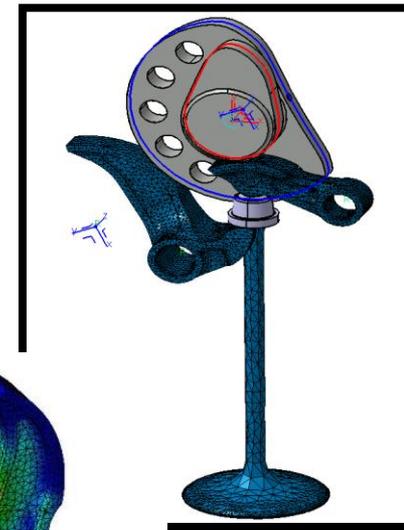
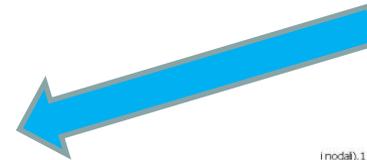
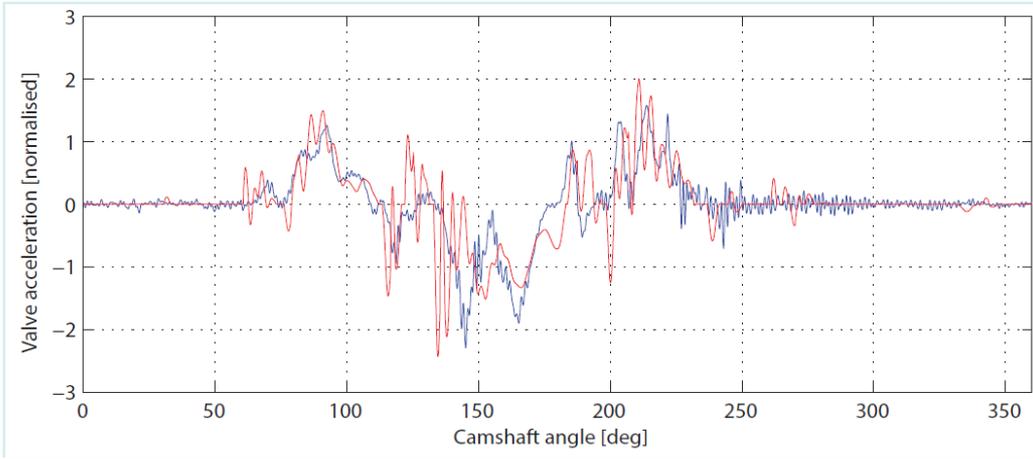
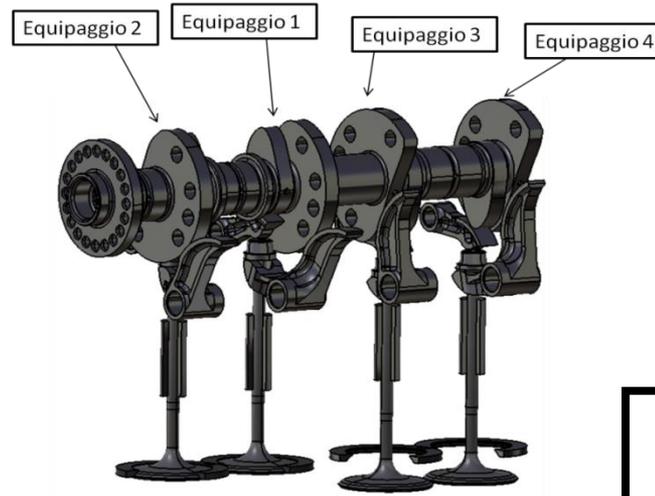
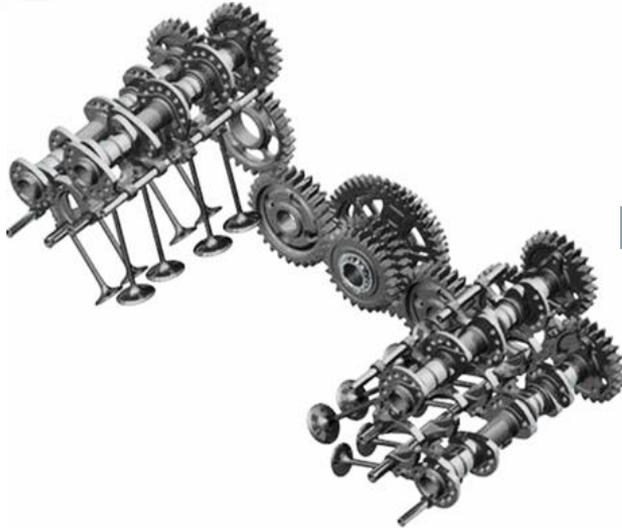
Diminuire il numero di test nello sviluppo di nuovi prototipi

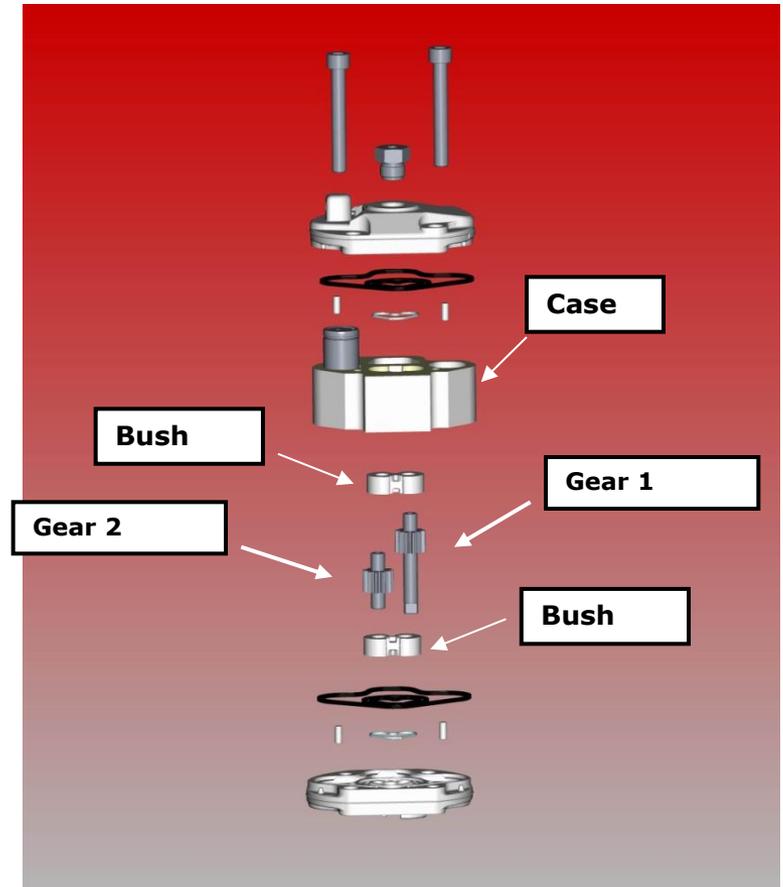
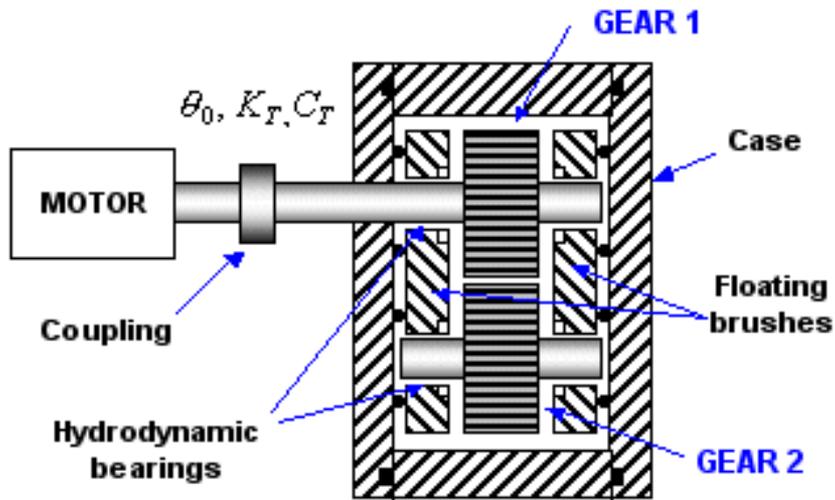


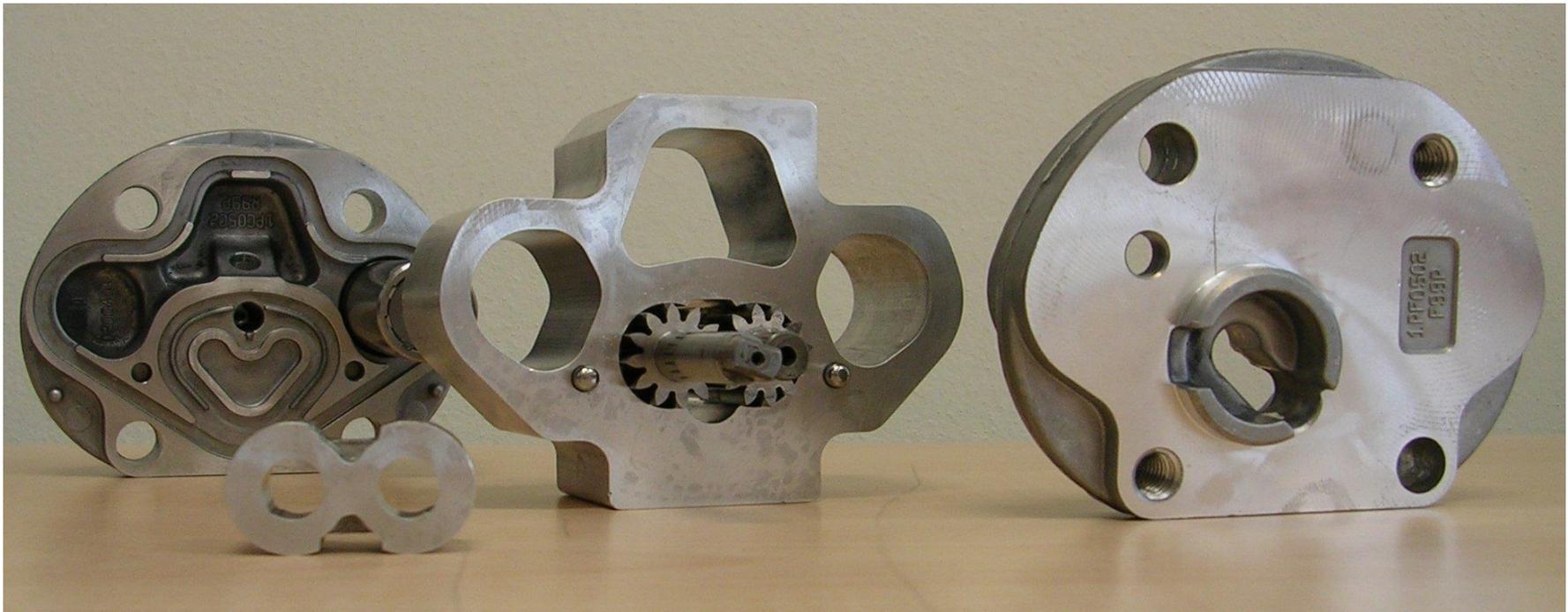


Riduzione del livello vibratorio in condizione operative mediante opportune modifiche progettuali verificate sul modello









## Gear

- 12 teeth
- Pressure angle:  $20^\circ$

## Operational parameters

- Pressure:  $3.5 \div 100$  bar
- Angular speed (range  $1500 \div 3400$  rpm)

1°

**Output:**  
variable forces,  
gear  
acceleration

LP model

Exp.  
Validation (by  
acceleration and  
force  
measurements)

2°

**Output:** casing  
acceleration

Structural FE  
model

Vibro-  
acoustic FE  
model

Exp.  
Validation (by  
acceleration, FRF  
measurements  
and modal  
analysis)

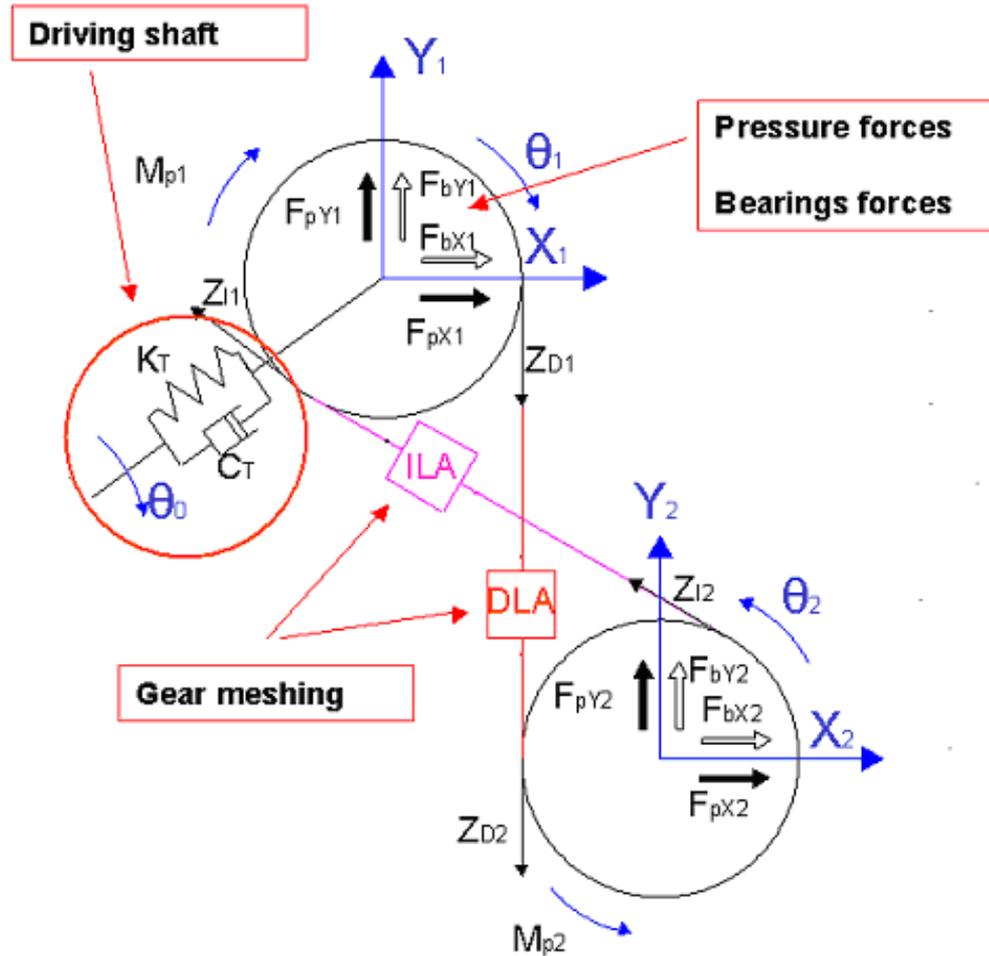
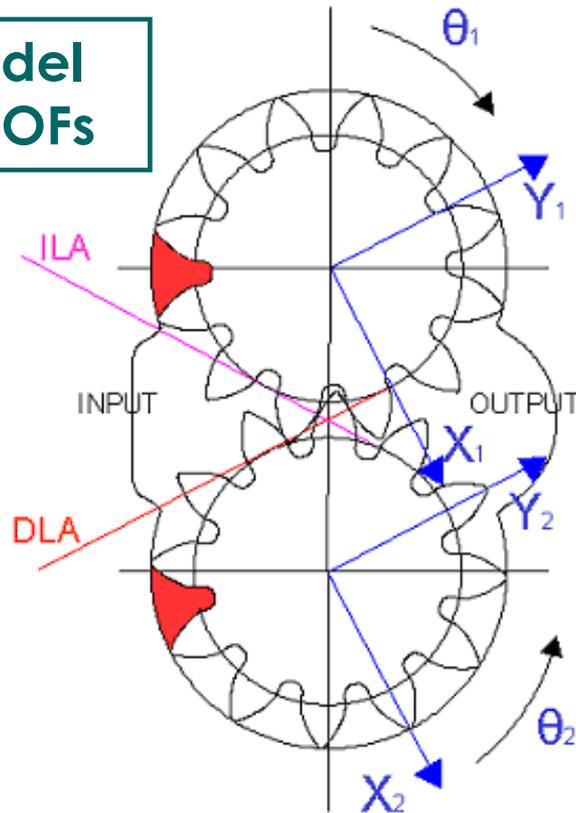
3°

**Output:**  
radiated noise

BE model

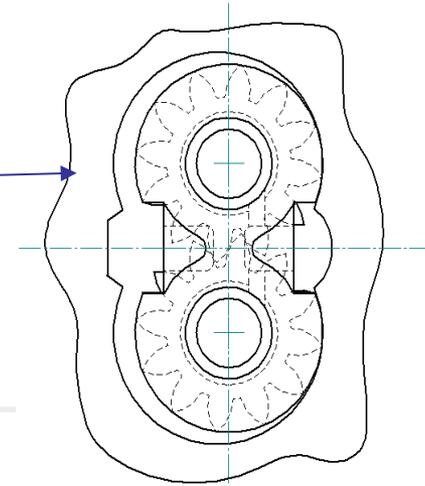
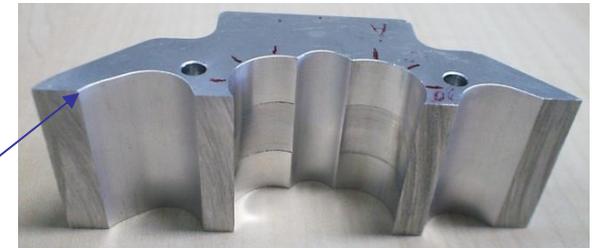
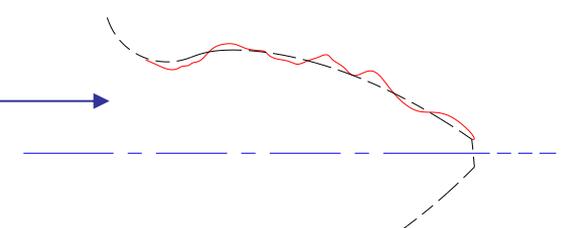
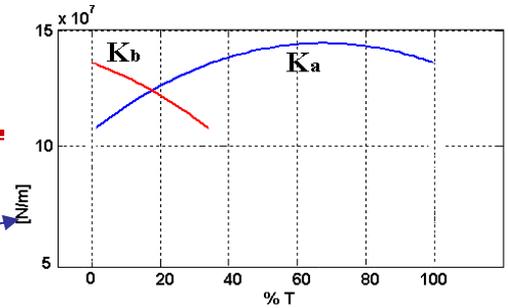
Exp.  
Validation (by  
acoustic pressure  
measurements)

