Politecnico di Milano

Dipartimento di Meccanica

Matteo Luca Facchinetti

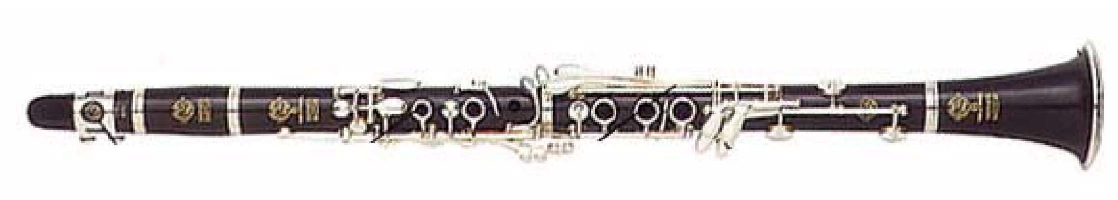
DYNAMIC ANALYSIS OF A B♭ CLARINET

Laboratoire de Mécanique des Solides
École Polytechnique (Paris)

Liste des exposés

B$\flat$ CLARINET

“beating” simple reed



mouthpiece barrel upper part lower part bell

target: dynamic analysis during sound production

Liste des exposés

DEVELOPMENT PLAN

computations FEM modeling → `Castem 2000`

real eigen modes
- sole reed
- reed + mouthpiece + barrel
- reed + clarinet

↓

time domain analysis dynamic

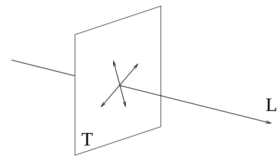
- ☐ **one-side contact reed-mouthpiece**
- ☐ **acousto-mechanical instability (sound production)**

↑

experiments
- eigenfrequencies measurement → *piezo-electric probe*
- eigenmodes visualization → *interferometric holography*

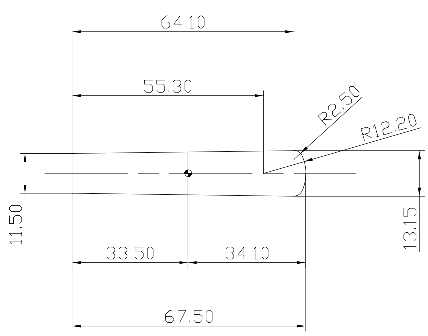
REED

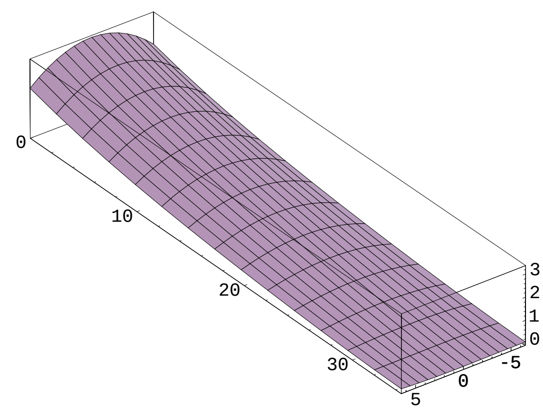
- **material**: homogeneous, elastic, transversely isotropic

$\rho, E_L, E_T, G_{LT}, \nu_{LT}$  (composite)

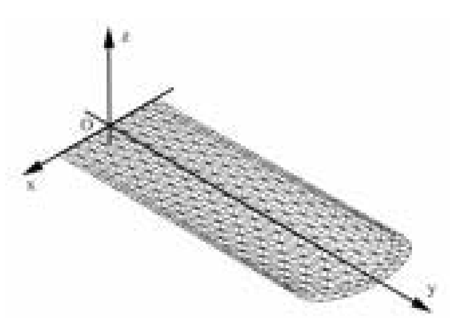
[Laine & Pinard (EP) - 1998]

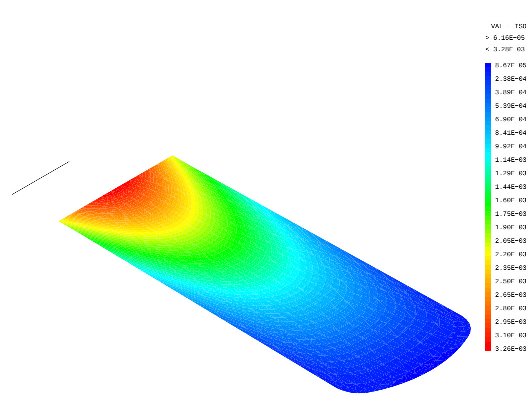
- **geometry**: $\begin{cases} \text{contour} & \rightarrow \textit{profil projector} \\ \text{thickness} & \rightarrow \textit{CMM} + \texttt{Mathematica} \end{cases}$





- **model**: thin plate *(Kirchhoff-Love)*

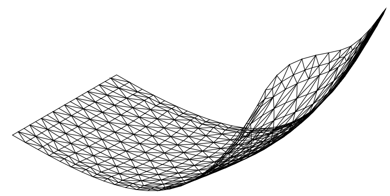


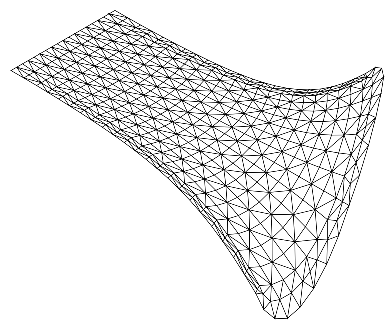


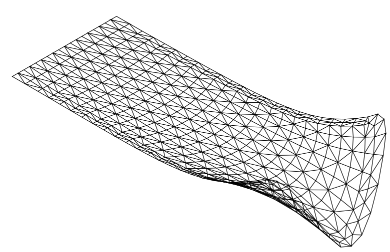
- **bond**: rigidly fixed end section (ligature)

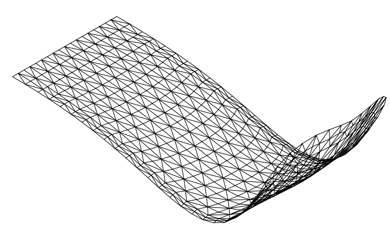
Liste des exposés

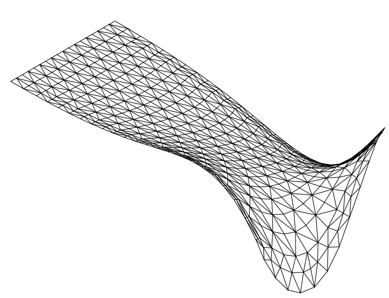
FREE REED
real eigenmodes

2312 Hz  FL

3257 Hz  T

5840 Hz  FT

6214 Hz  FL

7389 Hz  T

Liste des exposés

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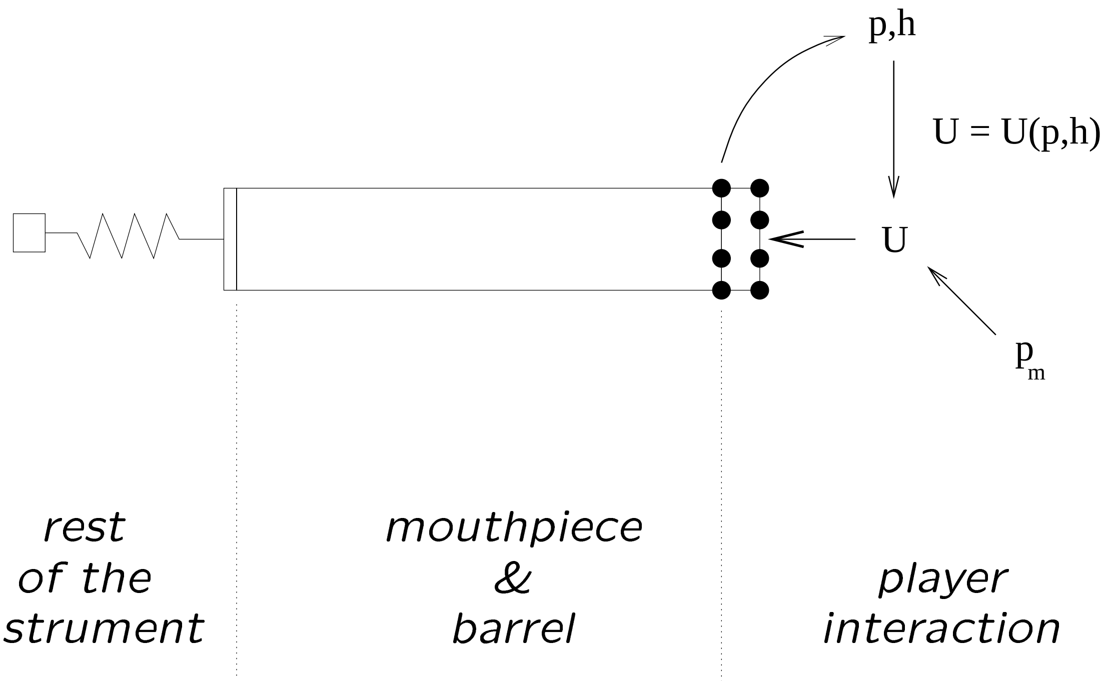
INSTRUMENT

hollow object $\left\{ \begin{array}{l} \text{perfectly rigid solid boundary} \\ \text{chamber = acoustic cavity} \end{array} \right.$



rest of the instrument	*mouthpiece & barrel*	*player interaction*
↓	↓	↓
dashpot system simulator	linear acoustic massive fluid finite elements	boundary conditions

Liste des exposés

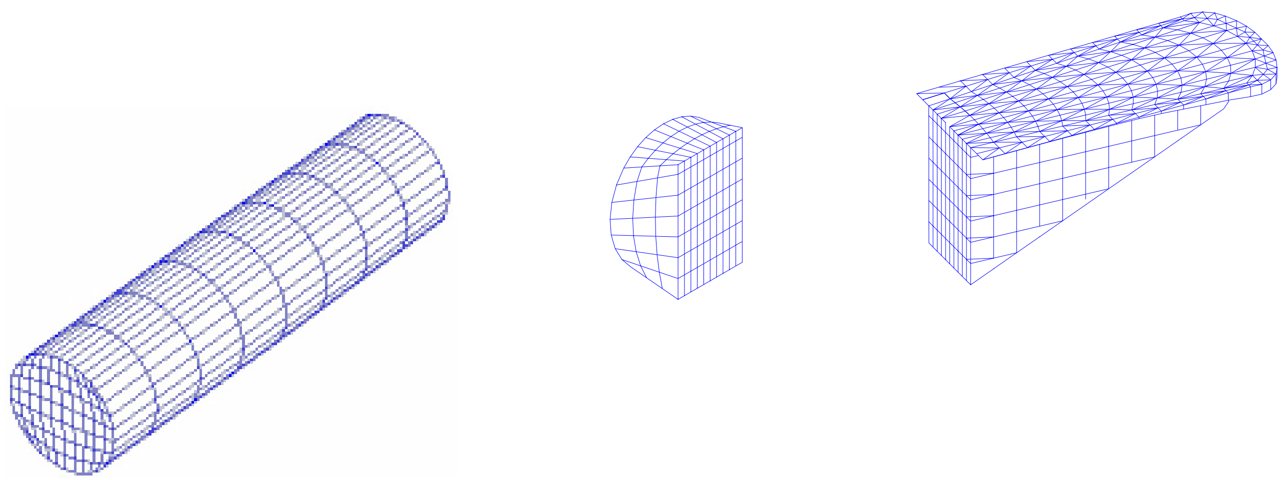
MOUTHPIECE & BARREL

- **material**: wet air, ideal mixture of ideal gases

$$\rho, c = f(T, \varphi) \qquad p_{atm}$$

(p, U) *perturbations with respect to equilibrium*
acoustic linear behaviuor

- **geometry**: *CMM* + manual mesh



- **boundary conditions**:
  - rigid surface: $\frac{\partial p}{\partial n} = 0$
  - free surface: $p = 0$
  - fluid-structure interface: $\begin{cases} \underline{U_s} \cdot \underline{n} = \underline{U} \cdot \underline{n} \\ \underline{\underline{\sigma_s}} \cdot \underline{n} = -p\,\underline{n} \end{cases}$
  - acoustic impedance: $Z_a(\omega) = \frac{p}{U}$

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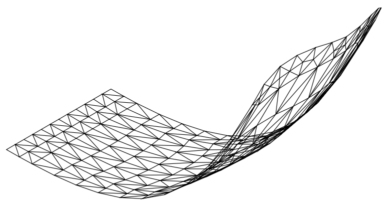
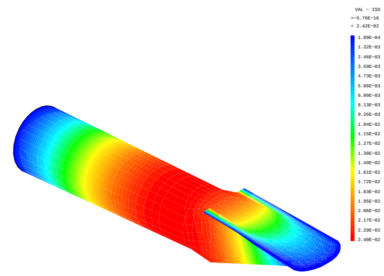
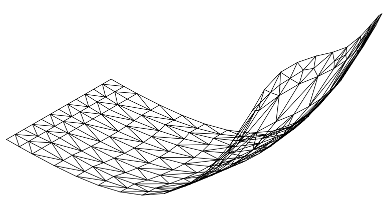
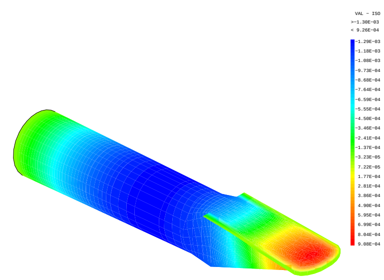
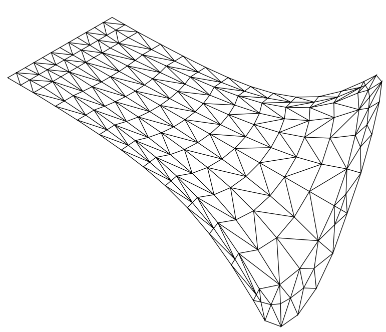
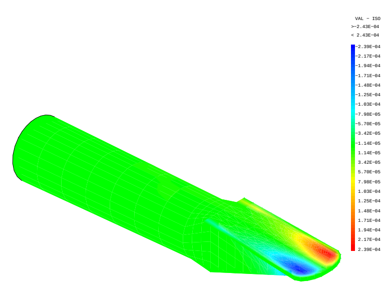
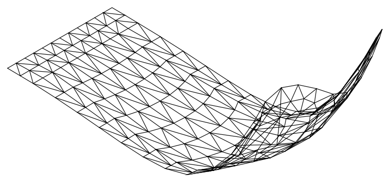
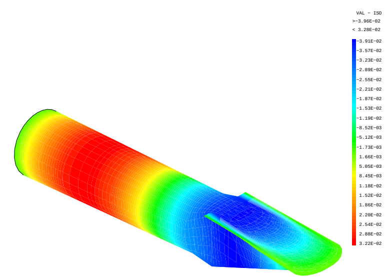
REED + MOUTHPIECE
real eigenmodes (1)

2059 Hz  FL 

2251 Hz  FL 

3239 Hz  T 

4496 Hz  FC 

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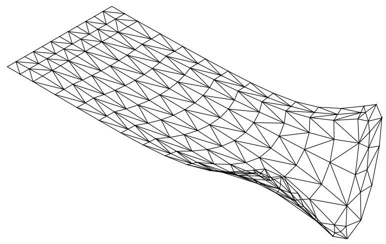
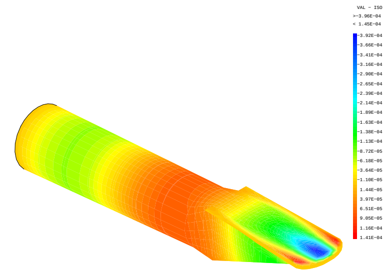
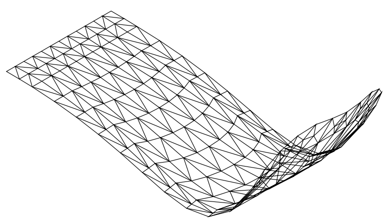
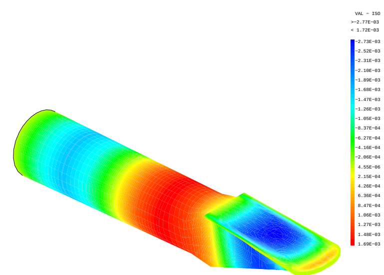
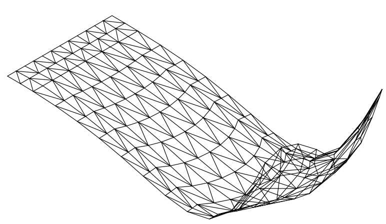
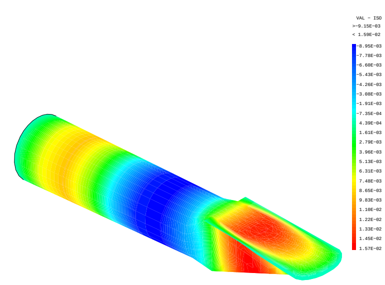
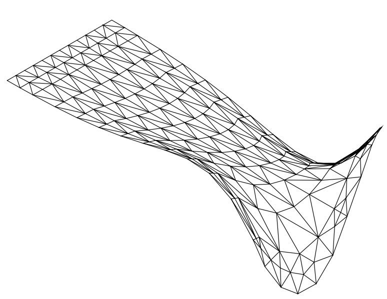
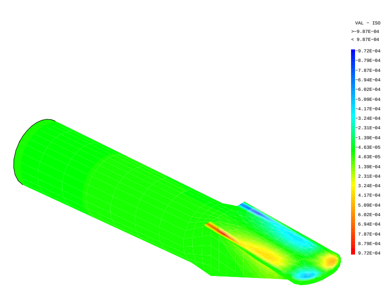
REED + MOUTHPIECE
real eigenmodes (2)