The model has 6 DOFs



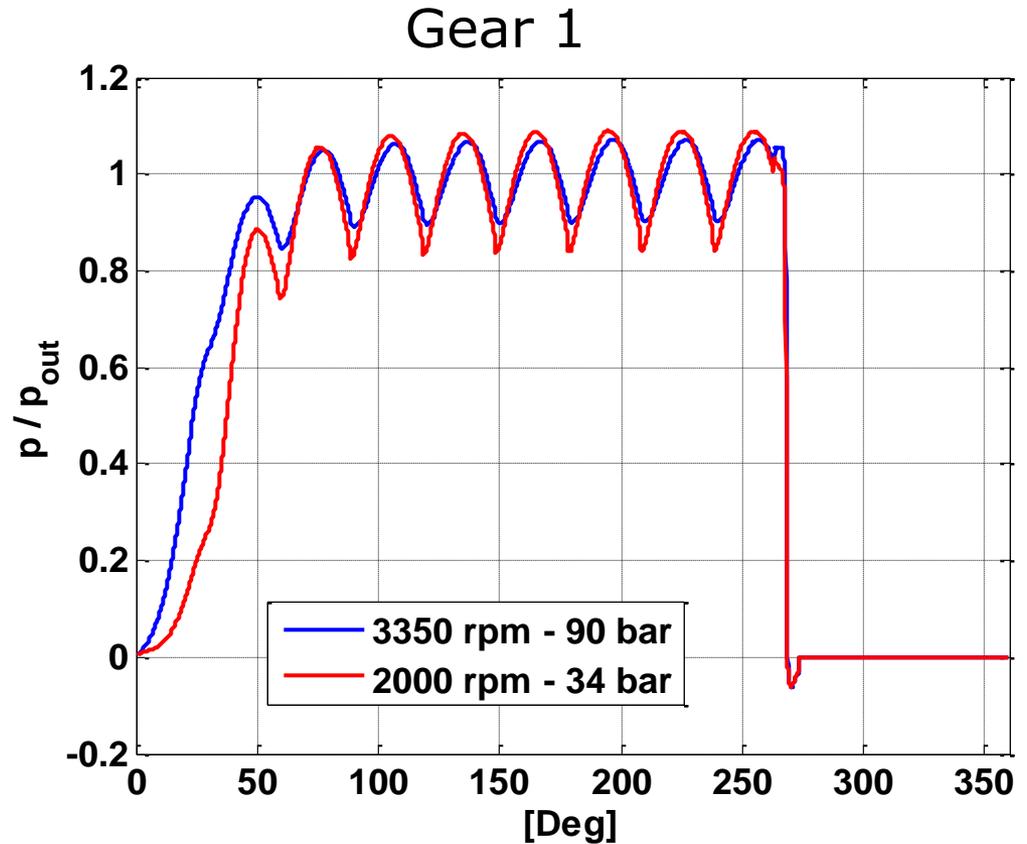
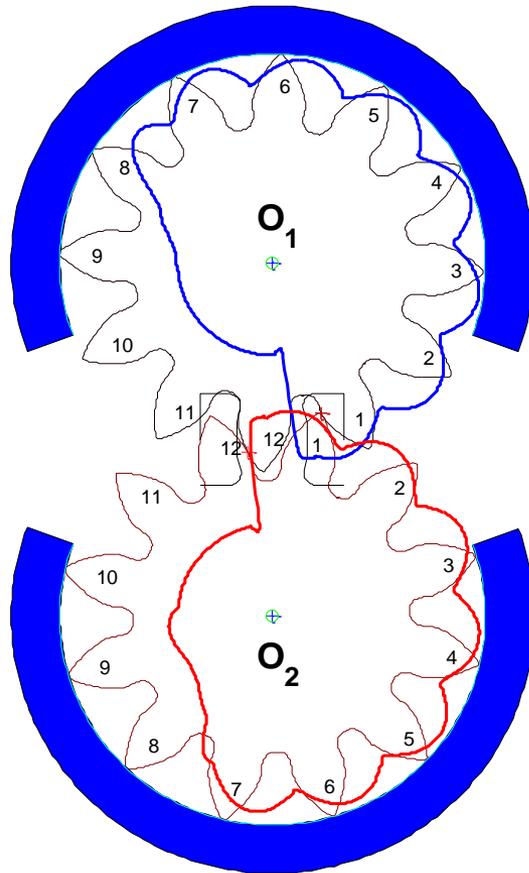
# Considered Effects

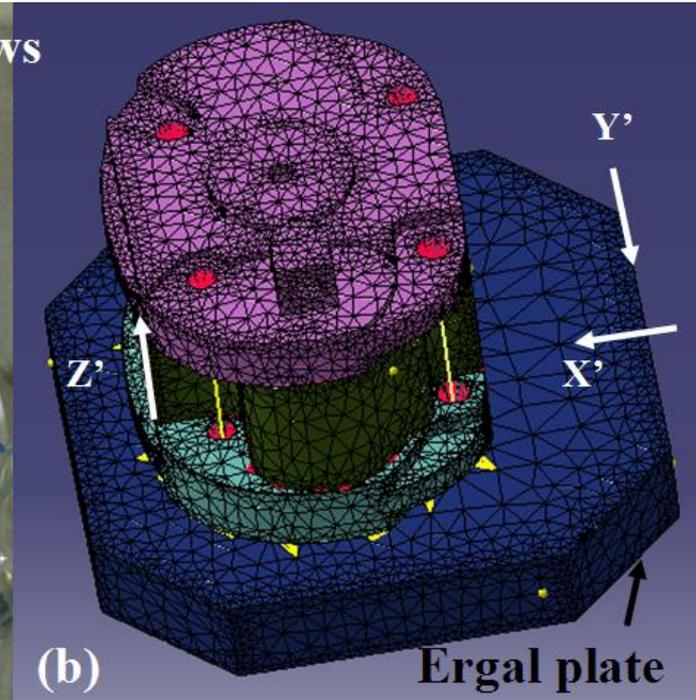
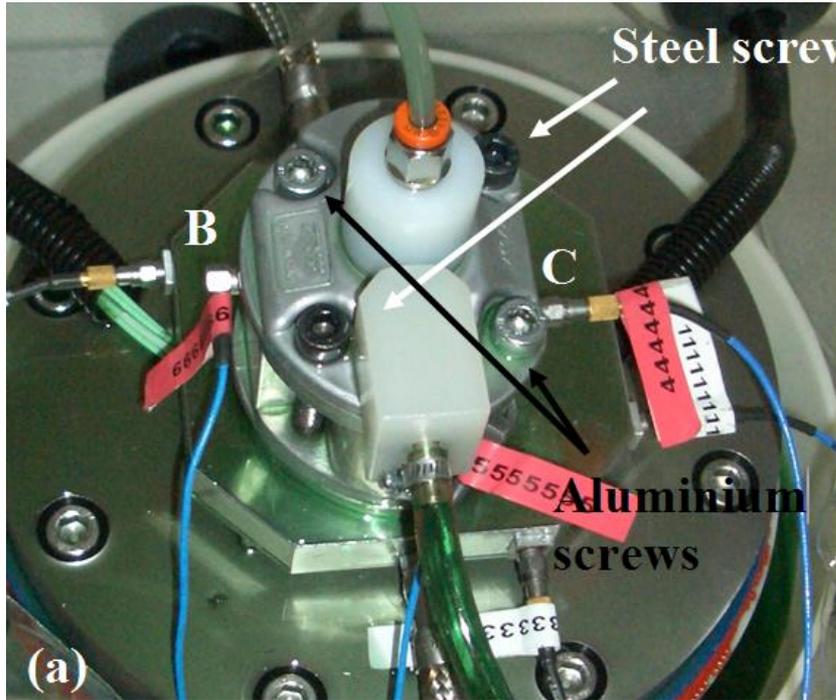
- **Variable Meshing Stiffness.**  
Formulation of Kuang-Yang
- **Tooth profile errors**  
Experimental data
- **Backlash between meshing teeth**  
Wildhaber measurements
- **Lubricant squeeze**
- **Possibility of tooth contact on both lines of action**
- **Torsional stiffness and damping of the driving shaft**
- **Variable pressure distribution (casing wear, displacement bearing blocks).**
- **Hydrodynamic journal bearing.**  
Formulation of Childs



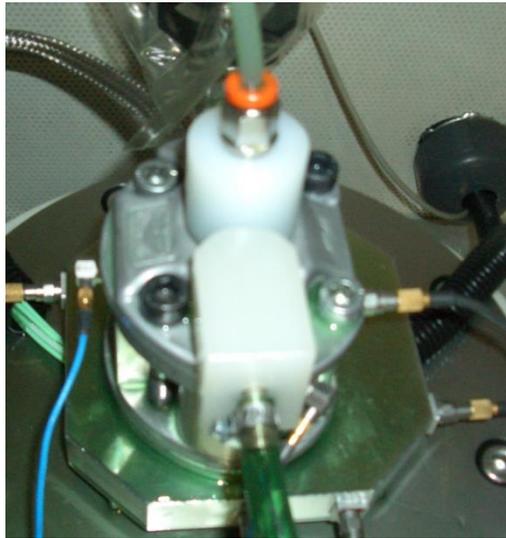
**Highly non linear model**

# Pressure evolution around the gears

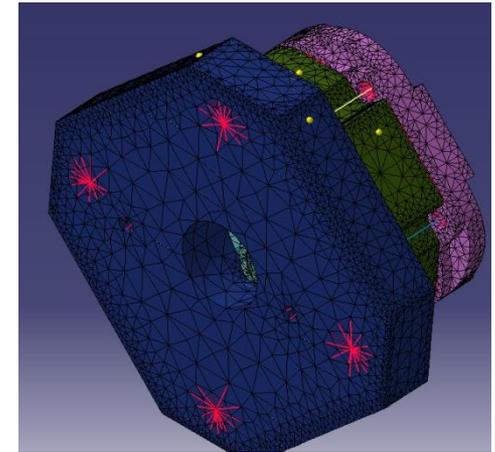
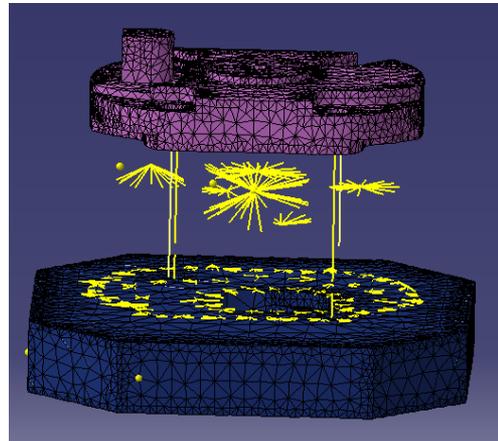
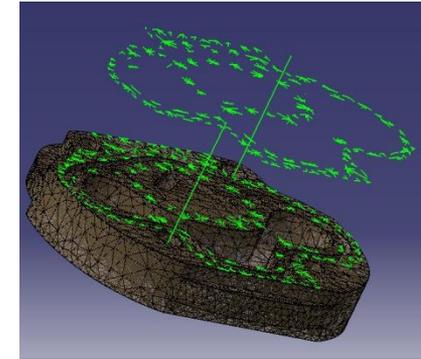
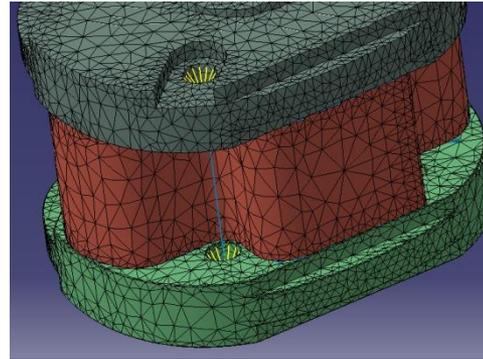




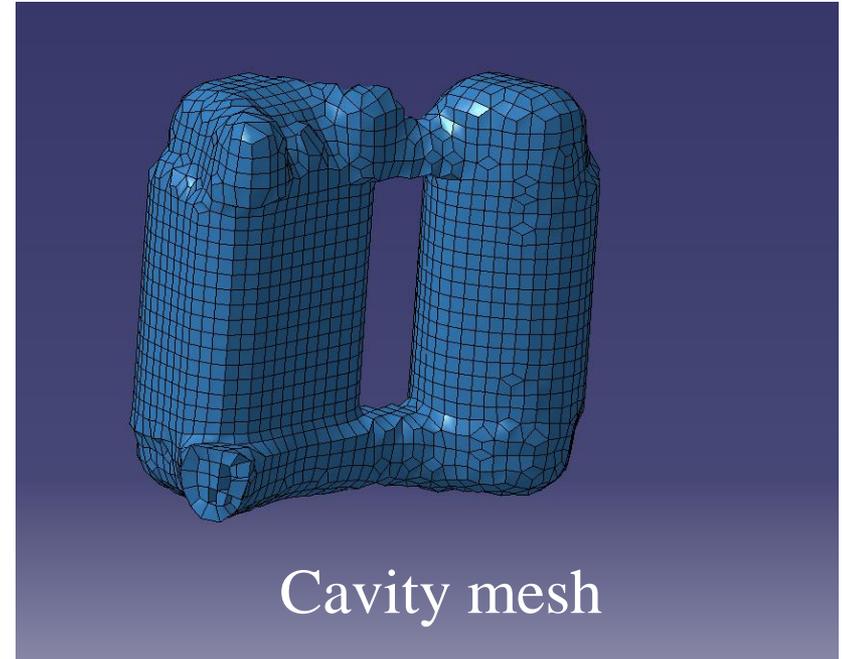
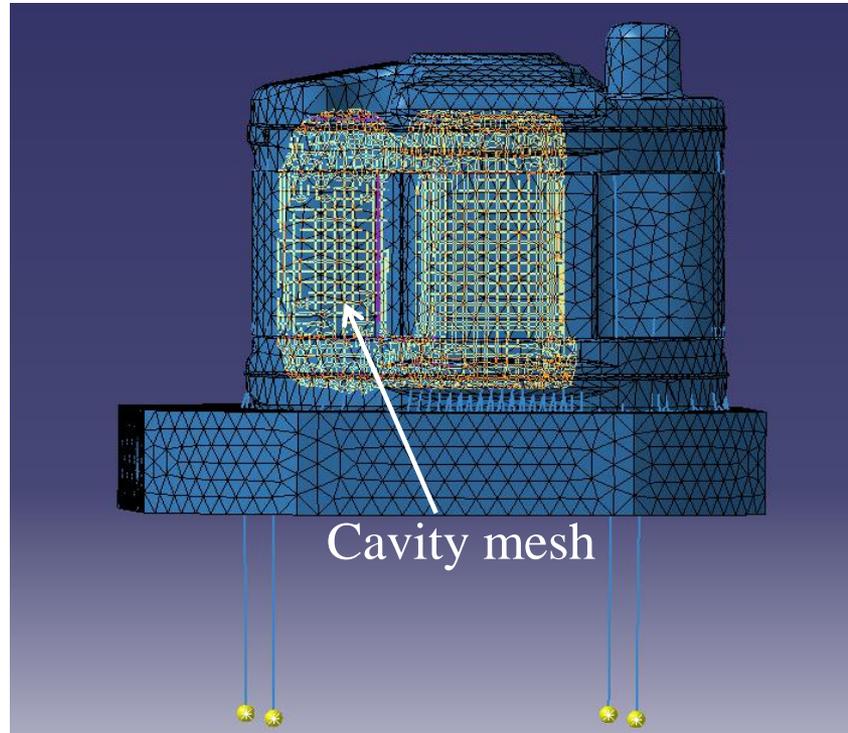
Evaluate the accelerations in the external surface of the pump



Mechanical system



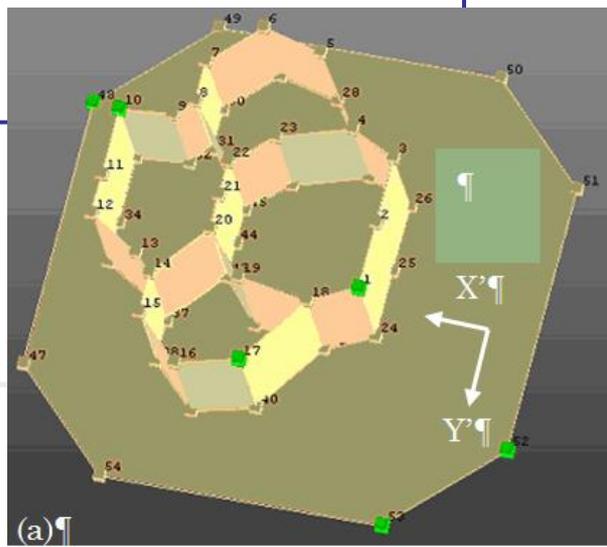
Oil has been included as lumped mass

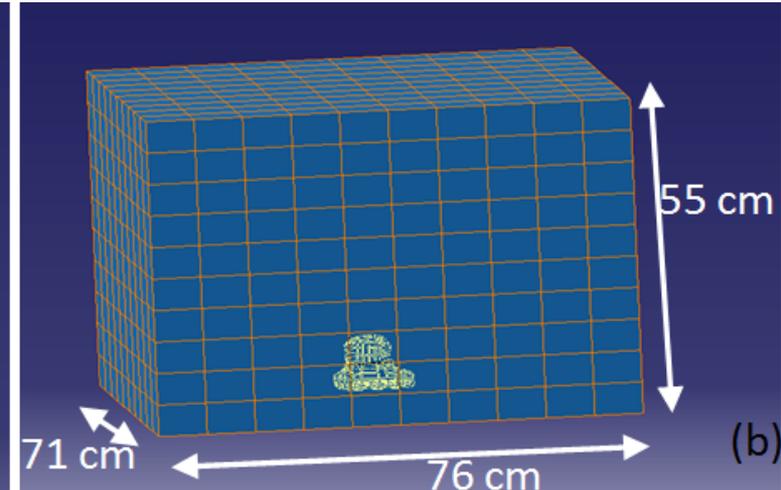
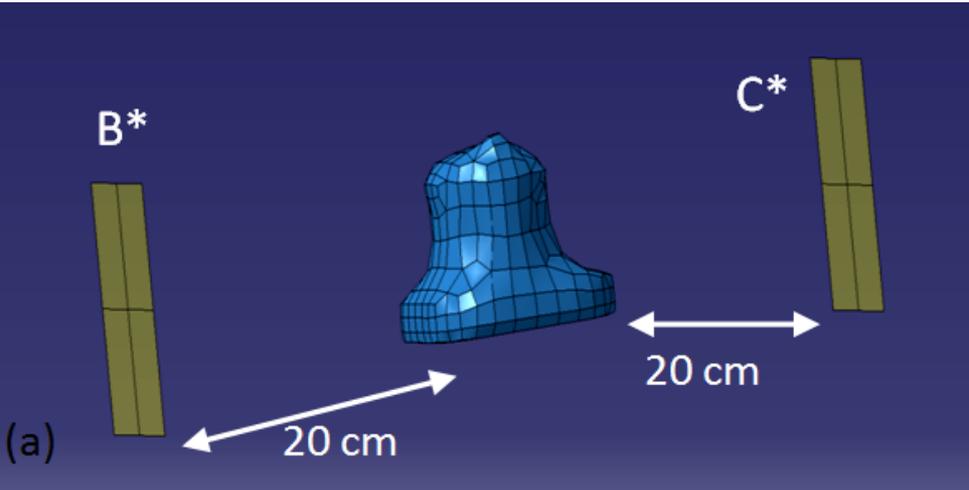


$$\left( \begin{bmatrix} K_s & K_c \\ 0 & K_a \end{bmatrix} + j * \omega * \begin{bmatrix} C_s & 0 \\ 0 & C_a \end{bmatrix} - \omega^2 * \begin{bmatrix} M_s & 0 \\ -\rho_0 * K_c^T & M_a \end{bmatrix} \right) * \begin{Bmatrix} w_i \\ p_i \end{Bmatrix} = \begin{Bmatrix} F_{s_i} \\ F_{s_a} \end{Bmatrix}$$