5908 Hz  FT 

6019 Hz  FL 

6709 Hz  FC 

7335 Hz  T 

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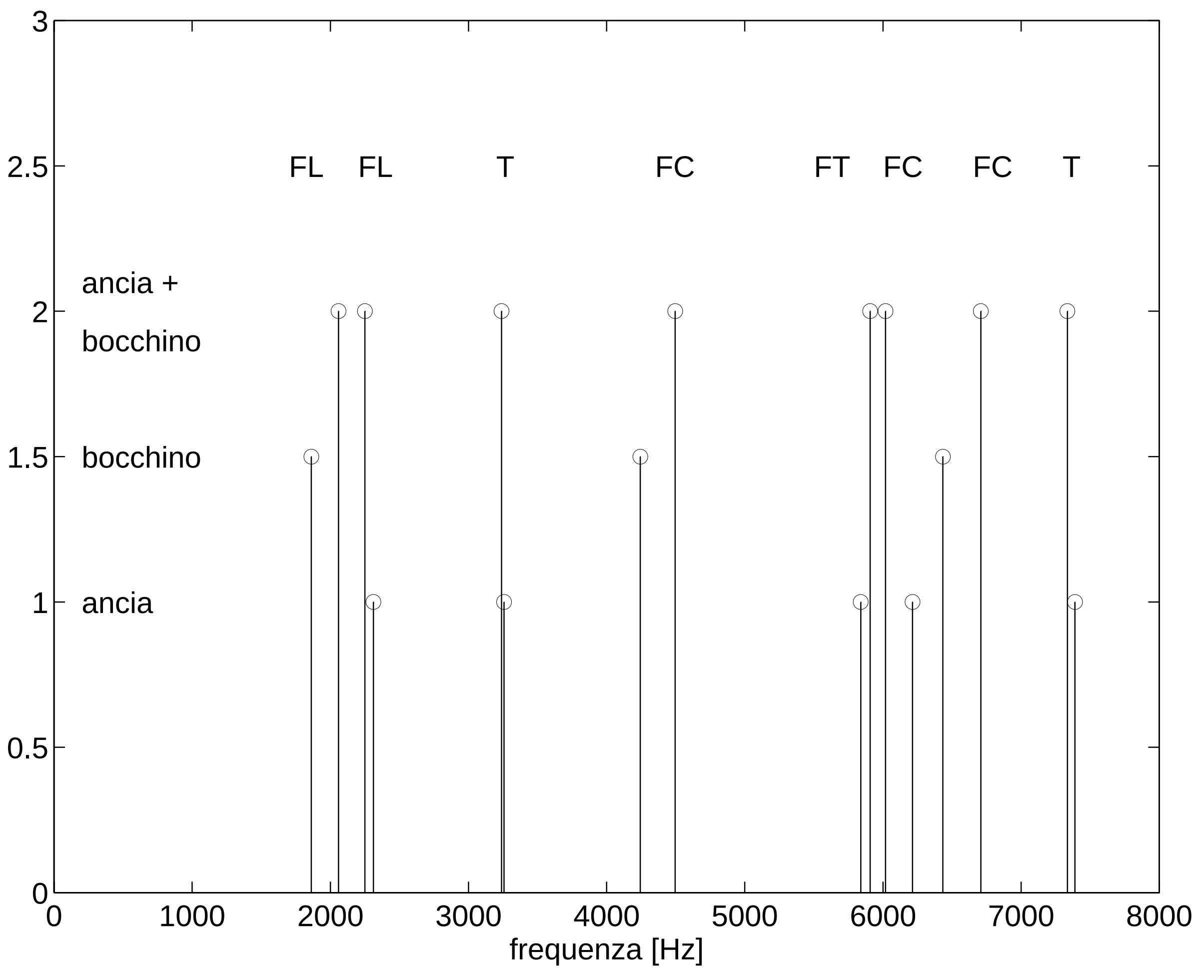
COMPARISON

REED		REED + MOUTHPIECE		MOUTHPIECE
f [Hz]	*eigenmode*	*f [Hz]*	*eigenmode*	*f [Hz]*
		2059	longitudinal flex	1863
2312	longitudinal flex	2251	longitudinal flex	
3257	torsion	3239	torsion	
		4496	“composite” flex	4243
5840	transversal flex	5908	transversal flex	
6214	longitudinal flex	6019	“composite” flex	
		6709	“composite” flex	6433
7389	torsion	7335	torsion	



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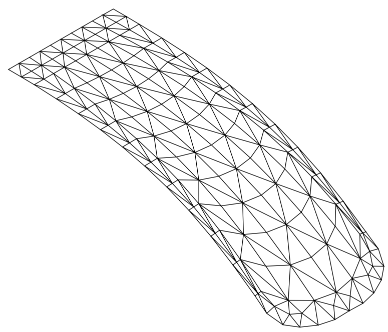
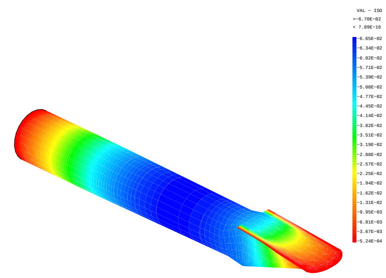
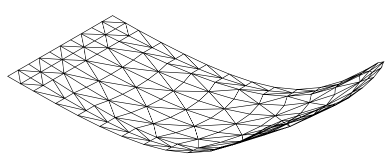
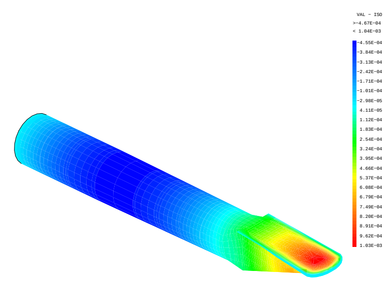
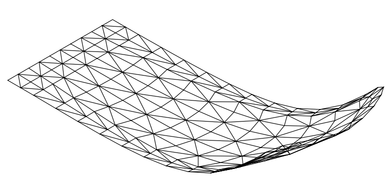
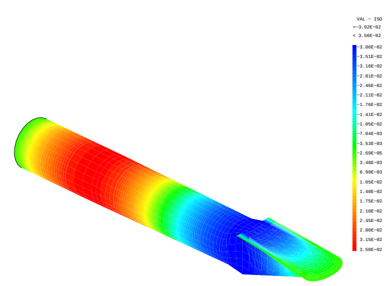
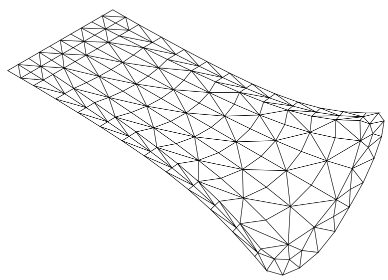
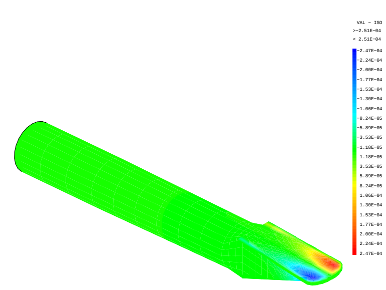
REED + MOUTHPIECE + BARREL
real eigenmodes (1)

1401 Hz  FC 

2228 Hz  FC 

3072 Hz  FC 

3213 Hz  FC 

Liste des exposés

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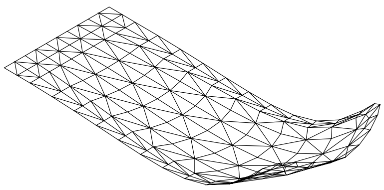
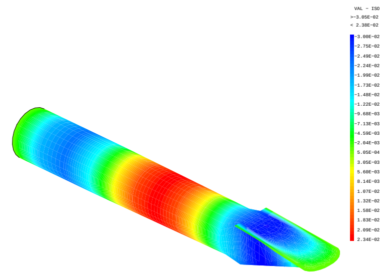
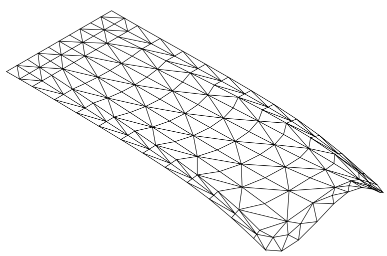
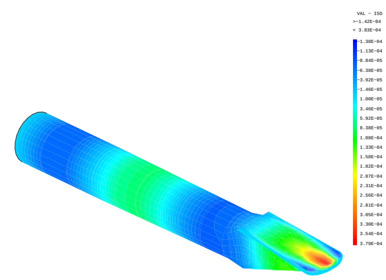
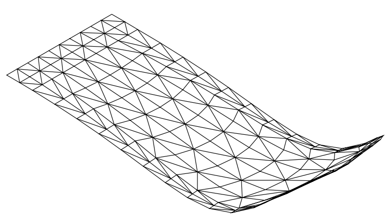
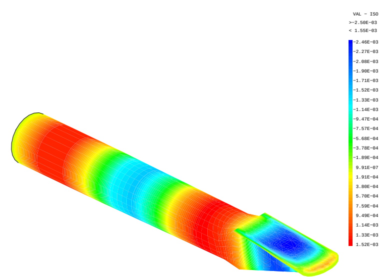
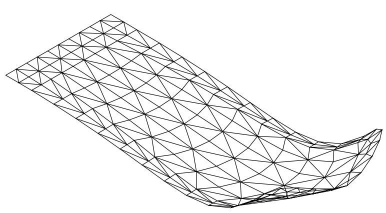
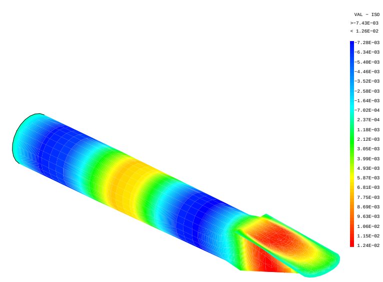
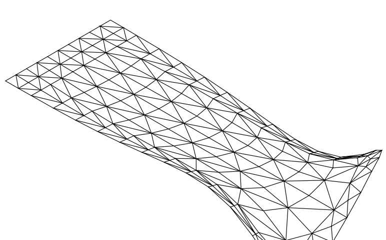
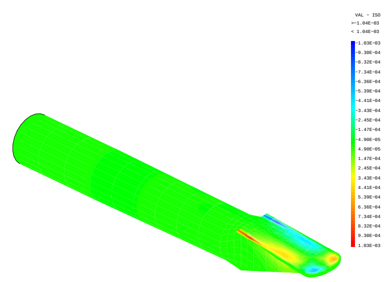
REED + MOUTHPIECE + BARREL
real eigenmodes (2)

4794 Hz  FC 

5897 Hz  FT 

5983 Hz  FL 

6491 Hz  FC 

7294 Hz  T 

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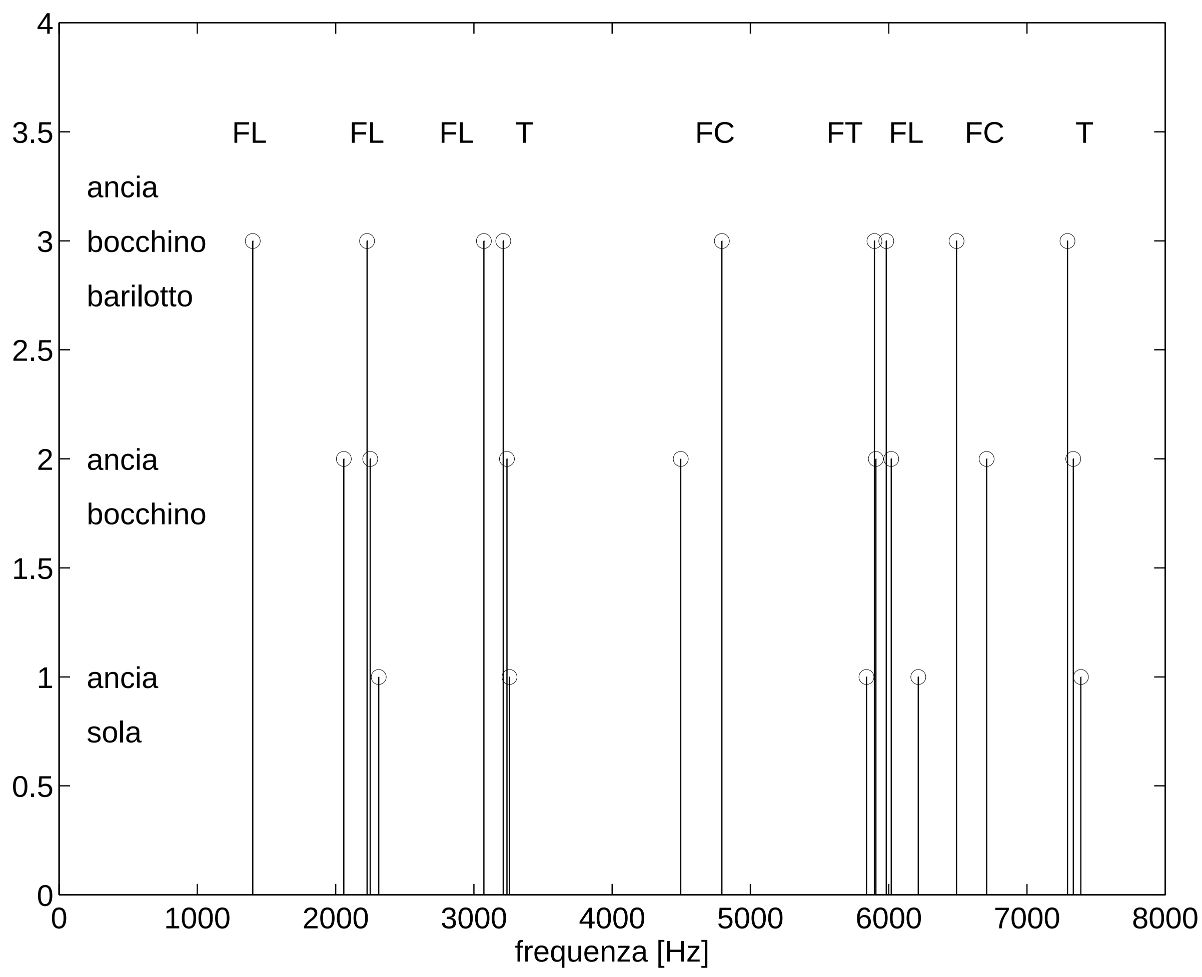
COMPARISON

REED		REED + MOUTHPIECE + BARREL	
f [Hz]	*eigenmode*	*f [Hz]*	*eigenmode*
		1401	longitudinal flex
2312	longitudinal flex	2228	longitudinal flex
		3072	longitudinal flex
3257	torsion	3213	torsion
		4794	"composite" flex
5840	transversal flex	5897	transversal flex
		5983	longitudinal flex
6214	longitudinal flex	6491	"composite" flex
7389	torsion	7294	torsion



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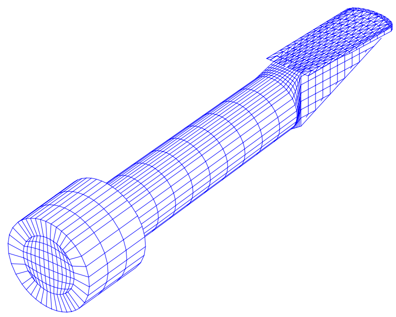
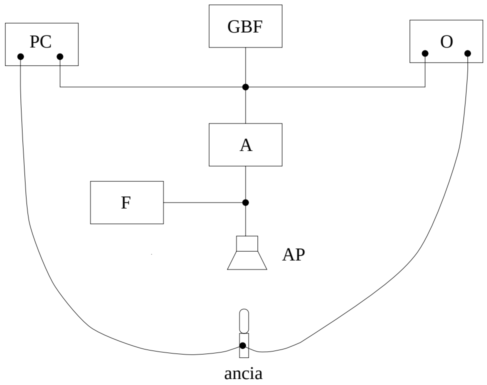
EXPERIMENTAL VALIDATION