	Modal damping [%] for the 1 <sup>st</sup> mode	Modal damping [%] for the 2 <sup>nd</sup> mode
<b>With oil at 23 bar</b>	<b>5</b>	<b>0.87</b>

- 6 PCB accelerometers
- $dF = 1.25\text{Hz}$
- 24 measurements in two directions
- H1 estimator



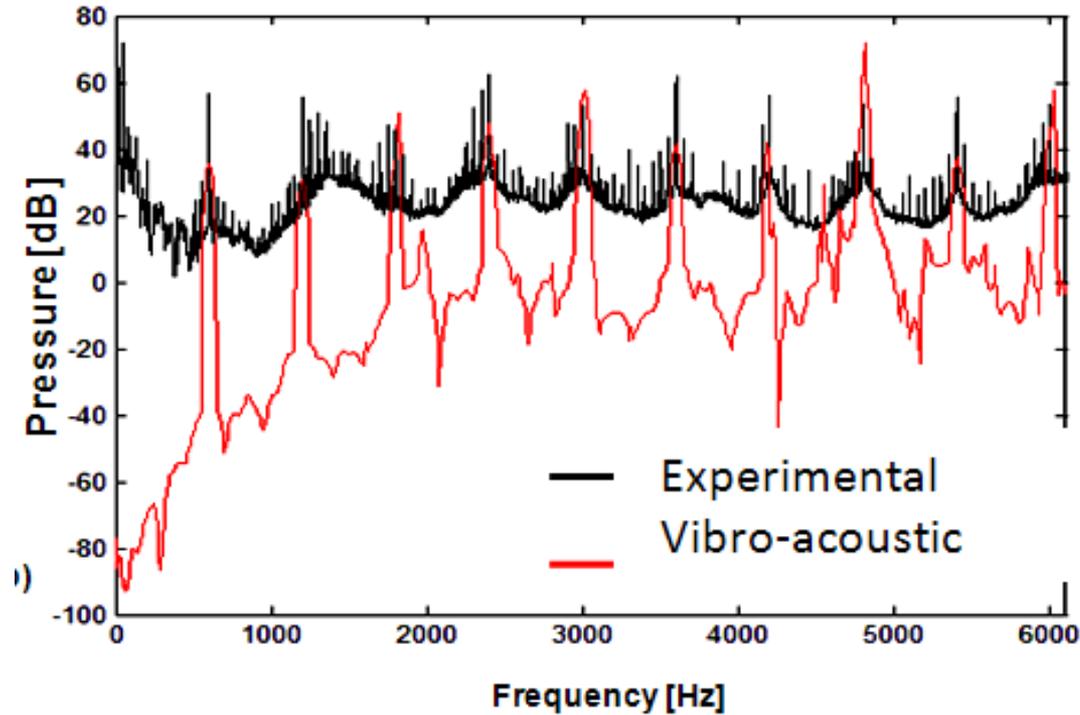


Test bench  
chamber's walls are  
sandwich panel of steel  
and mineral wool

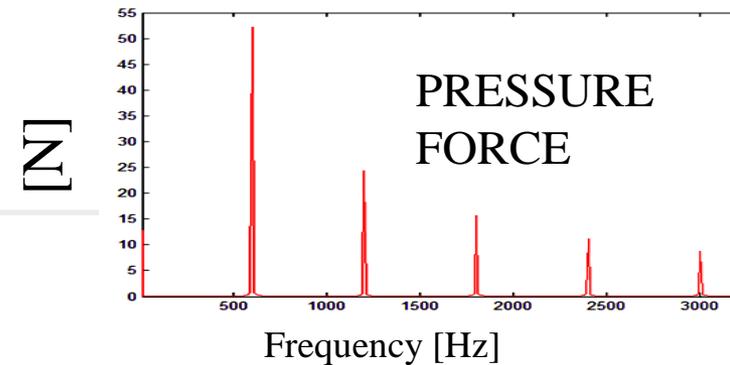


# Indirect BE model: results

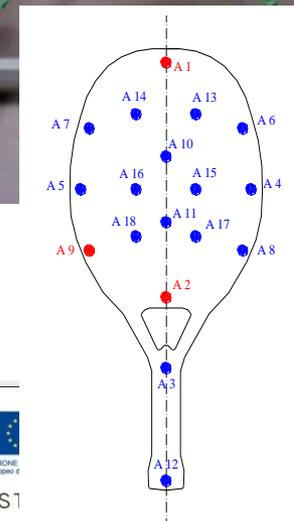
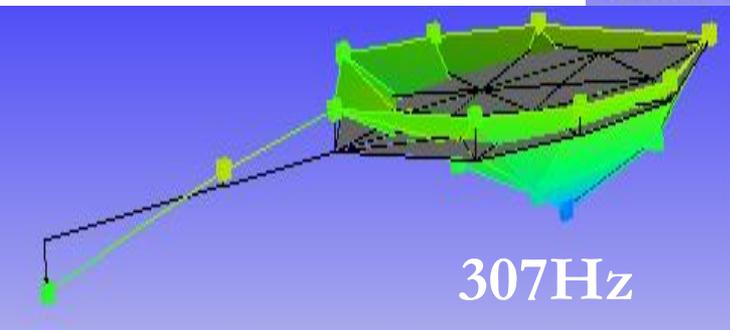
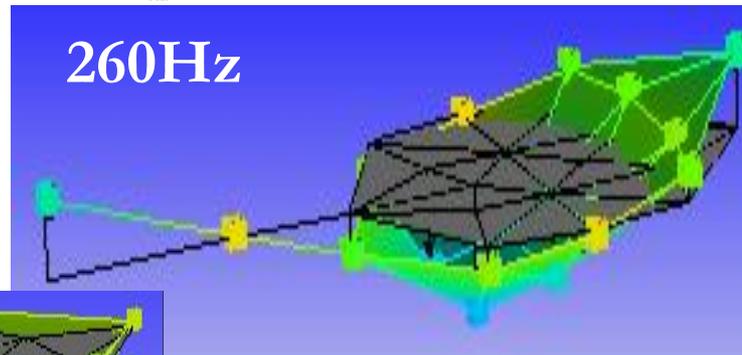
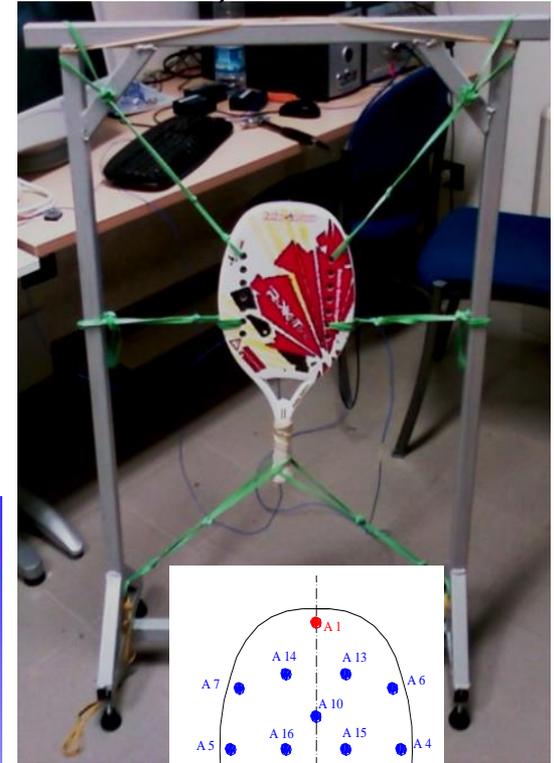
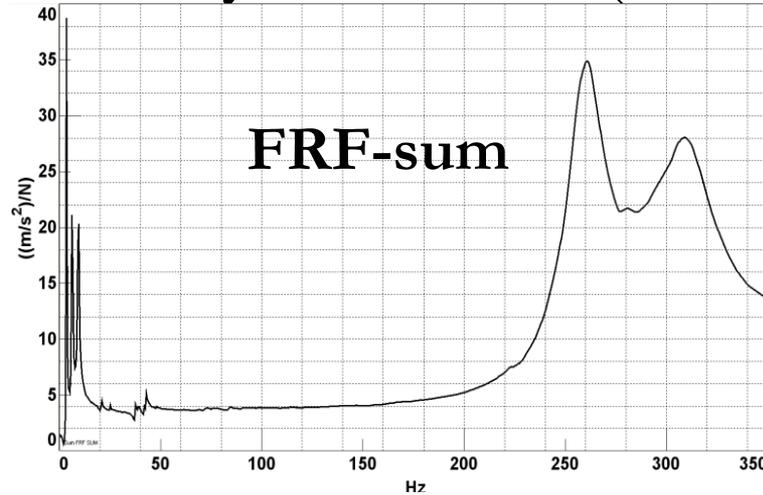
3000 rpm  
90 bar  
Point B\*

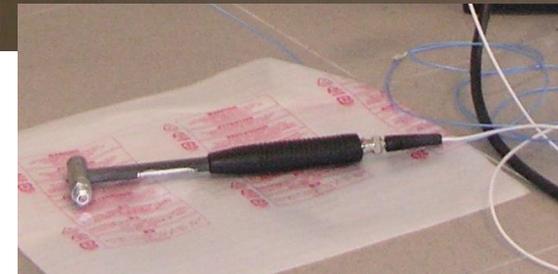
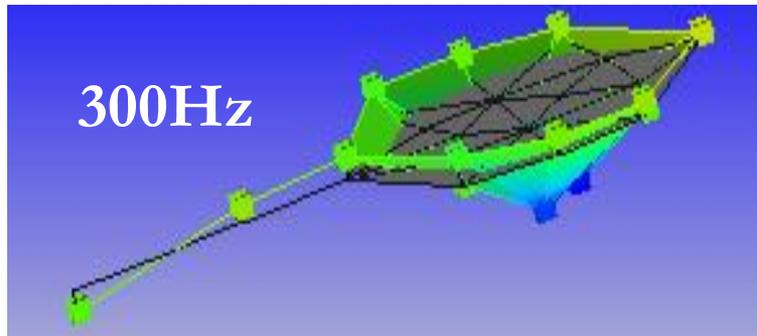
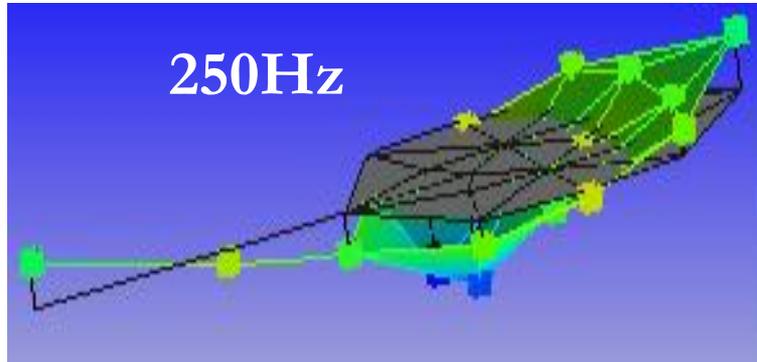


OA: 73.8 dB  
OA: 74.4 dB



**Band of analysis: 0-350Hz (tennis elbow problem)**





## EMA hypotheses:

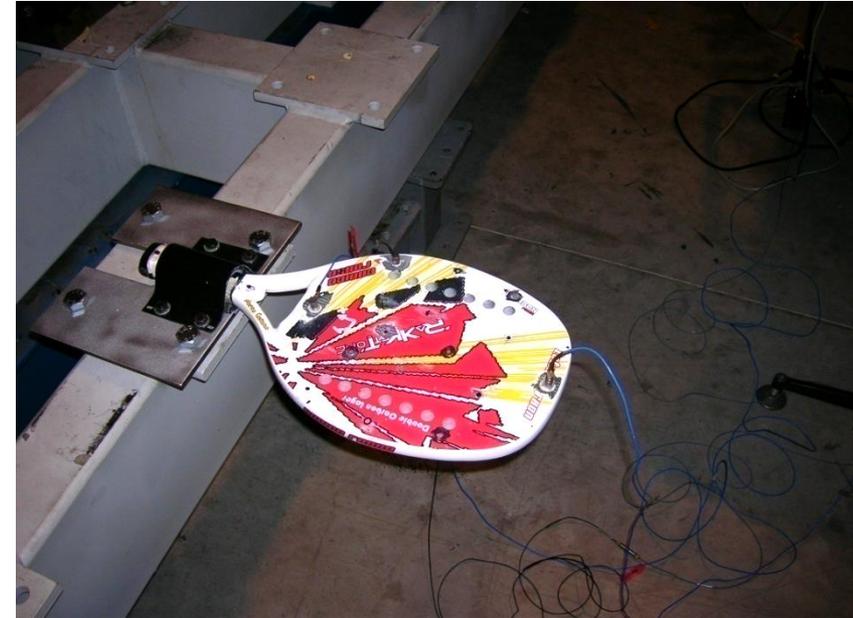
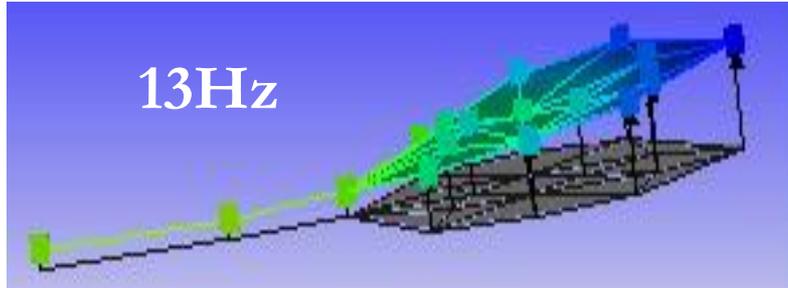
-linearity

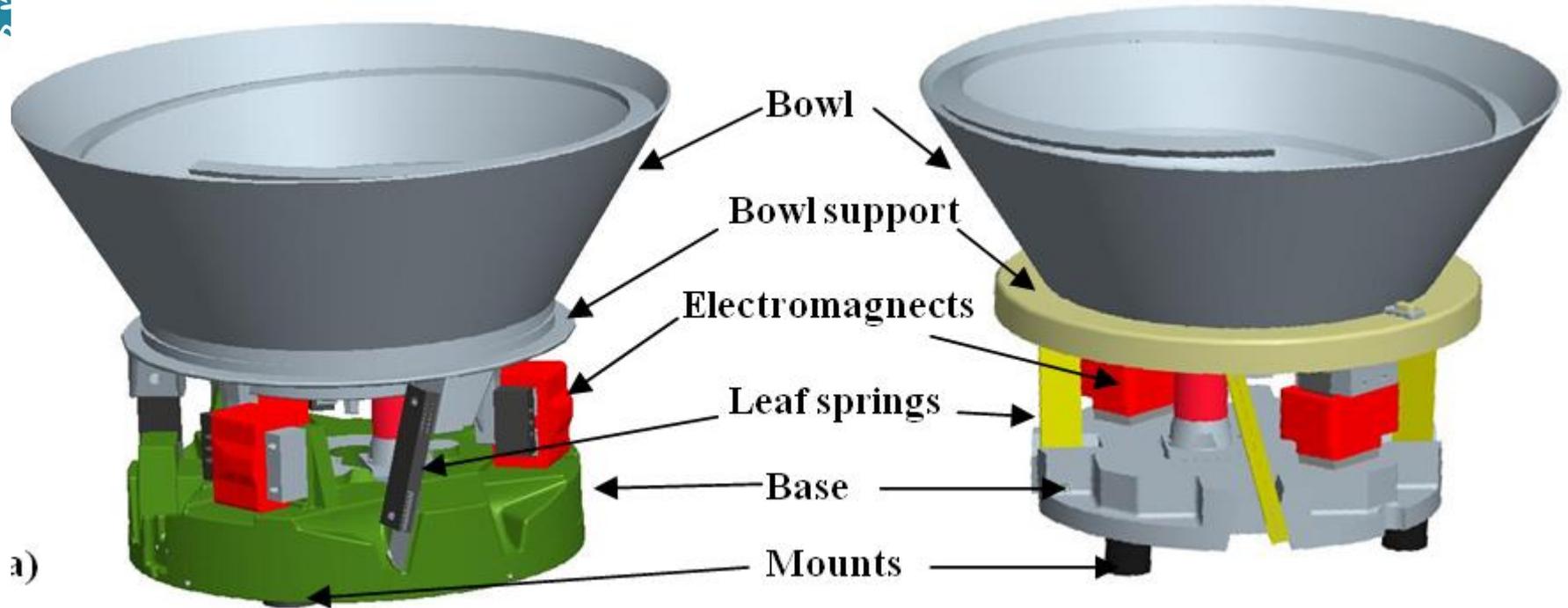
-time invariance (i.e. the structure dynamic characteristics do not change in time)