- **model:** reed + mouthpiece + barrel

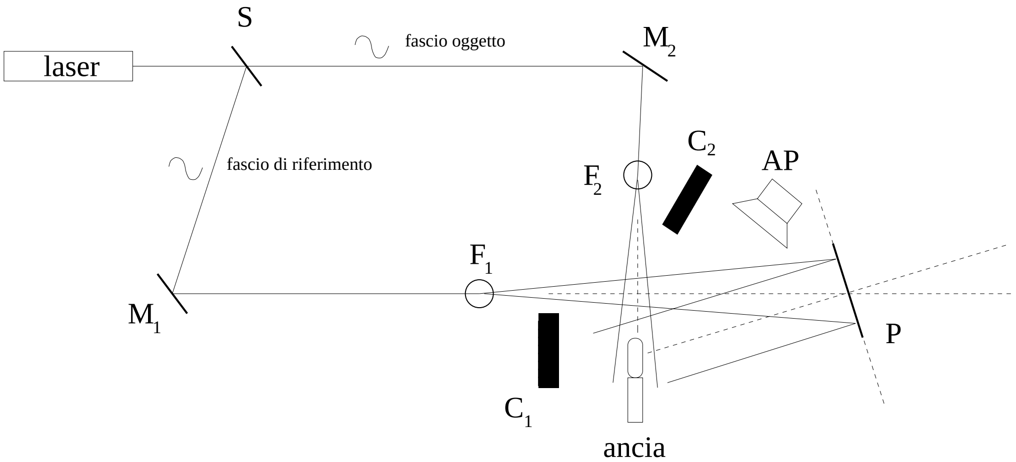


limited reed oscillations → no contact on mouthpiece lay

- **eigenfrequencies:** piezo-electric probe



- **eigenmodes:** interferometric holography



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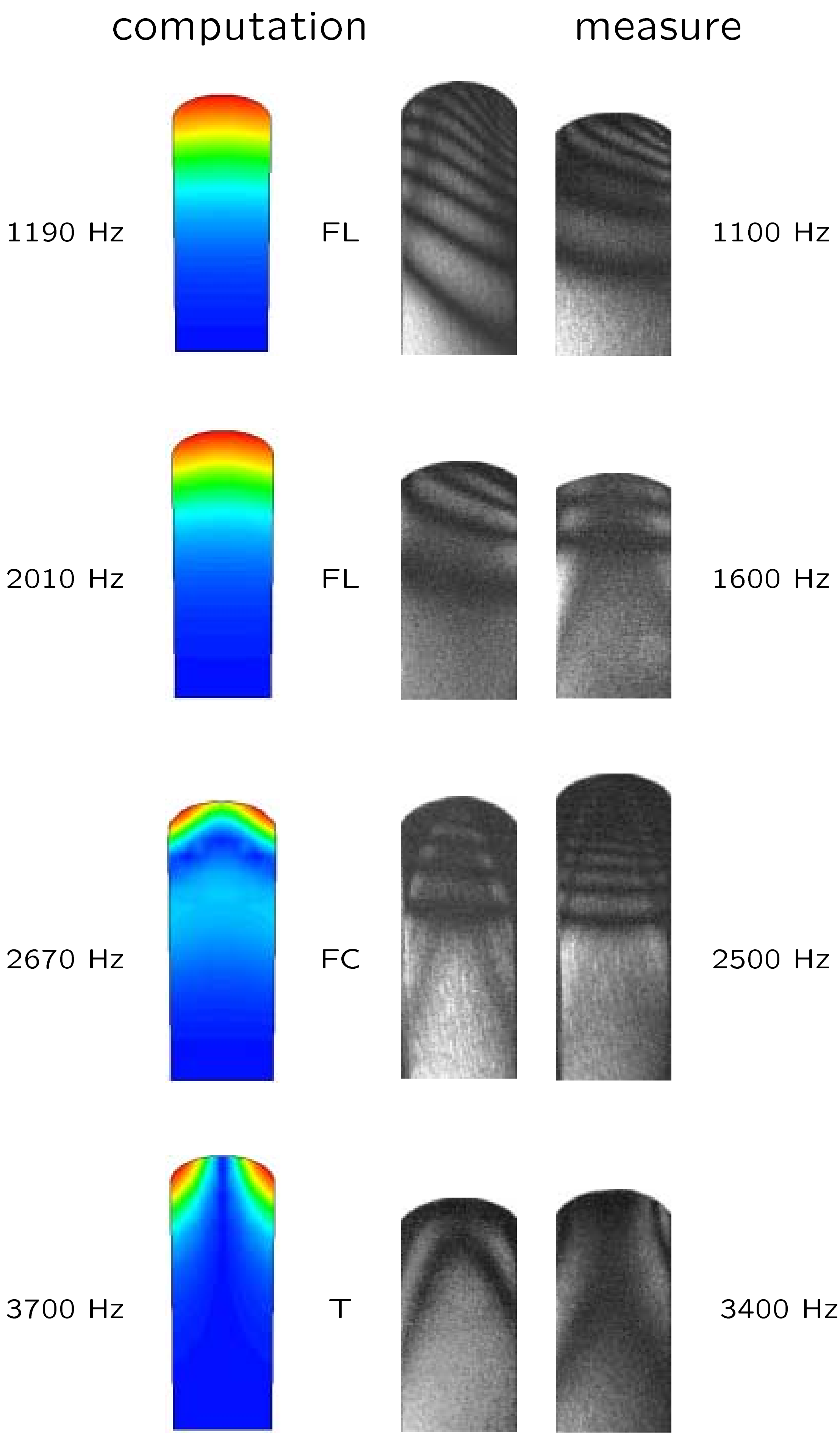
COMPARISON



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$$\lambda = 0.6328\,\mu m$$

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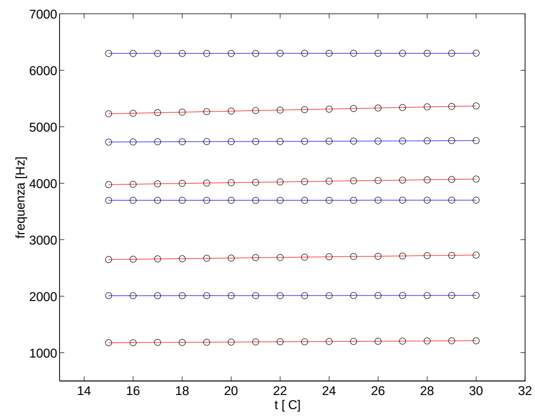
SENSIBILITY ANALYSIS

- **wet air physical properties:** $\rho, c = f(T, \varphi)$

mode	type	$\frac{Hz}{°C}$
8	FT	0.2
7	FL	9.2
6	FC	1.6
5	FC	6.4
4	T	0.1
3	FC	5.3
2	FL	0.4
1	FL	2.4

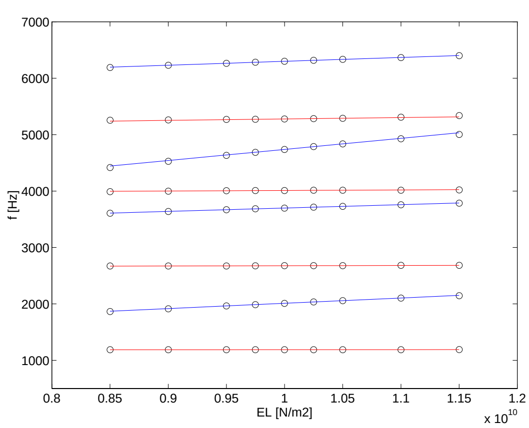
$\varphi = 1$

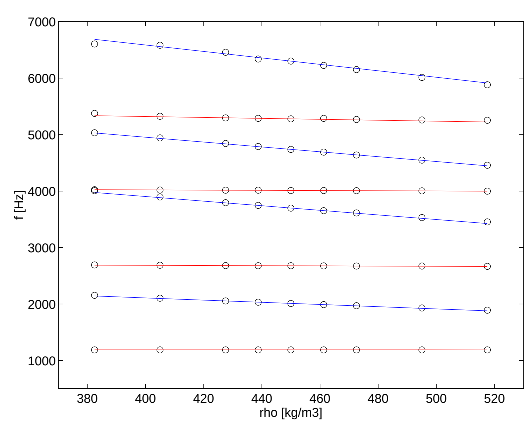
p_{atm}



- **reed mechanical properties**

$\Delta = 10\%$	E_L	E_T	G_{LT}	ν_{LT}	ρ
mean values	10e4 MPa	400 MPa	1300 MPa	0.22	450 $\frac{kg}{m^3}$
FL	2.3%	<0.05%	<0.05%	<0.05%	-2.2%
FC	4.9%	<0.05%	<0.05%	<0.05%	-4.5%
FT	1.7%	0.9%	4.9%	<0.05%	-4.8%
T	1.4%	0.1%	3.1%	<0.05%	-6.4%





- **cavity geometry** $\left\{ \begin{array}{l} 1\, mm \rightarrow 1\% \\ \alpha = 0° \div 25° \\ \text{“mouthpiece” mode 2230 Hz} \end{array} \right.$

Liste des exposés

REST OF THE INSTRUMENT

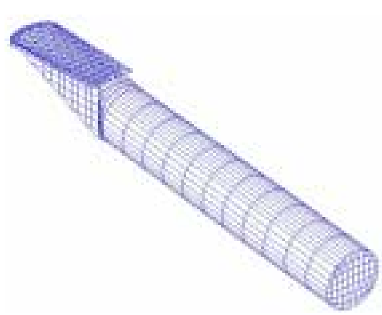
- **problem**: massive FEM model not efficient

$$\left\{ \begin{array}{c} \textit{computationally expensive} \\ \textit{1 note} \Leftrightarrow \textit{1 model} \end{array} \right.$$

- **idea**: impedance simulation by dashpot system

$$Z_m(\omega) = \frac{f}{x} \qquad Z_m(\omega) = S^2 \cdot Z_a(\omega) \qquad Z_a(\omega) = \frac{p}{U}$$

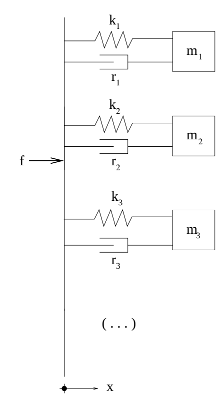
useful adaptability



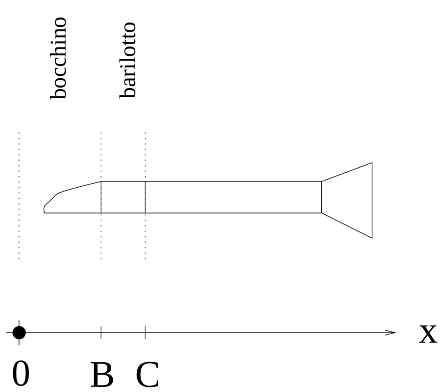
1D hypothesis

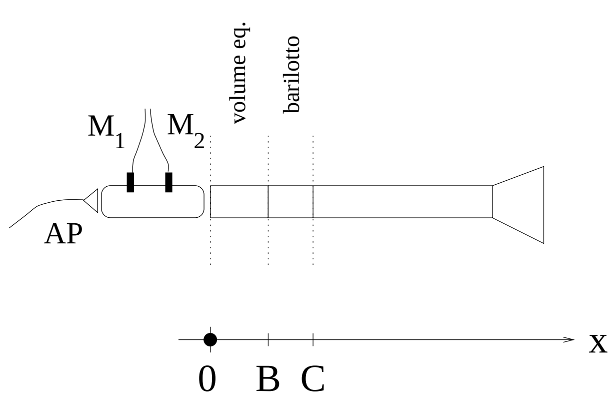
eigenmode analysis

∀ note



- **measures**: *[Vincent Gibiat (ESPCI) - 1998]*



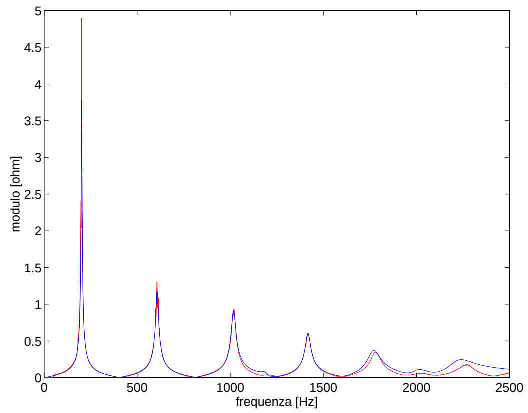


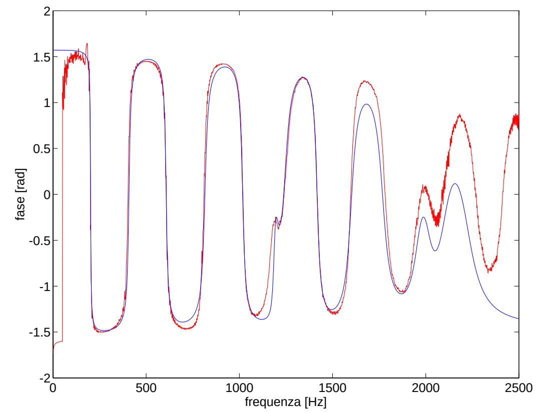
  - mouthpiece volume correction
  - analytic transformation: $Z_a(O) \rightarrow Z_a(C)$

Liste des exposés

IDENTIFICATION

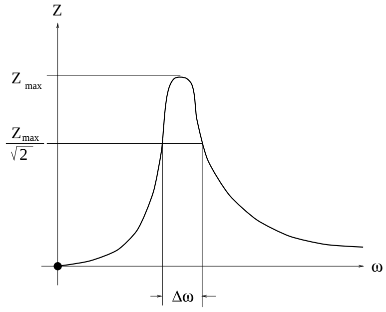
Matlab



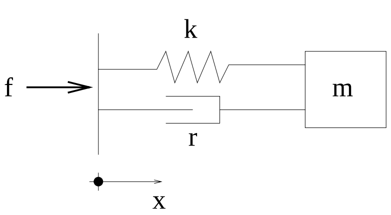


- **preliminary data analysis** $\left\{\begin{array}{l}\text{filtering } \textit{(splines)} \\ \text{phase correction} \\ \text{incomplete parts}\end{array}\right.$

- **single dashpot parameters: initial estimation**



eigenmode analysis



- **error function minimization**

$$E = \int_{\Omega} |f_{sperimentale}(\omega) - f_{calcolata}(\omega)|^2 d\omega$$

$$\begin{cases} E = \alpha\, E_{modulo} + \beta\, E_{fase} \\ \alpha + \beta = 1 \qquad 0 \leq \alpha, \beta \leq 1 \end{cases}$$

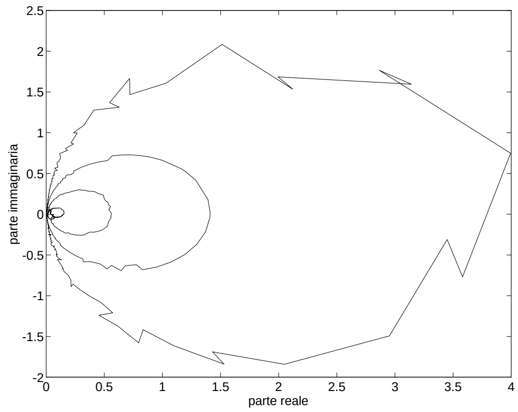
algorithm *Simplex Search - Nelder Mead*

Liste des exposés

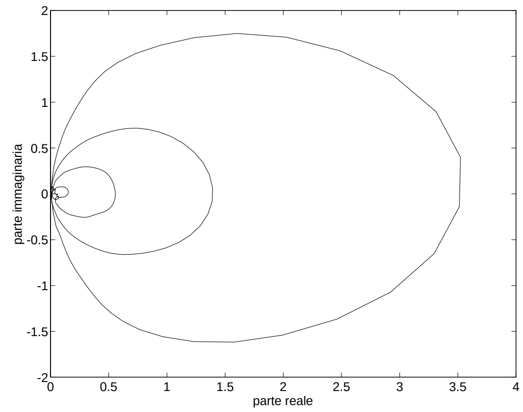
*

THOROUGH ANALYSIS

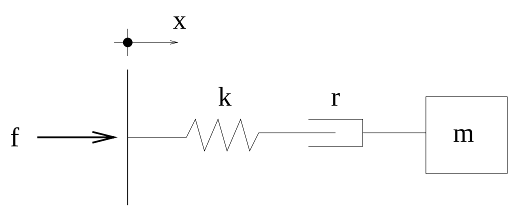
- **smoothing:** *cubic splines* (`Matlab`)



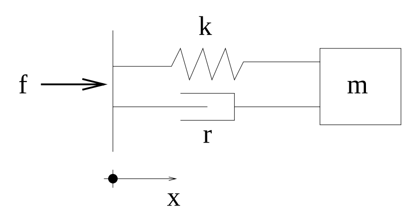
$\Rightarrow$



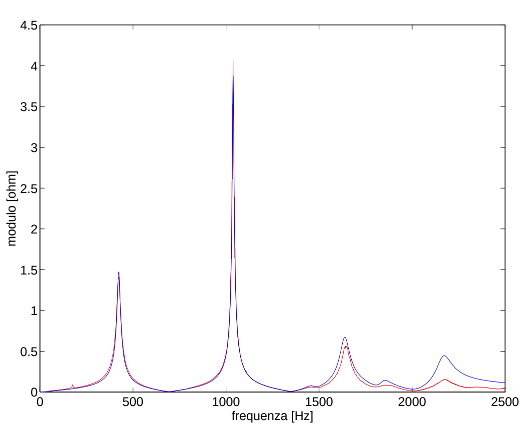
- **system transformation:** *chain* $\rightarrow$ *comb*

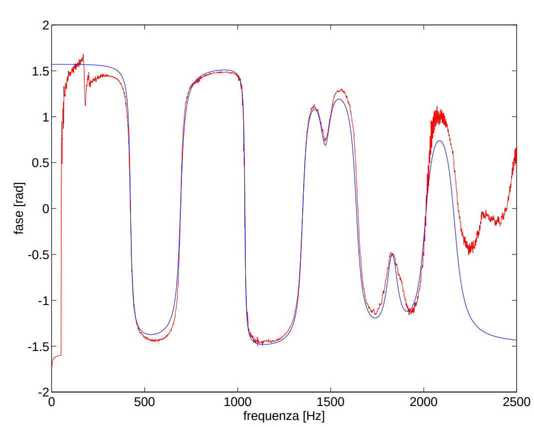


$\Rightarrow$



- **progressive opt.** $\left\{ \begin{array}{ll} \text{frequency domain} & \Delta f \uparrow \\ \text{module Vs phase} & \alpha \downarrow \end{array} \right.$



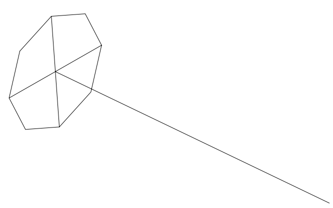


Liste des exposés

*

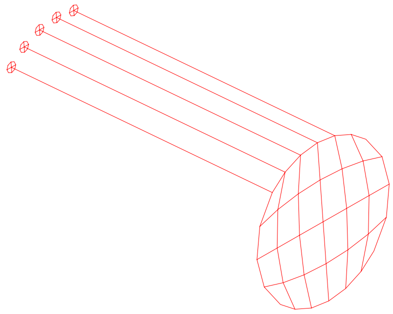
NUMERIC IMPLEMENTATION

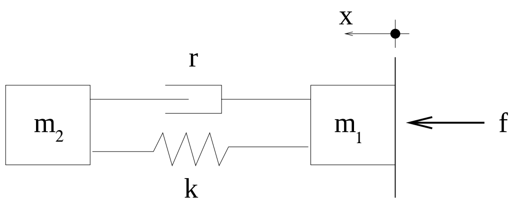
- **single dashpot** $\left\{ \begin{array}{ll} \text{mass} & \to \text{plate} \\ \text{stiffness} & \to \text{bar} \\ \text{damping} & \to \text{analytic} \end{array} \right.$



$$\frac{m_{plate}}{m_{bar}} \geq 10^3 \quad \Rightarrow \quad \Delta < 1\%$$

- **interface connection** $\left\{ \begin{array}{l} \text{dashpot system} \\ \\ \text{acoustical cavity} \end{array} \right.$



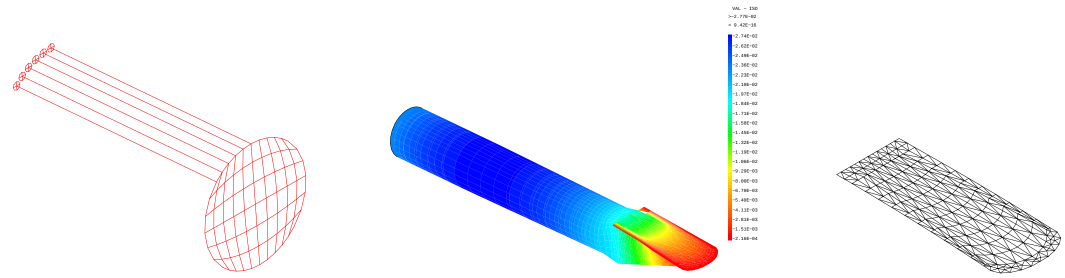


$$m_{connection} \leq 1.7 \cdot 10^{-8}\, kg \quad \Rightarrow \quad \Delta < 1\%$$