observability



# Clamped EMA



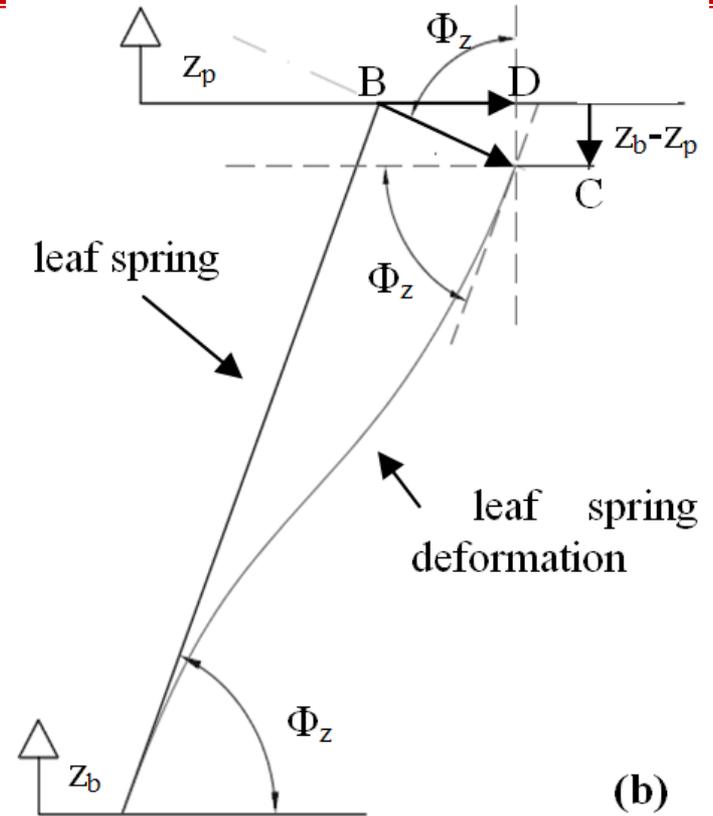
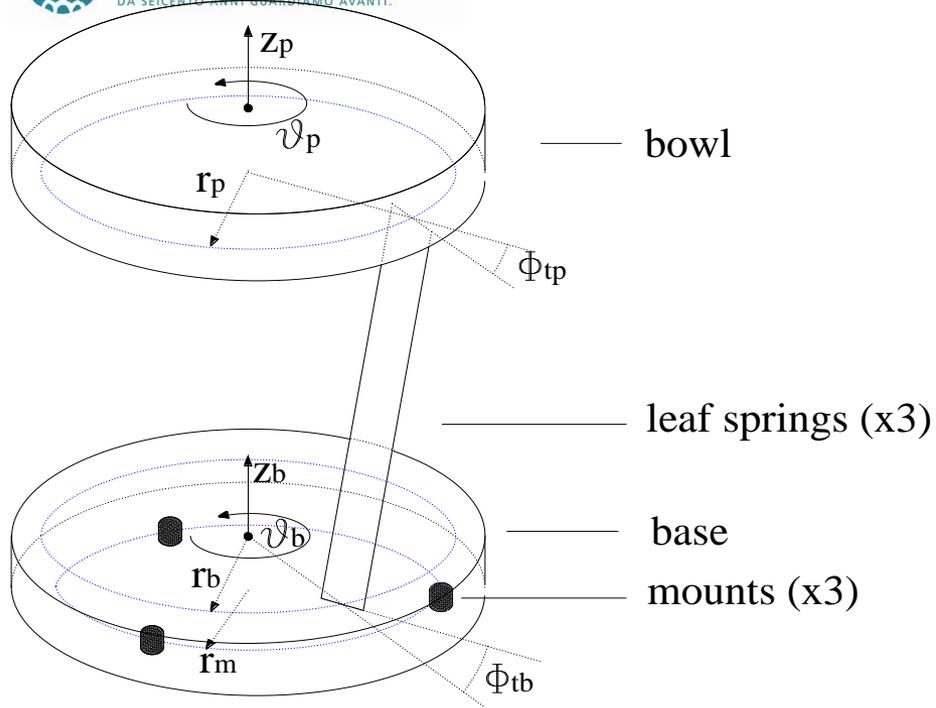


Alimentatore a magneti tangenziali

Alimentatore a magneti verticali

1. Analisi modali
2. Accelerazioni operative
3. Rigidezza degli antivibranti
4. Misura della forza elettromagnetica

# Modello a parametri concentrati



## Effetti considerati:

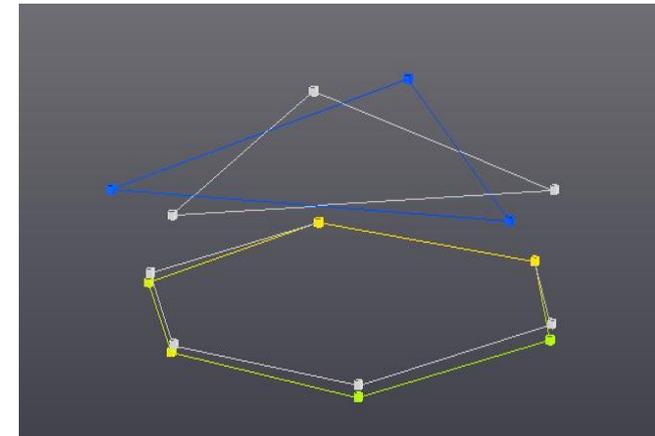
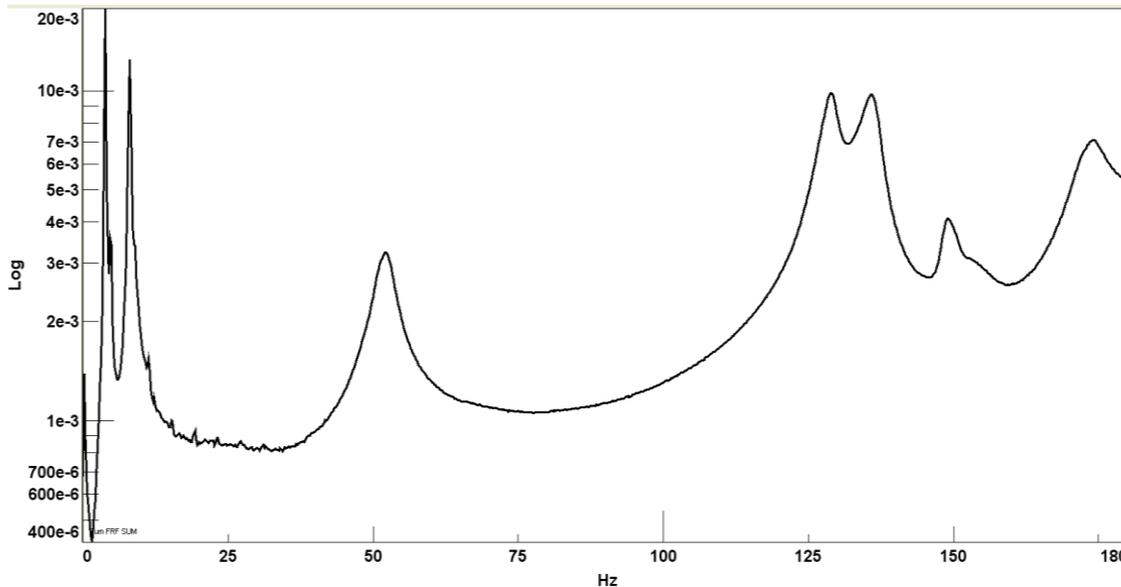
- Rigidezza delle balestre
- Rigidezza degli antivibranti (vert, tang)
- Smorzamento
- Forza elettromagnetica

Modello a  
3 g.d.l.

$z_b \theta_b z_p$

3 condizioni per  
ogni alimentatore

- A) senza tazza
- B) con tazza
- C) con tazza e con tappi ( $\xi_j$ )



Modo a 52Hz

# 1. *tuning* dei parametri del modello

- i. Rigidezza delle balestre (confr fra  $f_n$  nel caso "senza tazza");
- ii. Inerzia tazza (confr fra  $f_n$  nel caso "con tazza");

Mode #	Experimental data		Numerical data		Numerical data	
	$f_n$ [Hz] BFT	$f_n$ [Hz] BFV	$f_n$ [Hz]	BFT	$f_n$ [Hz]	BFV
1	4.8	7.7	5.9		8.0	
2	8.2	15.3	10		14.1	
3	52	50.1	52.6		52.0	

## Alimentatore a magneti verticali

	Forza trasmessa a telaio (orig)	Forza trasmessa a telaio (mod1)
Dir tangenziale	139 N	56 N
Dir verticale	169 N	103 N

Mod1: Variazione dell'inclinazione balestra di 5 deg

# OBJECT OF THE INVESTIGATION

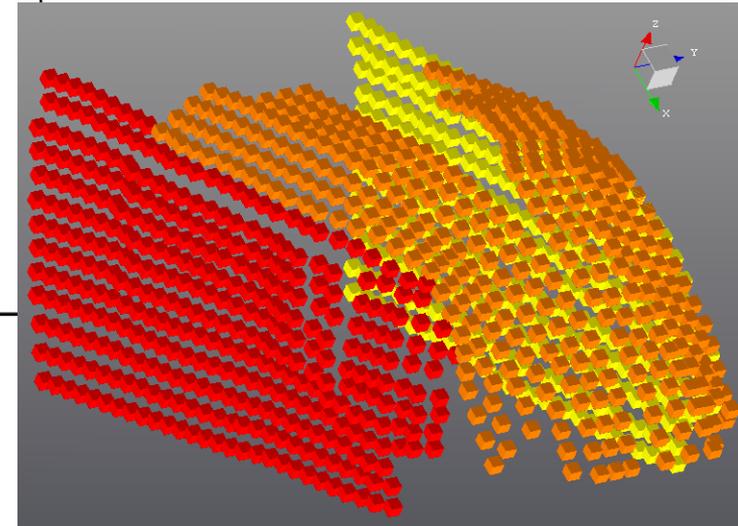
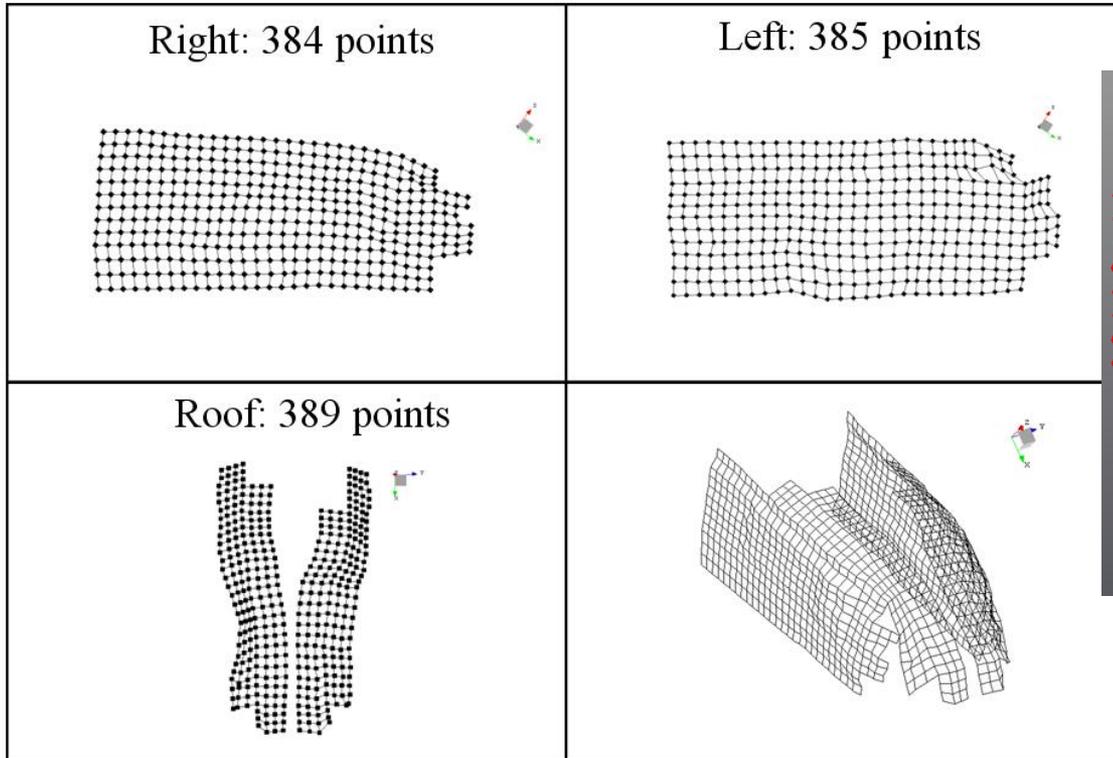
This research activity consists of an intensive campaign testing conducted on a EC-135 helicopter cabin.

## EUROCOPTER EC-135

*EC135 is a light twin-engine, multi-purpose helicopter with up to 8 seats for pilot/s and passengers.*

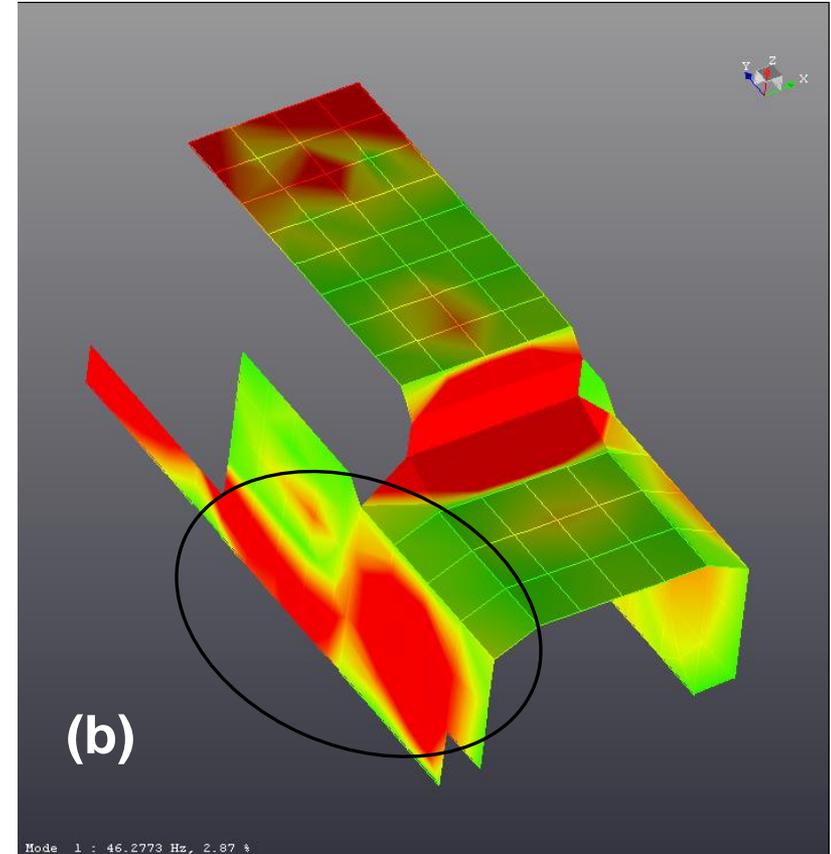
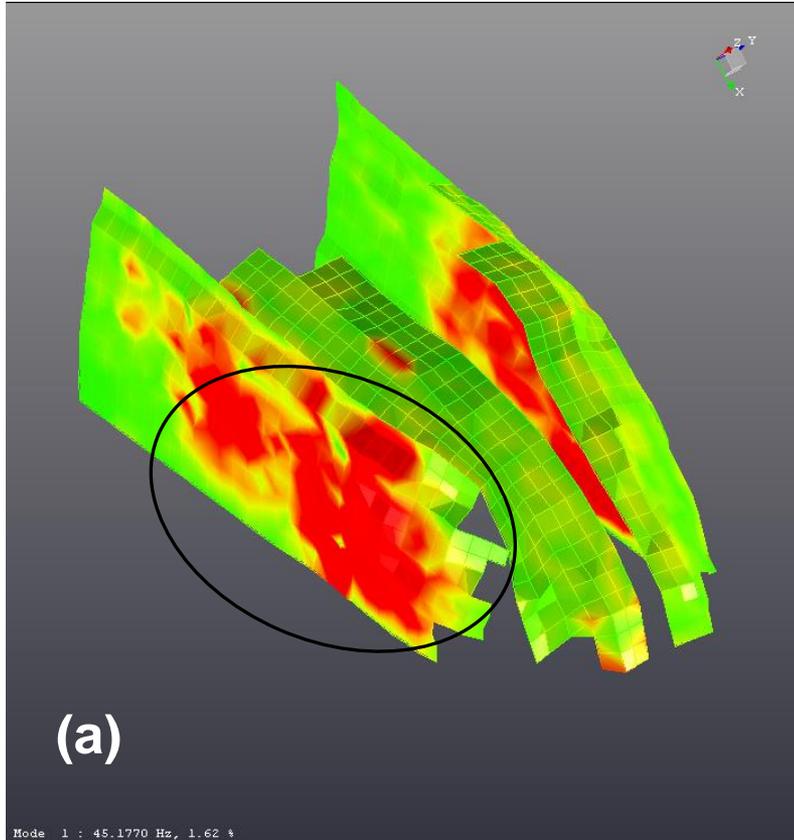


# MEASURED GRID POINTS



Measured grid points of the **cabin external surface** by means of Microflow sensors

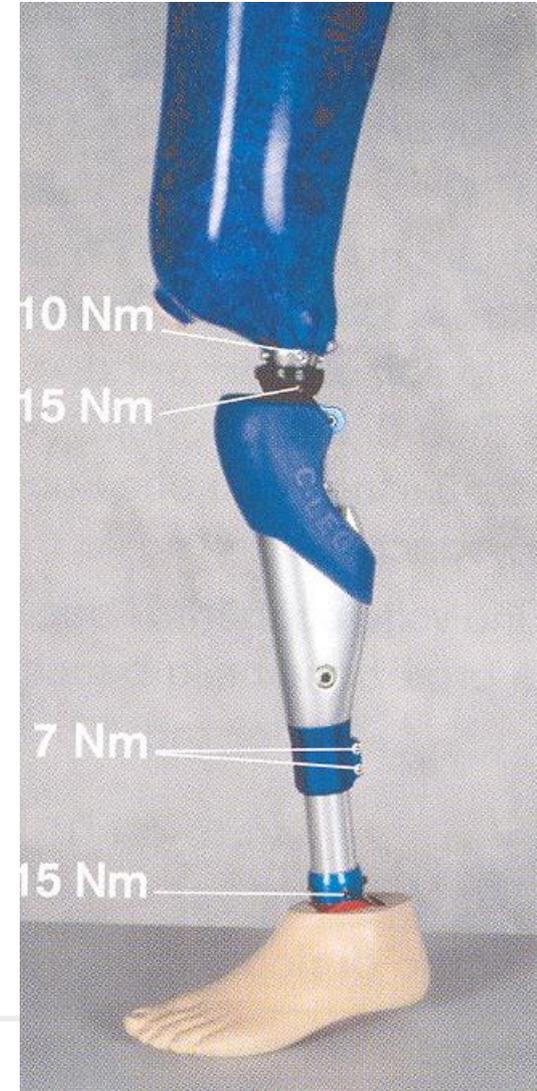
# RESULTS: mode shapes

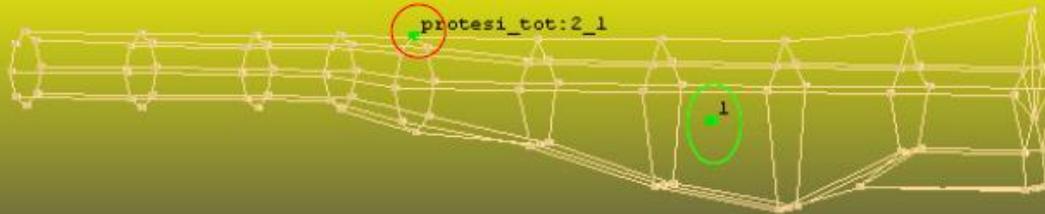


First mode shape coloured map of the cabin external surface (a) (45.2 [Hz]) and the cabin internal surface (b) (46.3 [Hz])