Liste des exposés

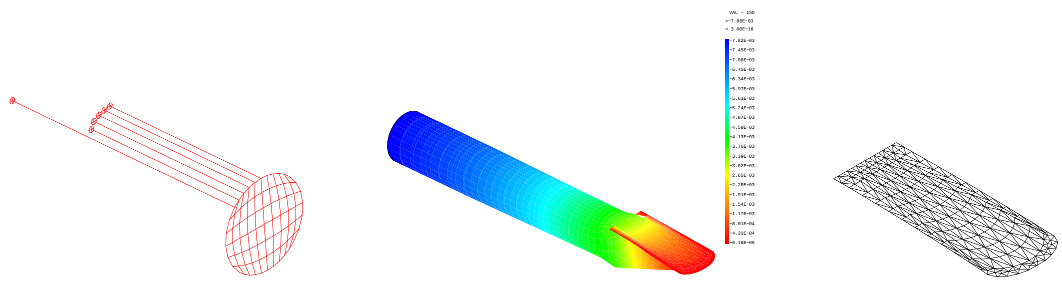
REED + INSTRUMENT
real eigenmodes (1)

0 Hz



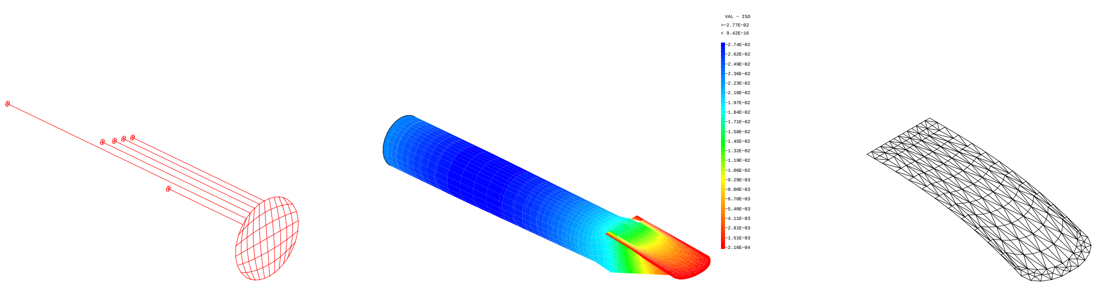
R

464 Hz



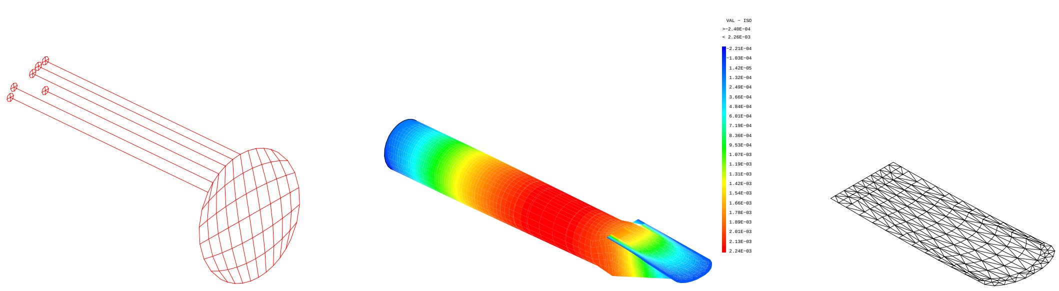
FL

873 Hz



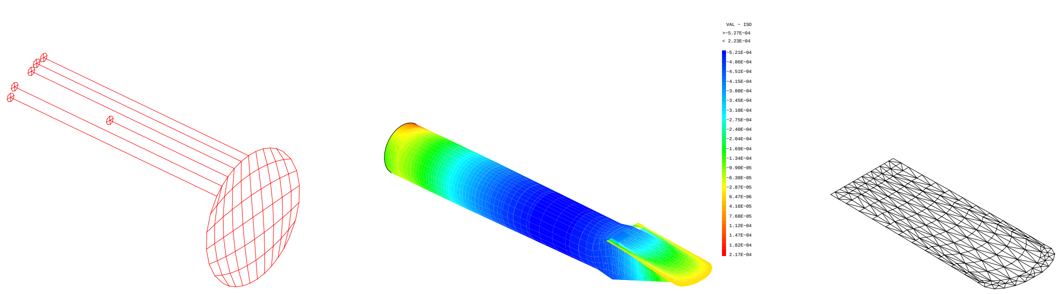
FL

1334 Hz



FL

1438 Hz

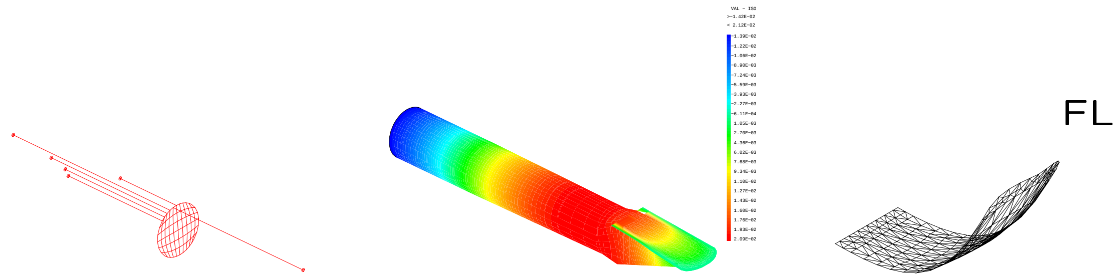


FL

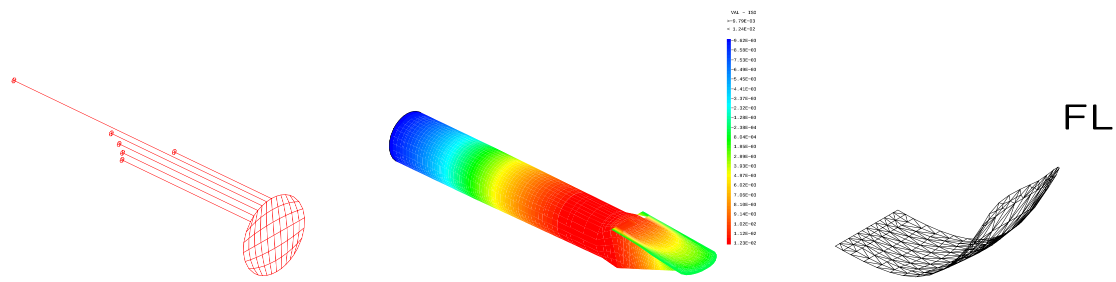
Liste des exposés

REED + INSTRUMENT
real eigenmodes (2)