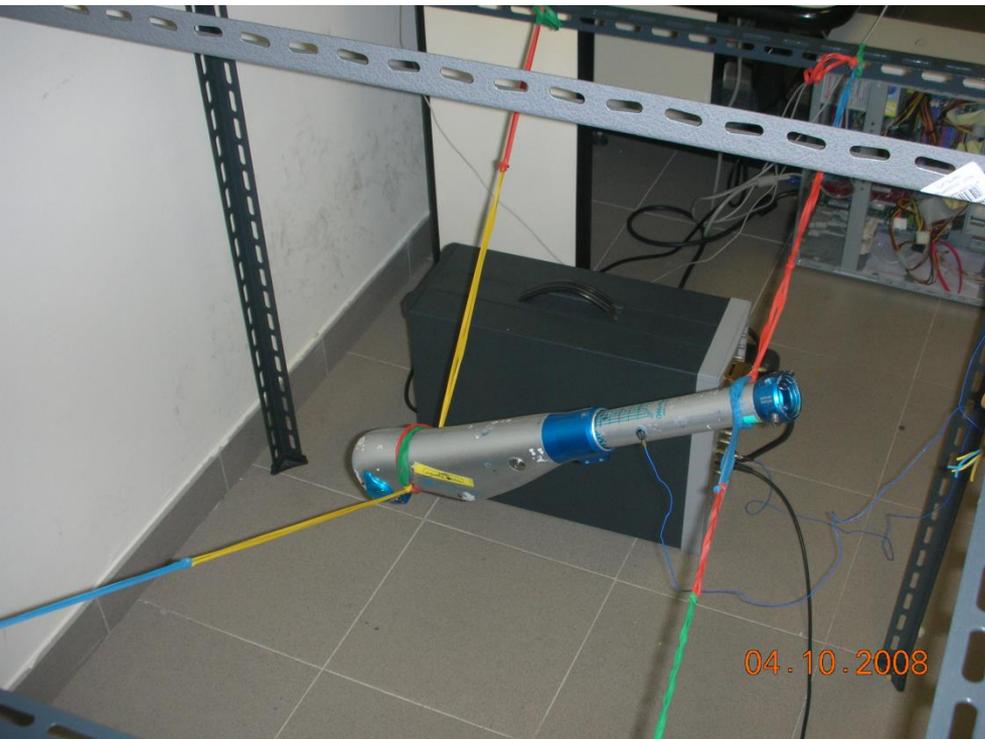
Evaluation of the **rigid-body inertia properties** (mass, COG and inertia tensor) of a **prosthesis** for trans-femoral amputees, namely the above-knee prosthesis

**C-Leg 3C100**





- Accurate geometrical wireframe
- weight



Practical tests showed that the best results are obtained with at least 6 excitation DOFs and 24 response DOFs

# Inertia Restrain Methods (IRM): Kinematics step

$$1) \quad \ddot{\mathbf{P}}_i = \ddot{\mathbf{O}} + \left[ \tilde{\boldsymbol{\omega}} + \tilde{\boldsymbol{\omega}}^2 \right] \mathbf{P}_i$$

Acceleration of the point  $P_i$

$$2) \quad \frac{\ddot{\mathbf{P}}_i}{F_j} = \left[ \mathbf{I}_3 \quad -\tilde{\mathbf{P}}_i \right] \begin{pmatrix} \ddot{\mathbf{O}}/F_j \\ \tilde{\boldsymbol{\omega}}/F_j \end{pmatrix}$$

more than 3 non-aligned response points ( between 8 and 12 response points in three directions are suggested) allow to calculates the 6 FRFs

~ skew-symmetric matrix

	Test 1	Test 2
<b>RB Inertia Property</b>	<b>Prosthesis</b>	<b>Hydraulic part+ modular pipe</b>
$G_x$	14.11	13.68
$G_y$	-0.2275	-0,3020
$G_z$	-3.6185	-3.3832
$J_{xx}$	0.003001	0.002384
$J_{yy}$	0.05909	0.05760
$J_{zz}$	0.05677	0.05696
$J_{xy}$	0.0005828	0.001172
$J_{xz}$	-0.008662	-0.006094
$J_{yz}$	-0.0001996	-0.0003415



## 2. Controllo qualità e diagnostica di difetti mediante analisi vibratoria

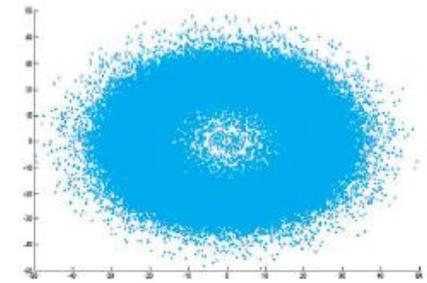
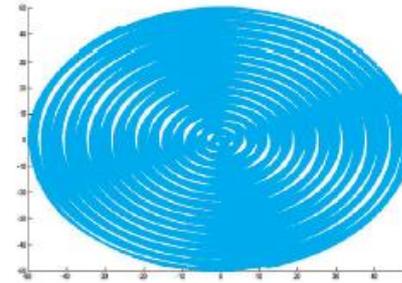
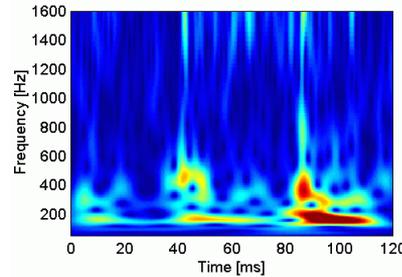
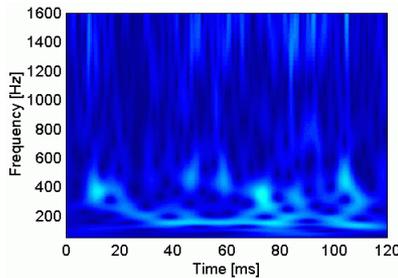
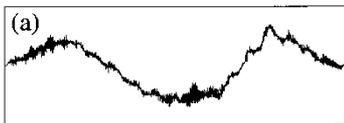
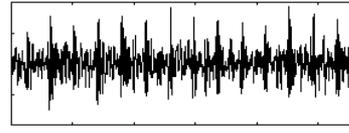
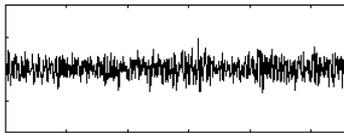
*Manutenzione predittiva*

*Diagnostica di malfunzionamenti*

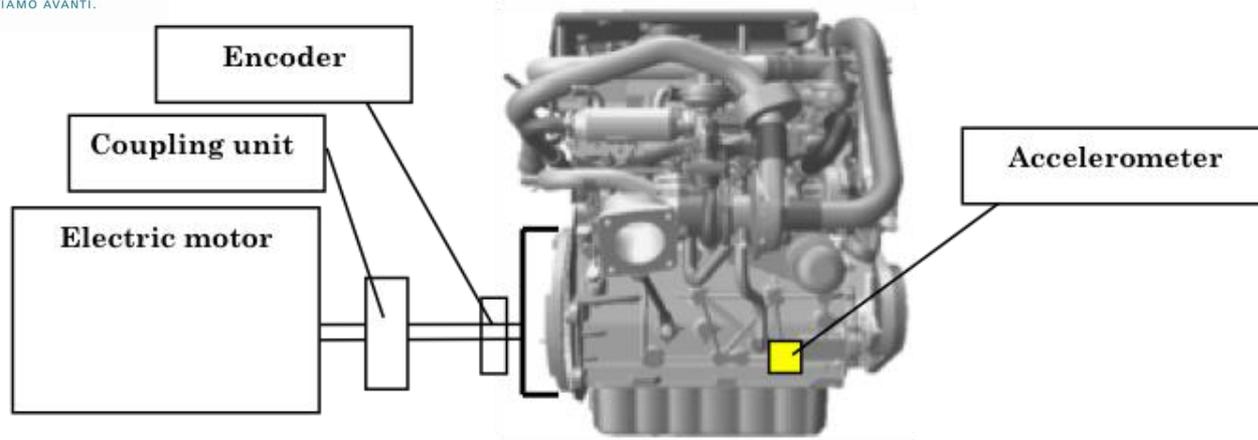
*Controllo qualità*

*Organo sano*

*Organo danneggiato*



*Tecnica basata sulla correlazione di immagini per la classificazione buono/scarto in motori a c.i.*



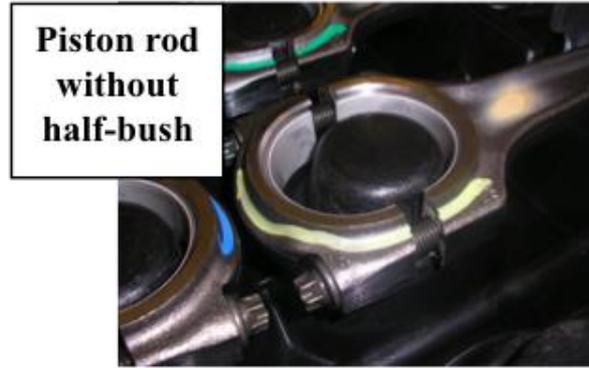
**Fault 1**



**Screws not tight with the correct load**

**Cylinder 3 (RC3 engine)**

**Fault 2**



**Piston rod without half-bush**

**Cylinder 4 (RC4 engine)**

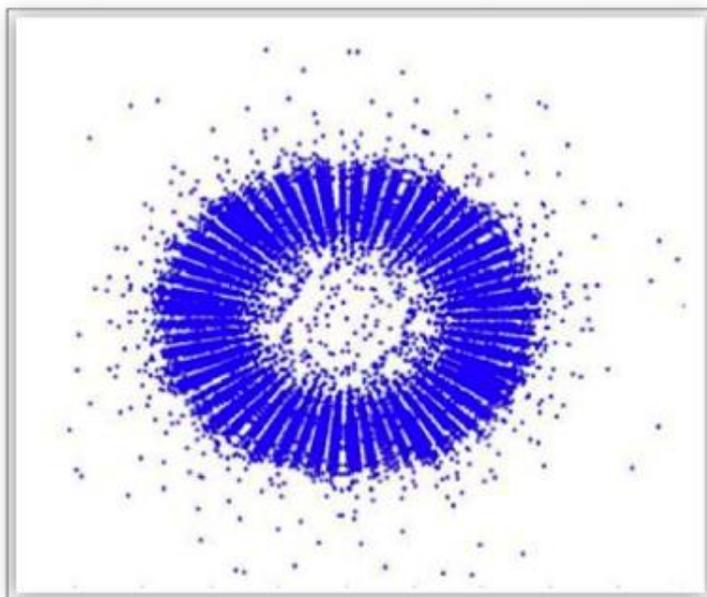
**Fault 3**



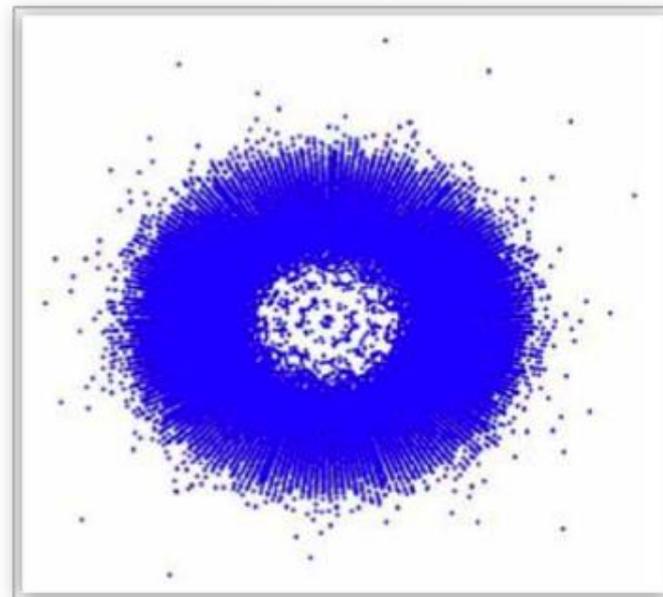
**Counter-rotating masses mounted with a phase lag**

**CRM engine**

## Healthy REFERENCE Pattern



## Rod screws tightened with a pre-load of only 3 kgm (RS3 engine)



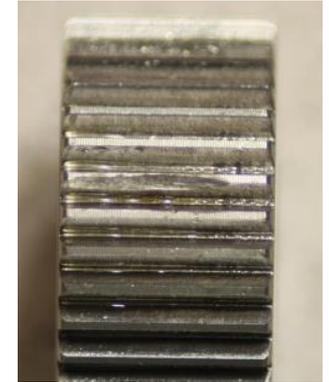
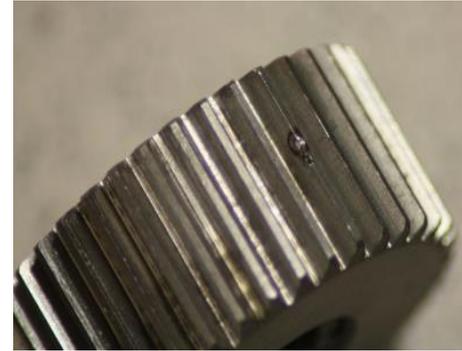
### Percentage of common white pixel correlations

- ▶ Pattern REFERENCE Healthy – Pattern Healthy engine (THRESHOLD) = **25.08%**
- ▶ Pattern REFERENCE healthy – Pattern Faulty RS3 engine = **10.80%**
- ▶ Pattern REFERENCE healthy – Pattern Faulty RS4 engine = **21.83%**
- ▶ Pattern REFERENCE healthy – Pattern Faulty CRM engine = **22.07%**

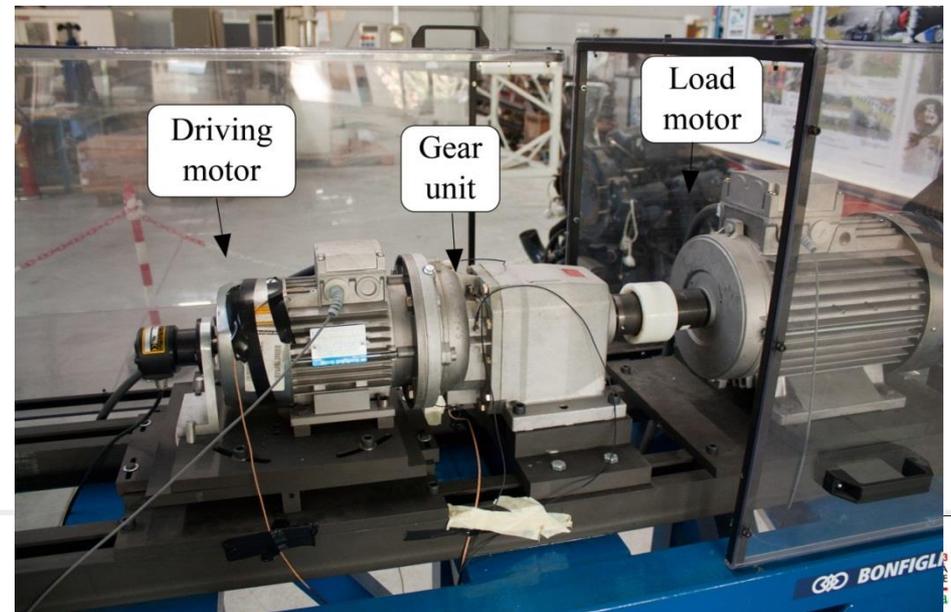
# Diagnostica e controllo qualità in ruote dentate e riduttori (ordinari e epicicloidali)

## Tipologie di difetti studiati:

- cattiva lavorazione
- usura
- scarsa lubrificazione
- cricche
- ammaccature

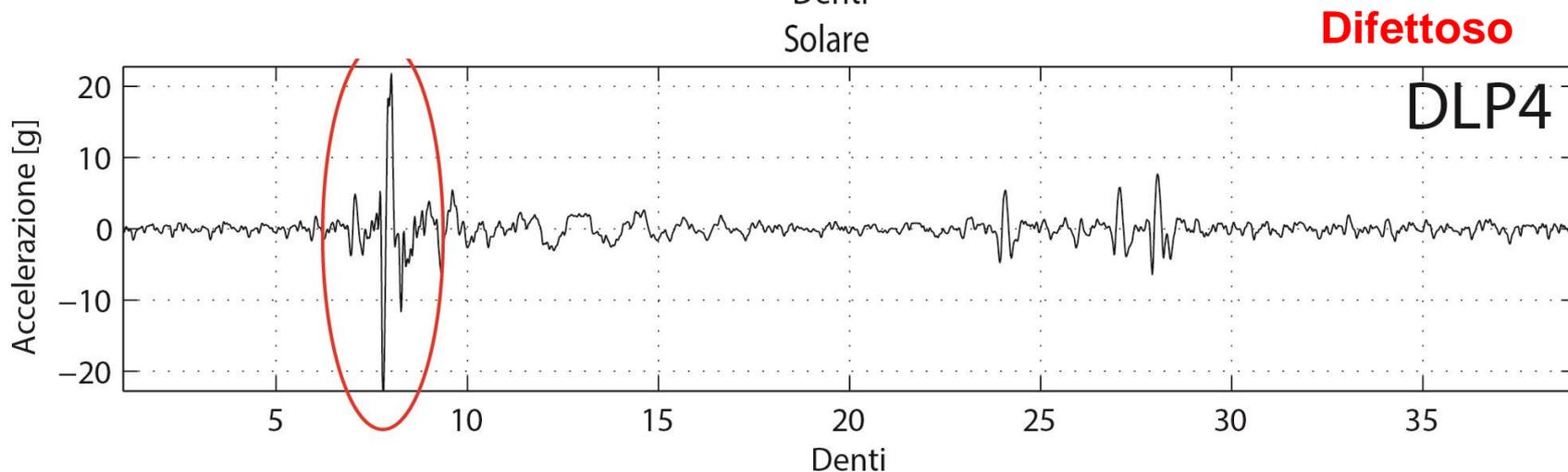
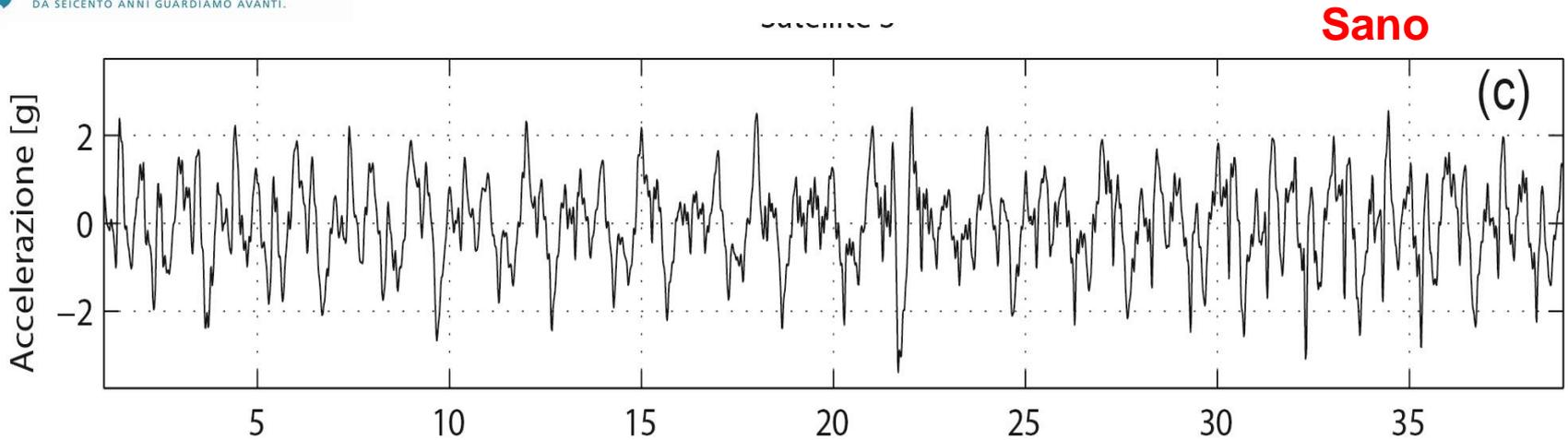


5 mm



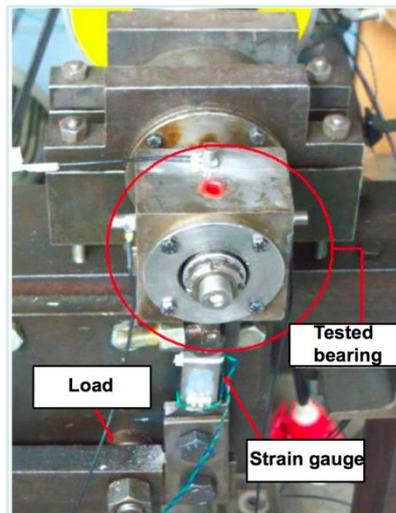
COSTRUIAMO INSIEME IL FUTURO





## Tipologie di difetti studiati:

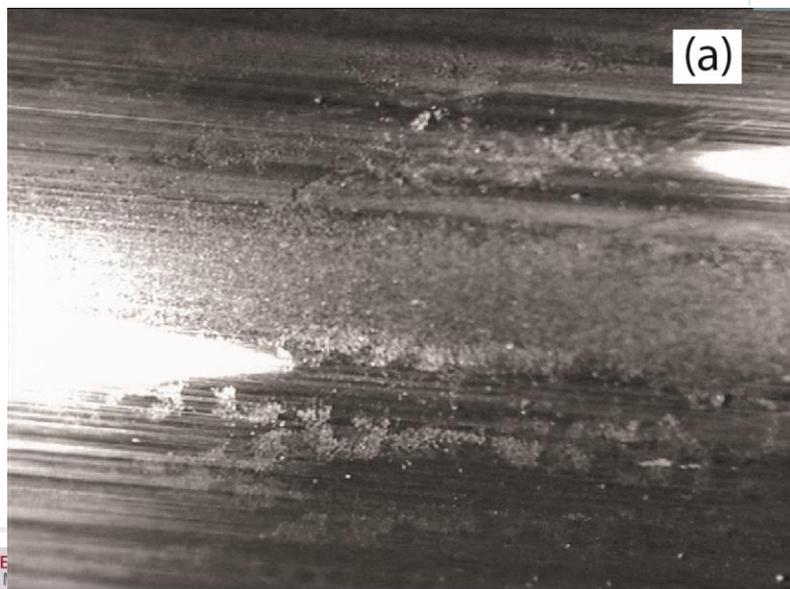
- cattiva lavorazione
- usura
- pitting
- cricche
- piste e/o sfere danneggiate



(a)



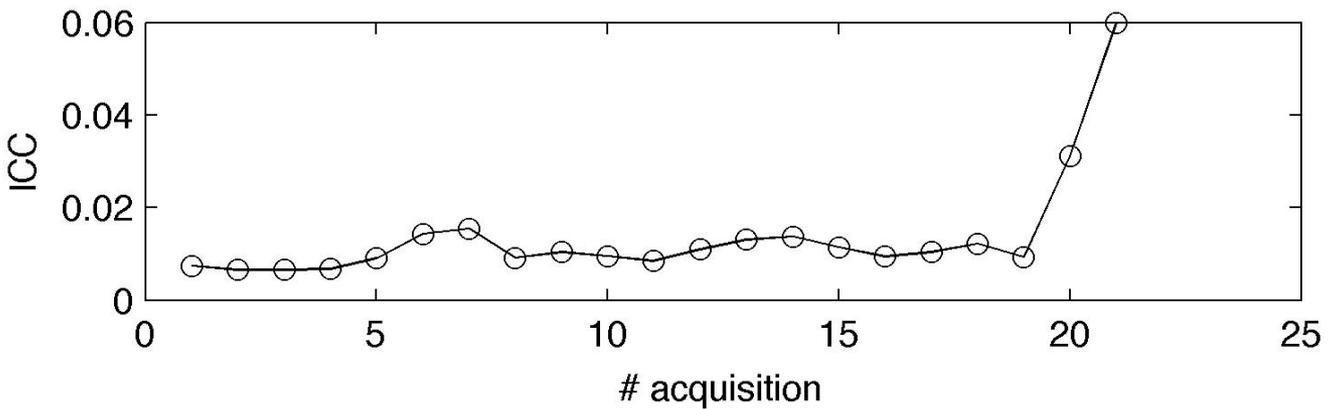
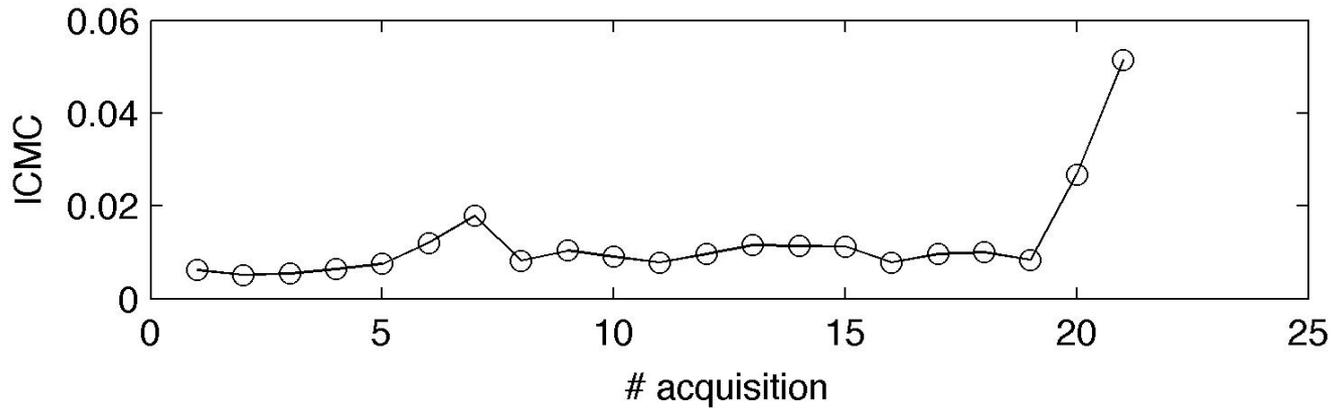
(b)



(a)



(b)



**Comparsa del difetto alla 22° acquisizione durante un test di durata**

## Componente analizzato: possibili criticità

Le difettosità più critiche sono:

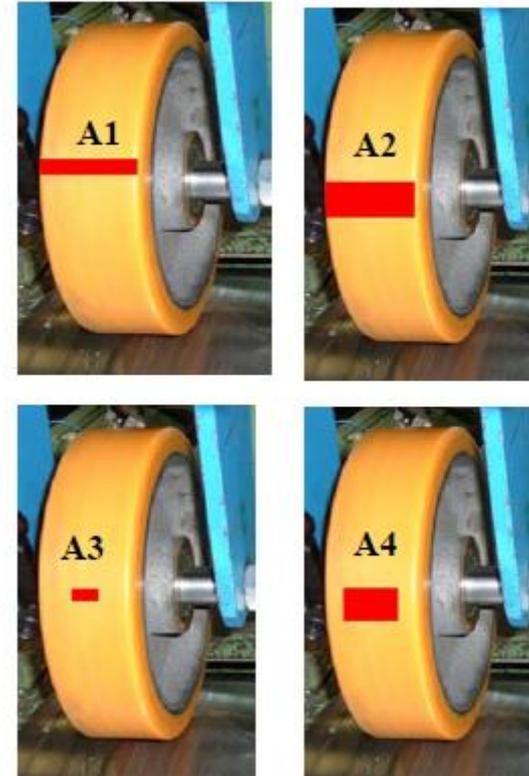
- Mancato incollaggio tra battistrada e mozzo;
- Presenza di ruggine sulla superficie del mozzo



Battistrada in poliuretano

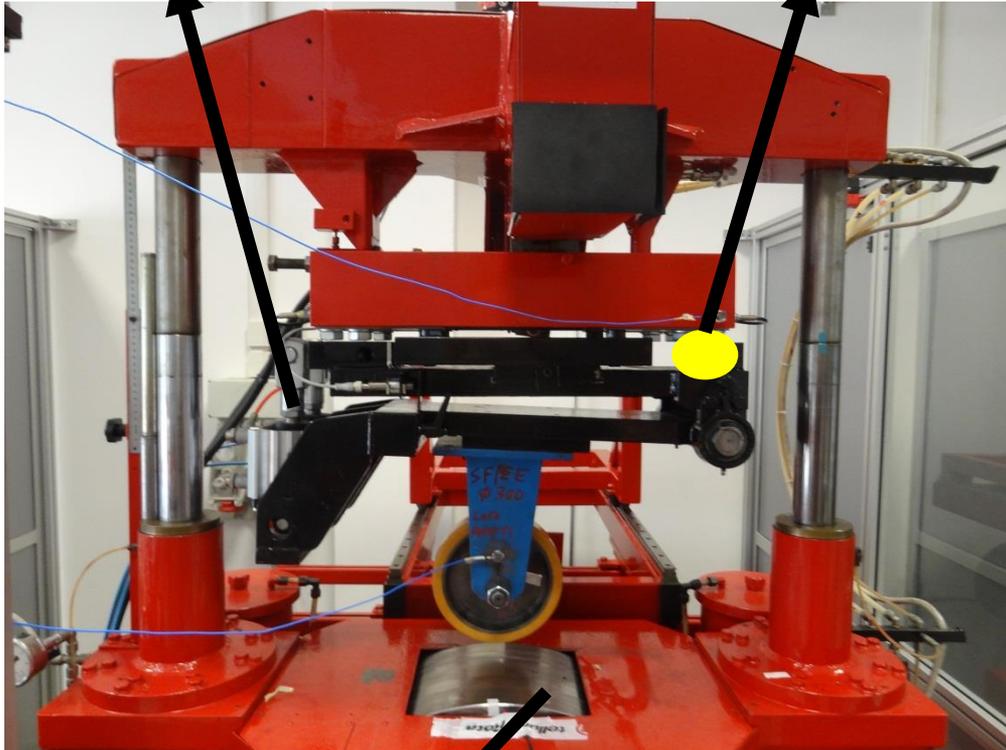
Mozzo in ghisa

- Mancato incollaggio tra battistrada e mozzo;
- Presenza di ruggine sulla superficie del mozzo



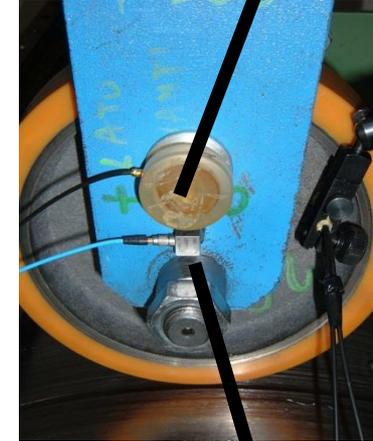
università di ferrara  
DA SEICENTO ANNI GUARDIAMO AVANTI.  
**Attuatori pneumatici**

**Celle di carico**



**Rullo guidato da un motore elettrico comandato da inverter**

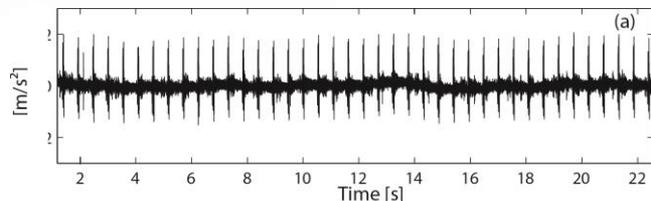
**Sensore di emissione acustica**



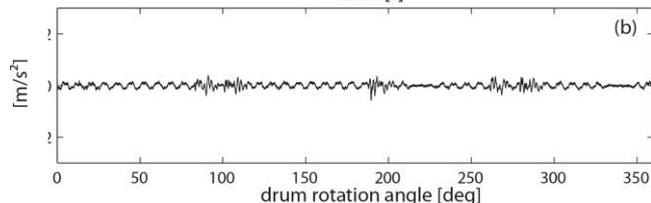
**Accelerometro triassiale**



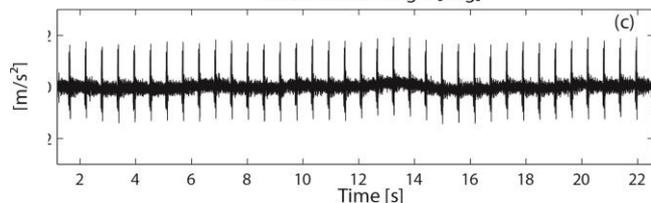
**Microfono**



**Segnale acquisito**



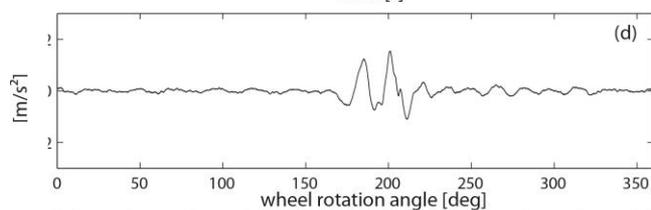
**Segnale mediato con il giro del rullo**



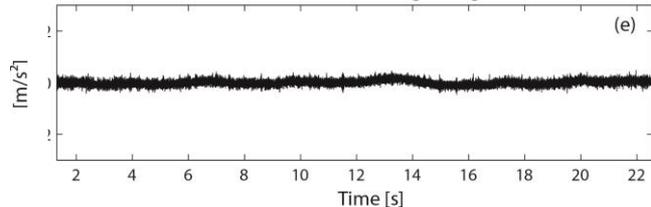
**Segnale depurato dalla periodicità del rullo**



**ANALISI  
CICLOSTAZIONARIETA'  
DEL PRIMO ORDINE**



**Segnale mediato con il giro della ruota**



**Segnale residuo**



**ANALISI  
CICLOSTAZIONARIETA'  
DEL SECONDO ORDINE**

$$K = \frac{1}{M} \sum_{i=1}^{M-1} \frac{(\hat{m}_x [i] - \bar{m}_x)^4}{\sigma^4}$$

$$x_{RMS} = \sqrt{\frac{1}{M} \sum_{i=1}^{M-1} \hat{m}_x^2 [i]}$$

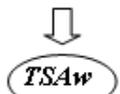
$$ICS_{1x} = \frac{\sum_{\alpha \neq 0} |\hat{C}_{1x}^\alpha|^2}{|\hat{C}_{2x}^0(0)|}$$

$$ICS_{2x} = \frac{\sum_{\alpha \neq 0} |\hat{C}_{2x}^\alpha(0)|^2}{|\hat{C}_{2x}^0(0)|^2}$$

Parametri statistici applicati alla media  
sincrona (Kurtosis, RMS)

Indicatori di ciclostazionarietà del primo e del  
secondo ordine

RAW ACCELEROMETER SIGNAL



IF

KURTOSIS > 5.48 → DEFECT

ELSE IF

KURTOSIS < 5.48

&

RMS < 0.039 m/s

RESIDUAL SIGNAL

&

RMS > 0.039 m/s

DEFECT

$ICS_{2x} < 0.0167$

$0.0167 < ICS_{2x} < 0.0208$

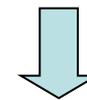
$ICS_{2x} > 0.0208$

HEALTHY

POSSIBLE DEFECT

DEFECT

*I parametri statistici applicati alla media sincrona, valutata sul giro di rotazione della ruota, sono sensibili a difetti di mancato incollaggio di dimensione minima pari a circa 8 mm di estensione circonferenziale*



*L'indicatore di ciclostazionarieta' del secondo ordine permette di evidenziare la presenza di difetti di mancato incollaggio piu' piccoli o difetti di ruggine*

- **SCHEDA ACQUISIZIONE NATIONAL INSTRUMENTS NI 9234**, 24-Bit Sigma-Delta ADCs, 51.2 kS/s Max SampRate, 4 Input Simultaneous, Software Selectable IEPE AC/DC Coupling, Anti-Aliasing Filters, 102 dB Dynamic Range cDAQ-9174, CompactDAQ chassis (4 slot USB)
- **ACCELEROMETRO MODELLO 623C00**, SERIAL NUMBER 10763 ICP ACCELEROMETER IMI SENSITIVITY: 9.7 mV/g, peso 30-40 g - sensibilità 10mV/g - ICP - range frequenza[0.5 10kHz
- **sensori tachimetrici PCB** per la stima della velocità di rotazione delle ruote.

Scheda acquisizione



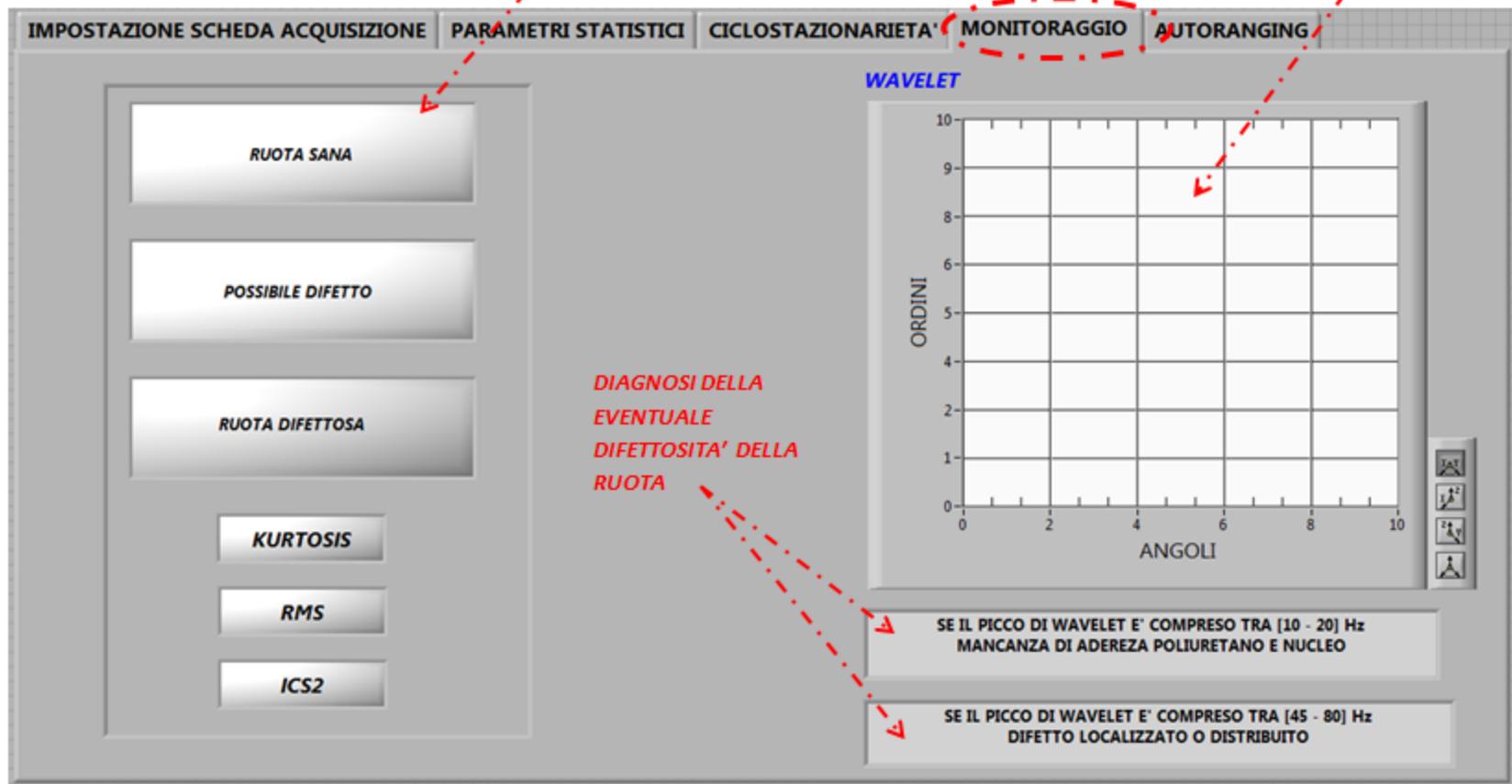
•ACCELEROMETRO INDUSTRIALE



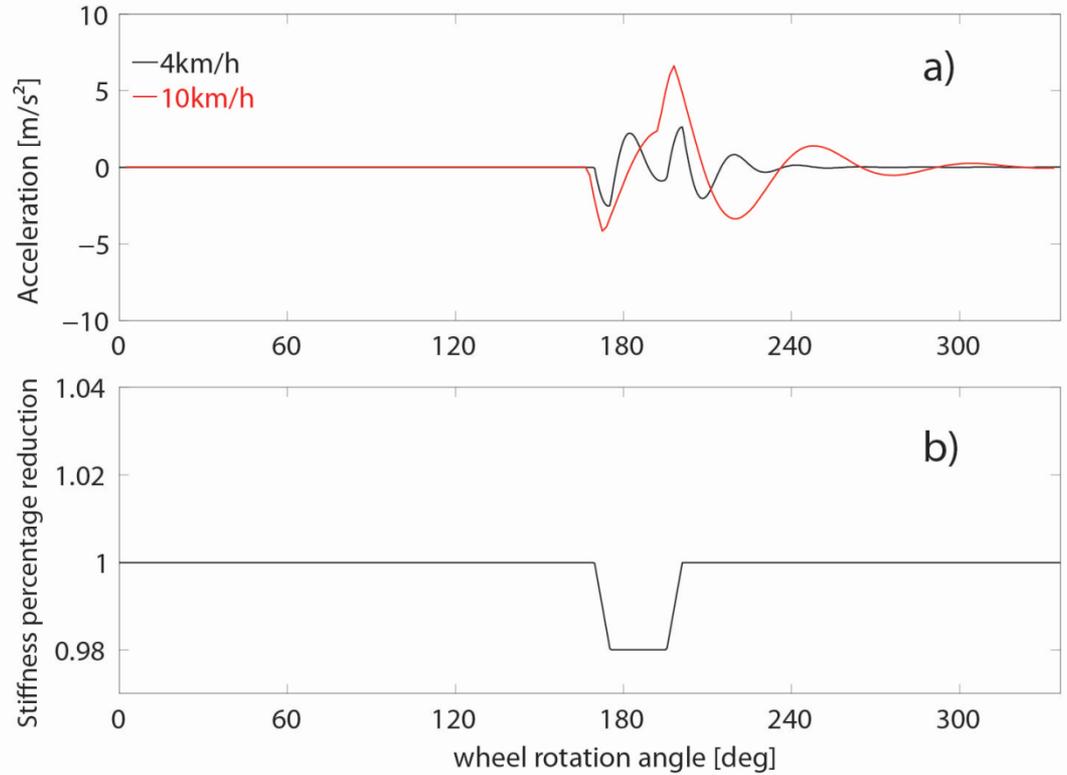
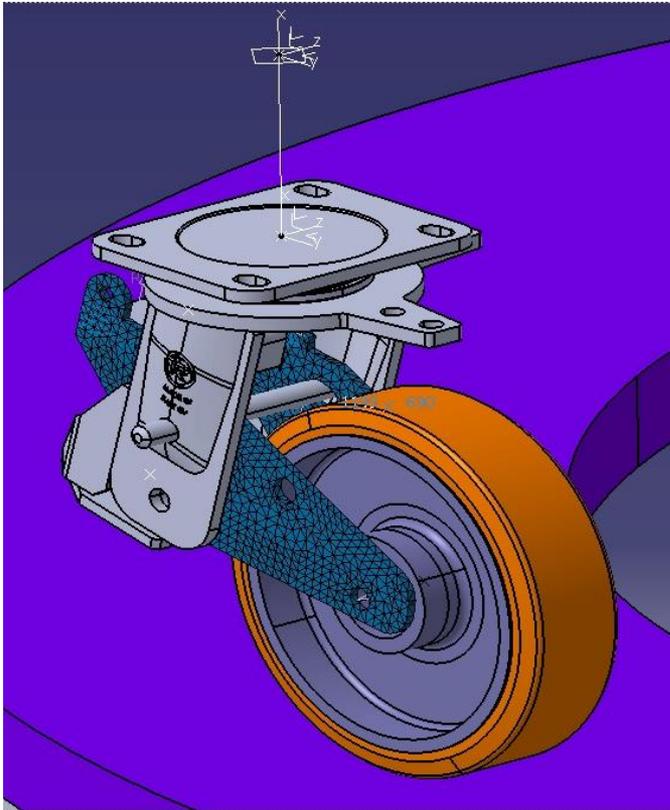
•KIT TACHIMETRICO.



• **MONITORAGGIO:**

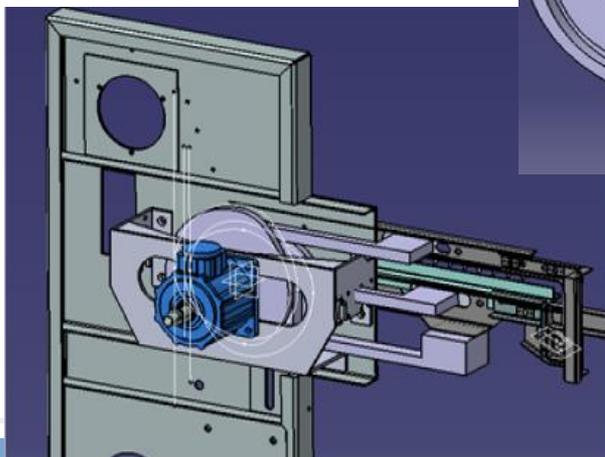
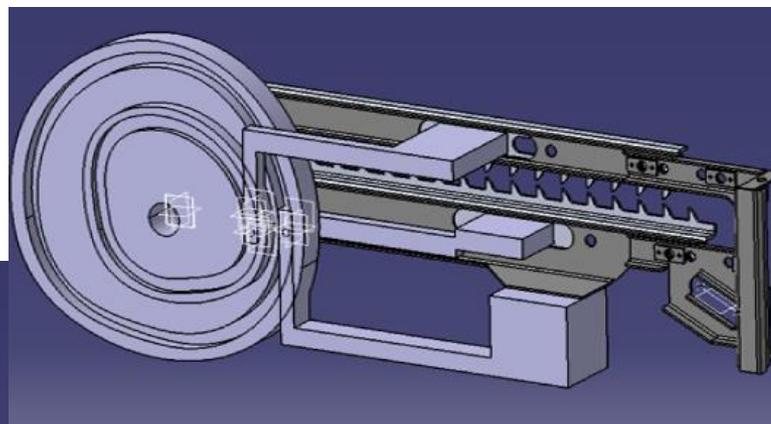


## Model based diagnostics (on-going)



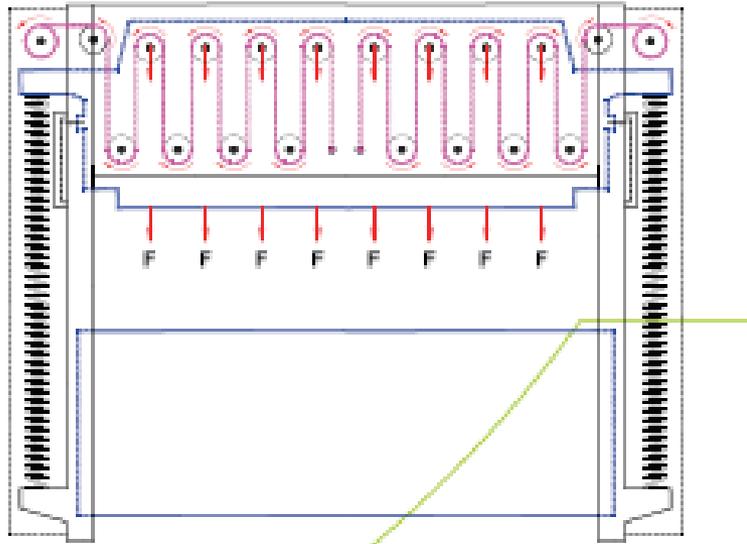
### 3. Progettazione ed analisi di meccanismi/sistemi meccanici (co-progettazione)

**Co-progettazione di sistemi meccanici complessi comprendente ideazione dell'architettura meccanica, analisi cinematica, progettazione degli azionamenti, progettazione e verifica dei componenti, analisi di affidabilità, verifiche sperimentali.**

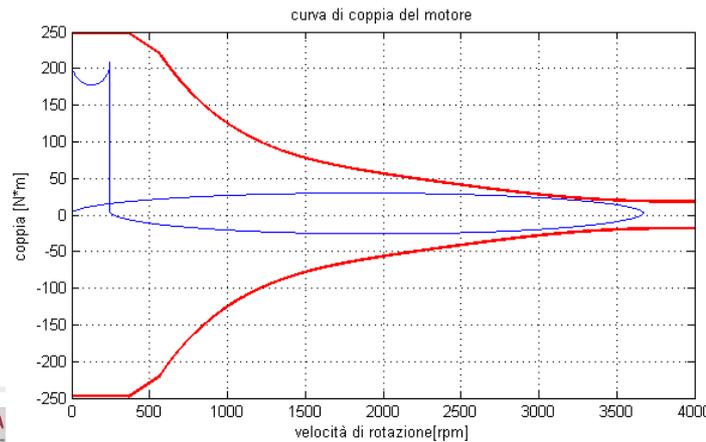


***Progettazione dinamico/vibratoria di meccanismi per trasporto pasta alimentare per ridurre gli effetti inerziali (miglioramento di leggi di moto)***

### 3. Progettazione ed analisi di meccanismi/sistemi meccanici (co-progettazione)



*Progettazione cinematica/dinamica di presse piegatrici per miglioramento di leggi di moto*



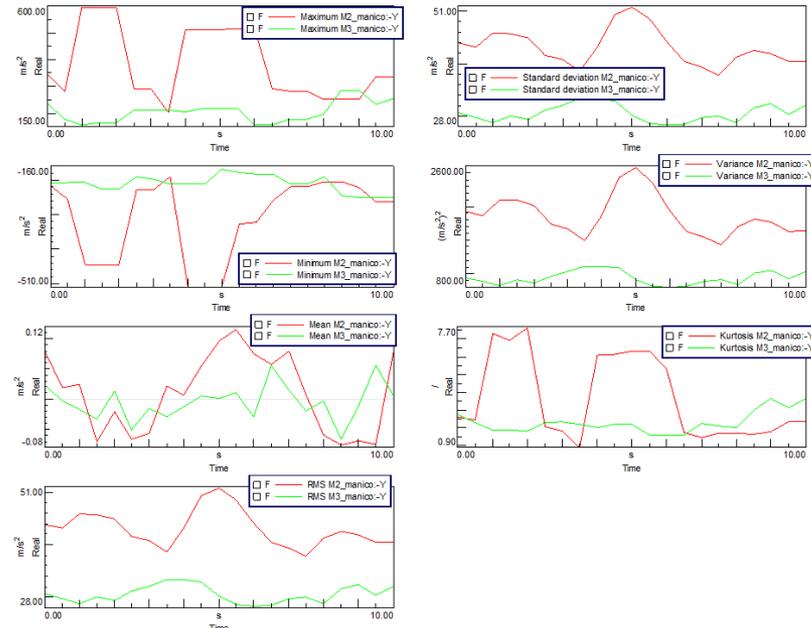
**Obiettivo:** confronto dei livelli vibratori con std cliente.



# Individuazione di soluzioni progettuali migliorative

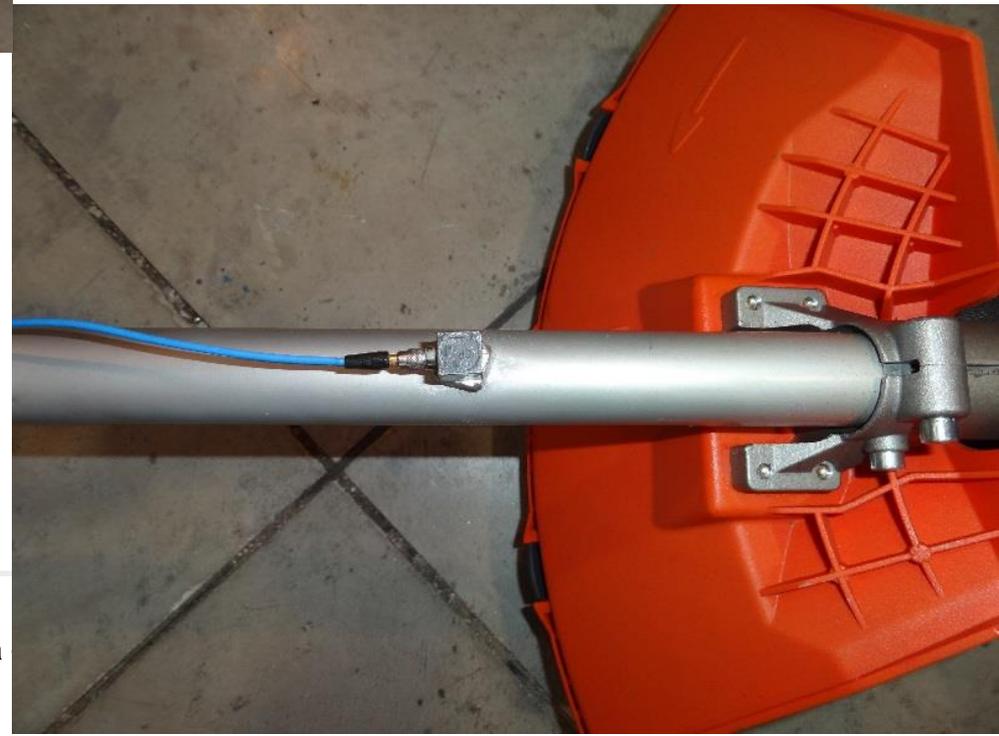
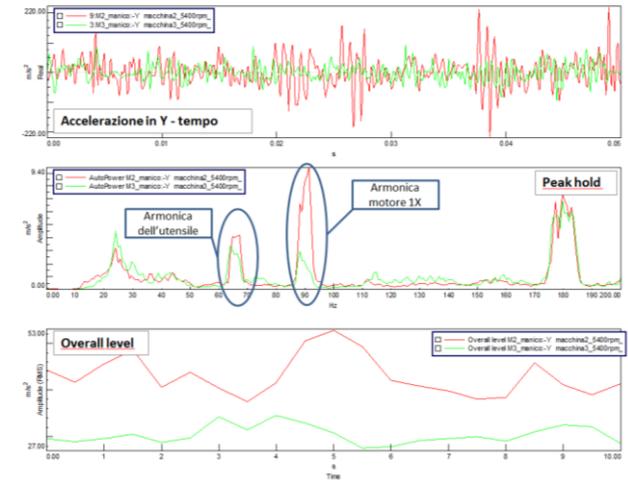


5400rpm – direzione Y del manico



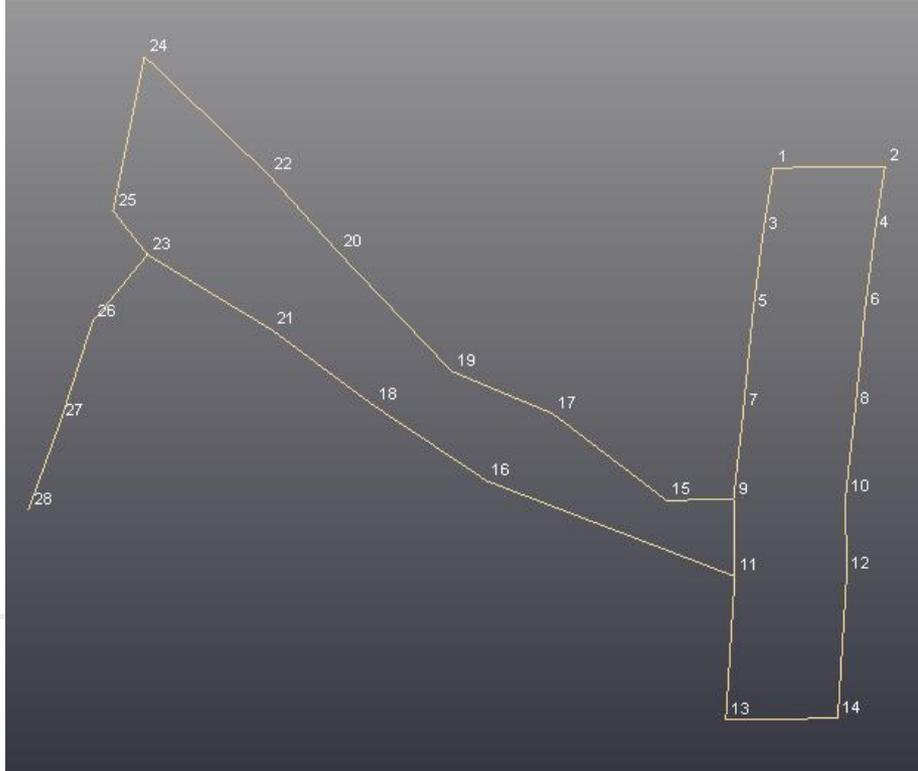
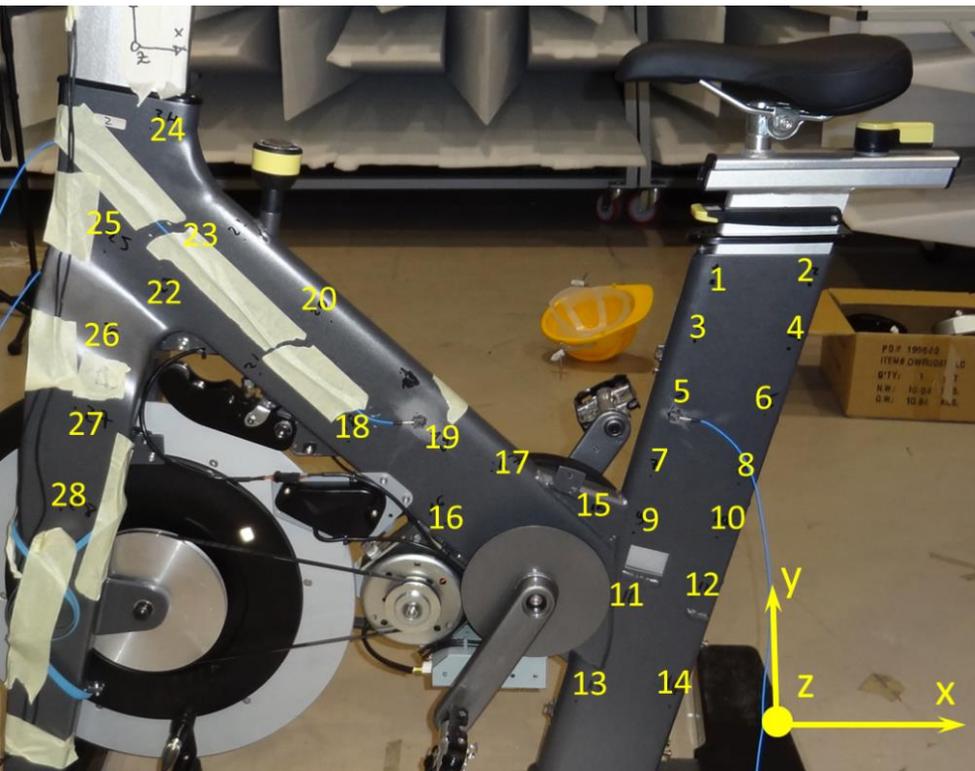
Data

5400 rpm – direzione Y del manico

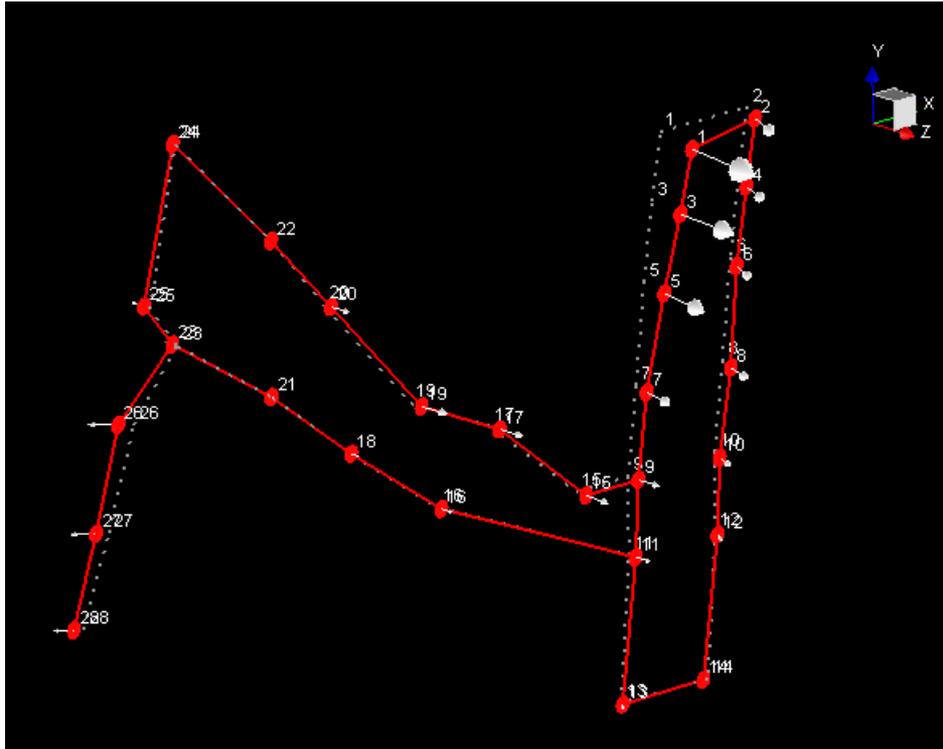


Il telaio e la sella sono stati eccitati mediante martello strumentato misurando la risposta vibratoria con accelerometri triassiali.

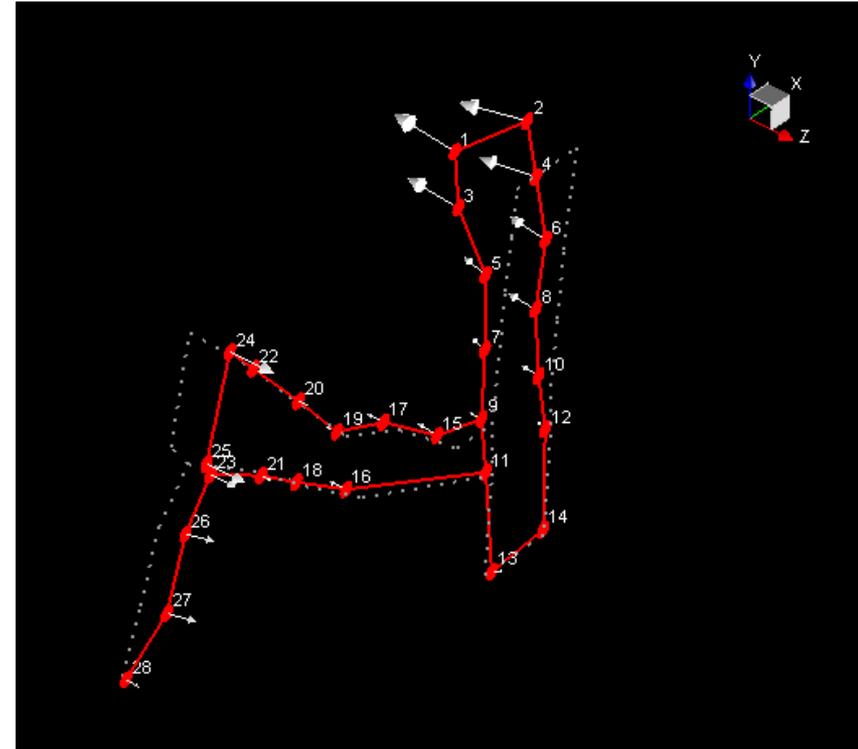
Sono stati eccitati complessivamente 28 punti (punti da 1 a 28) prevalentemente in direzione x e z. La risposta vibratoria è stata misurata in 2 punti (punti 5 e 19).



La forma modale è evidenziata in rosso mentre l'indeformata con il tratteggio grigio. Le frecce indicano la direzione e l'ampiezza relativa dello spostamento.

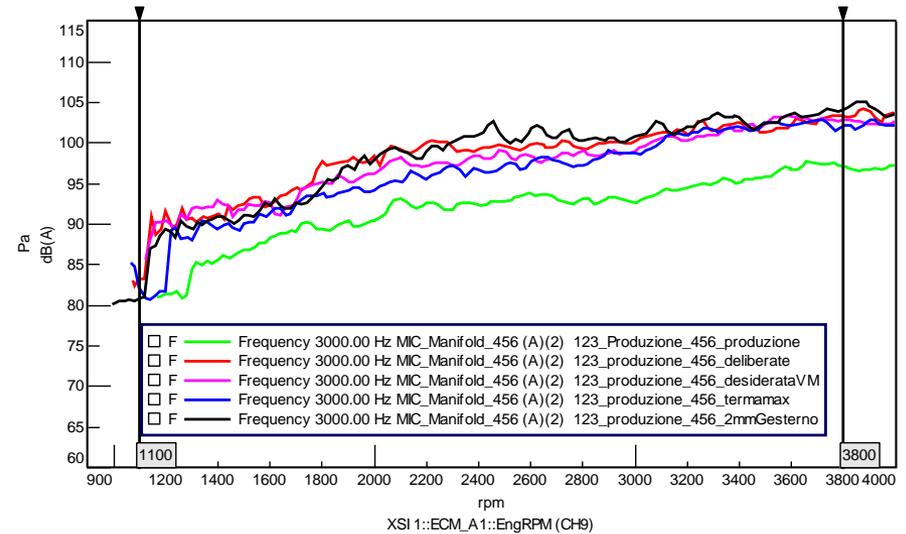
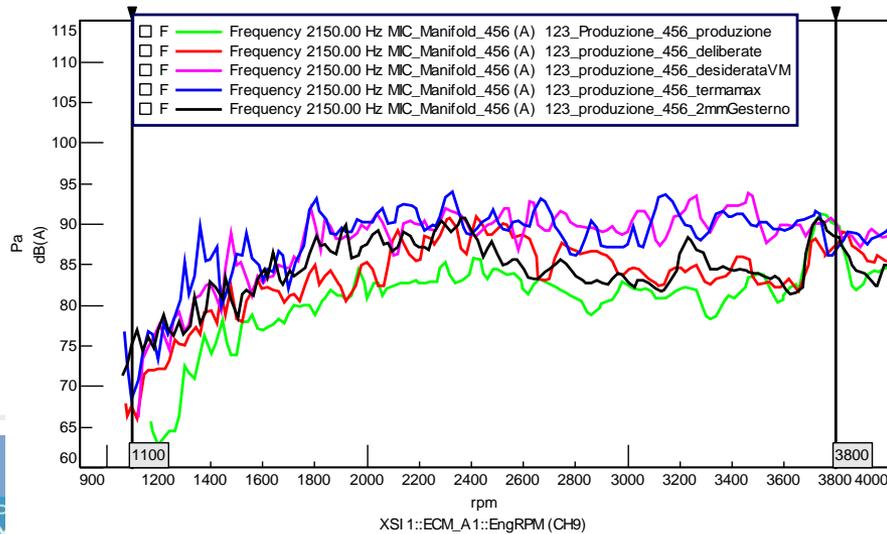


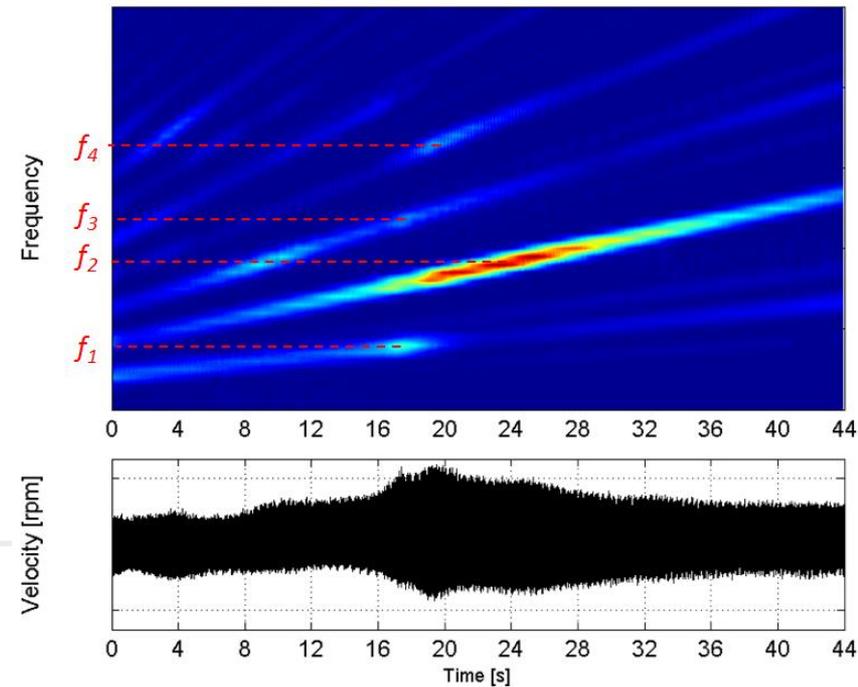
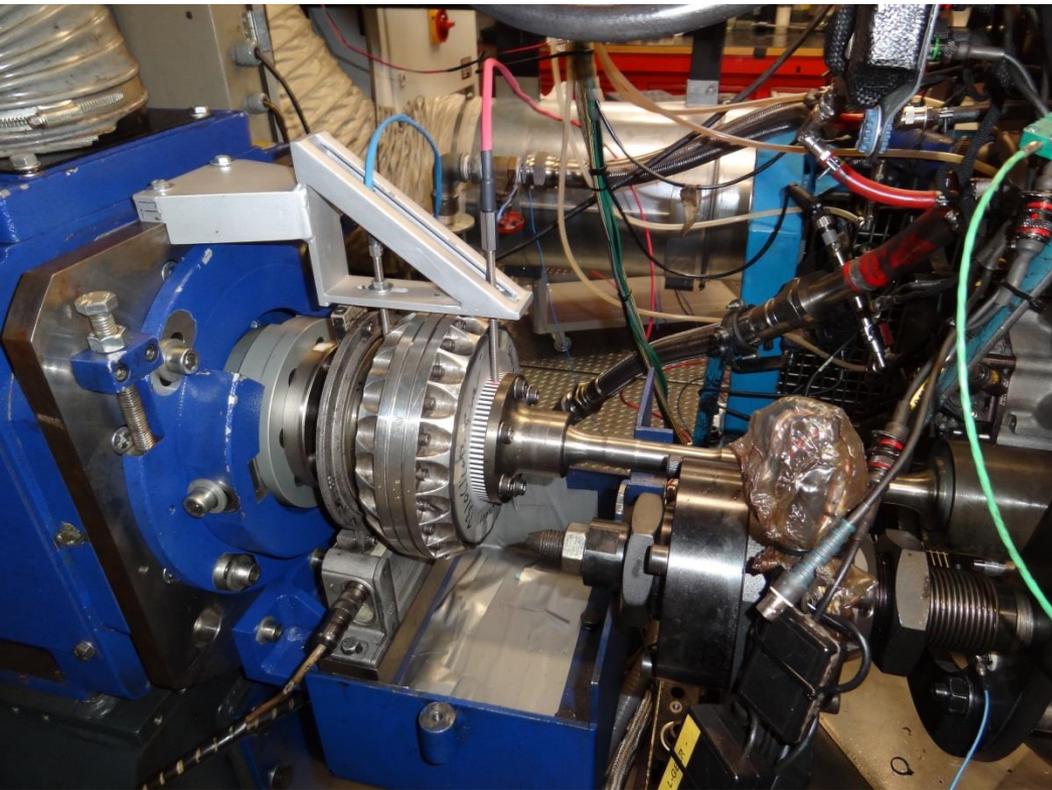
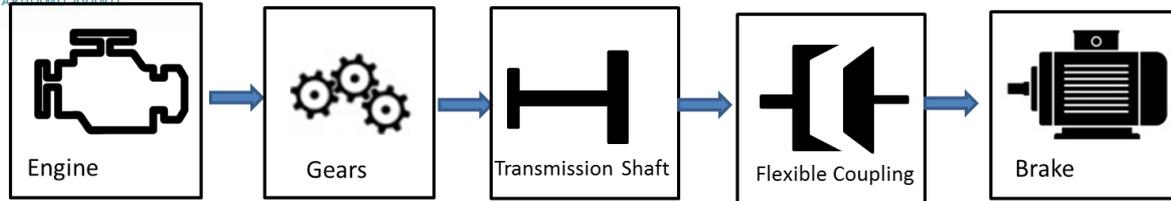
Modo 1: 27.55 Hz  
Spostamento prevalente lungo Z che si intensifica nei punti vicino alla sella e ai pedali.



Modo 2: 127.34 Hz  
Spostamento prevalente lungo Z.

# Verifica di soluzioni progettuali





## Strumentazione disponibile

- Strumentazione completa per analisi modale sperimentale e analisi vibro-acustica (accelerometri, martelli strumentati, shaker)
- Frontali di acquisizione dati da laboratorio e imbarcabili fino a 50 canali
- Software Multibody e ad elementi finiti per la simulazione e ottimizzazione dinamica.
- Banco prova per test di componenti rotanti (giunti, ruote dentate, riduttori, cuscinetti)
- Sensori senza contatto (laser doppler e Microflow)
- Workstation ad alte prestazioni