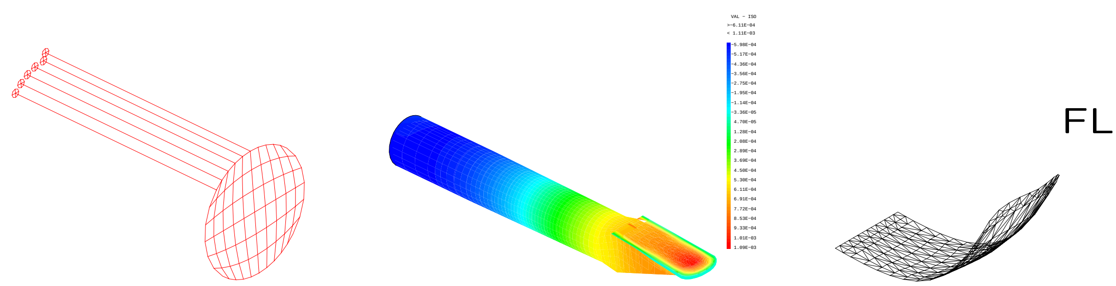
1767 Hz



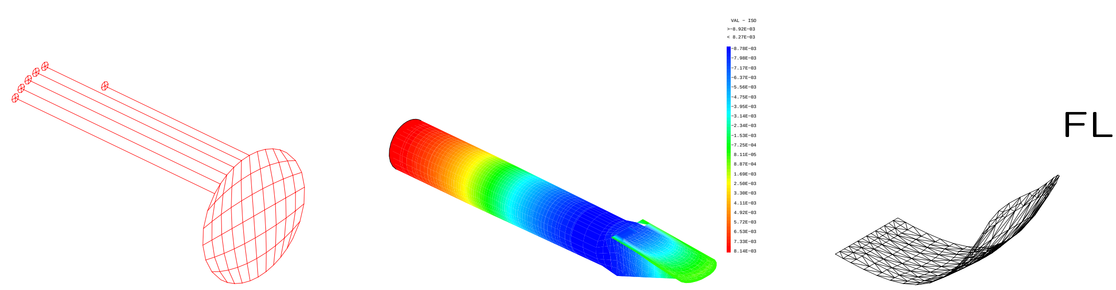
1864 Hz



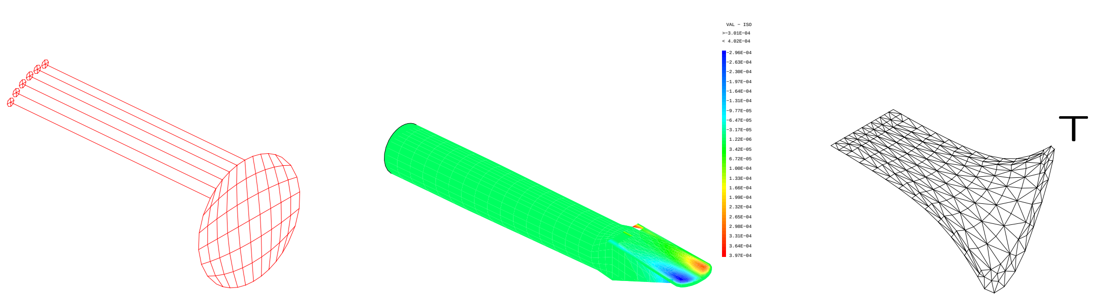
1980 Hz



2234 Hz



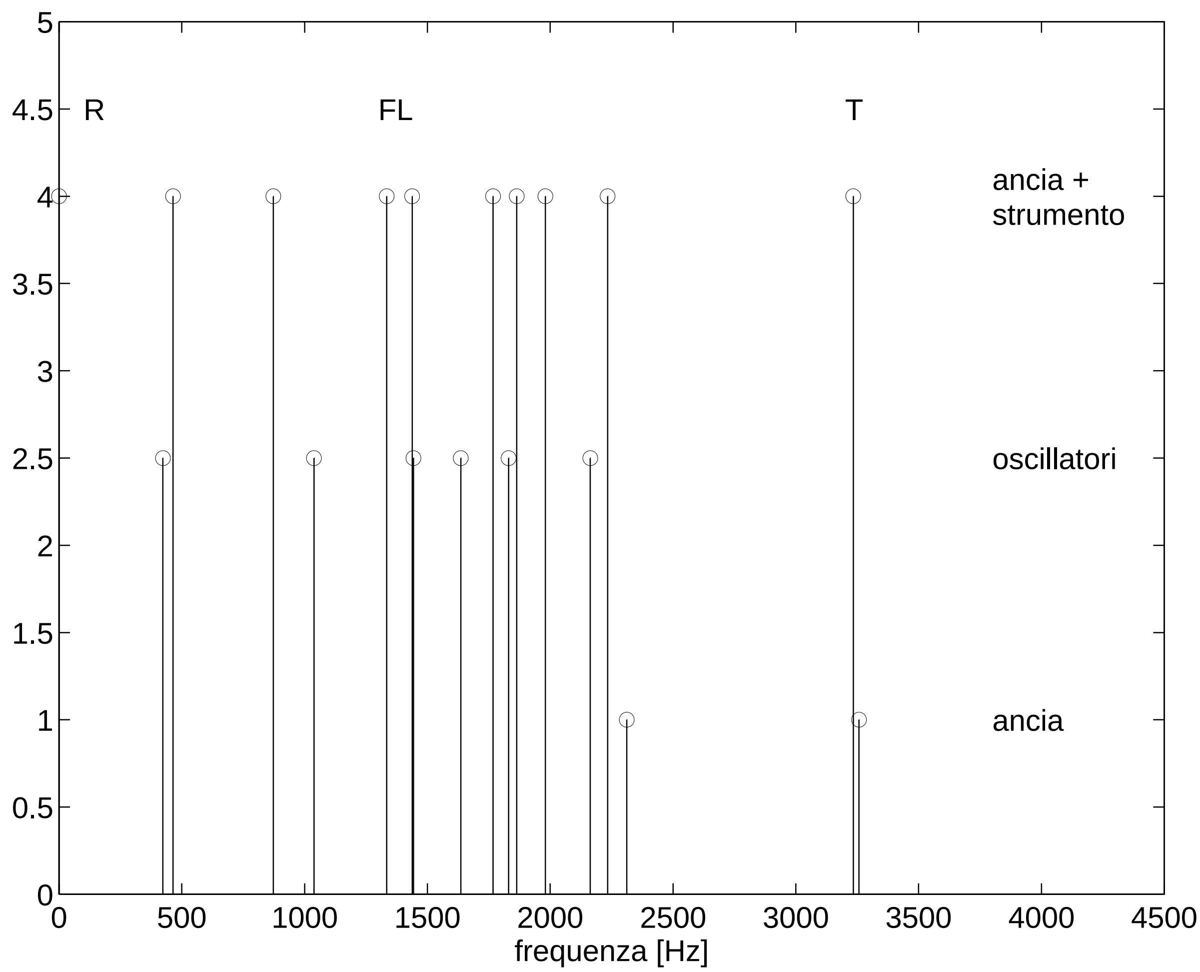
3234 Hz



Liste des exposés

COMPARISON

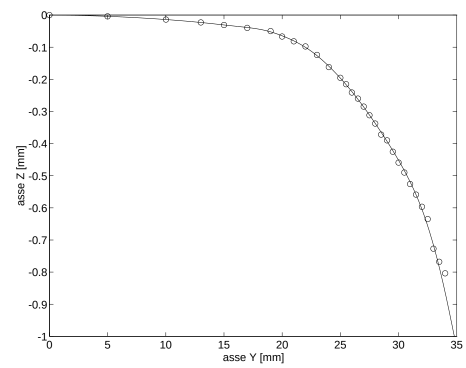
REED		REED + INSTRUMENT		DASHPOTS
f [Hz]	*eigenmode*	*f [Hz]*	*eigenmode*	*f [Hz]*
		0	rigid	
		464	longitudinal flex	423
		873	longitudinal flex	1038
		1334	longitudinal flex	
		1438	longitudinal flex	1443
		1767	longitudinal flex	1636
		1864	longitudinal flex	1831
		1980	longitudinal flex	2163
2312	longitudinal flex	2234	longitudinal flex	
3257	torsion	3234	torsion	



Liste des exposés

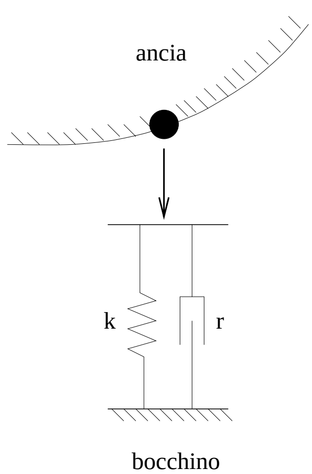
BEATING REED (1)
set-up

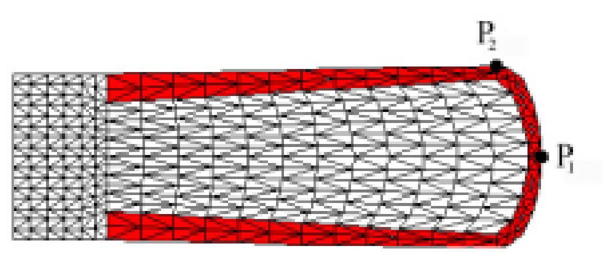
- **geometry:** *CMM* + `Matlab`



- **contact law:** $$f_{choc}(x,t) = k\,(u-u_0) + r\,\dot{u}$$

$$u(x,t) \geq u_0(x)$$

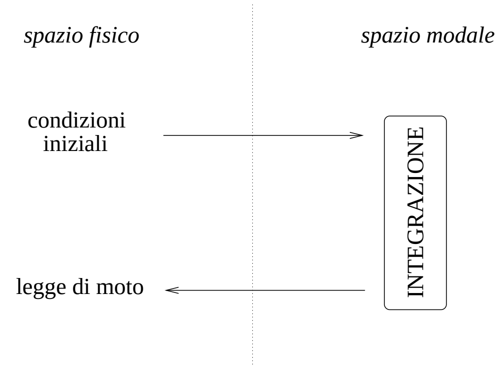




- **computation:** eigenmode projection

$$u(x,t) \simeq \sum_{i=1}^{N} \alpha_i(t)\, w_i(x)$$

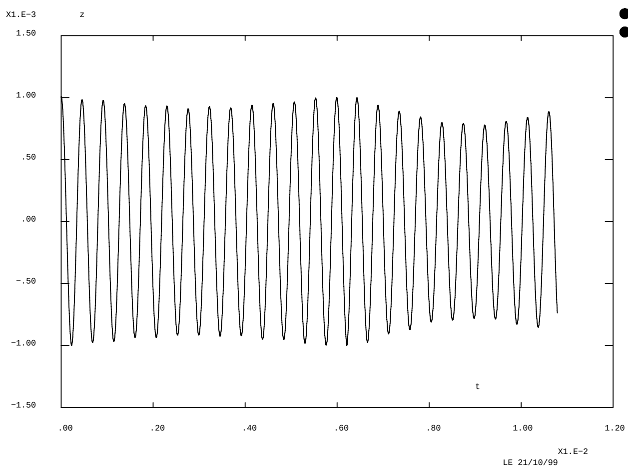
algorithm
Fu - de Vogelære
4^{th} ordre, explicit

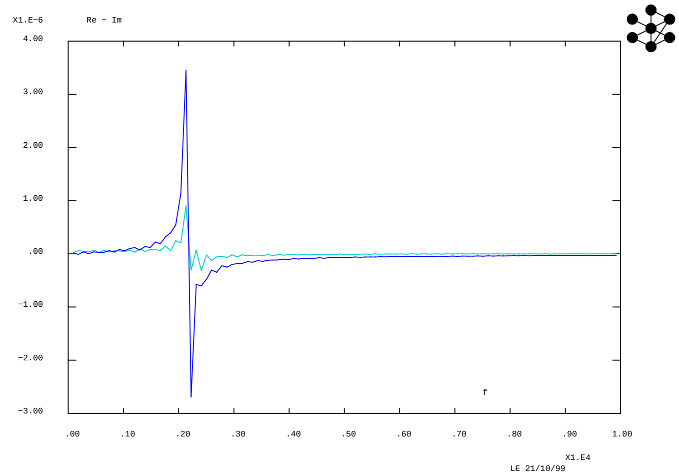


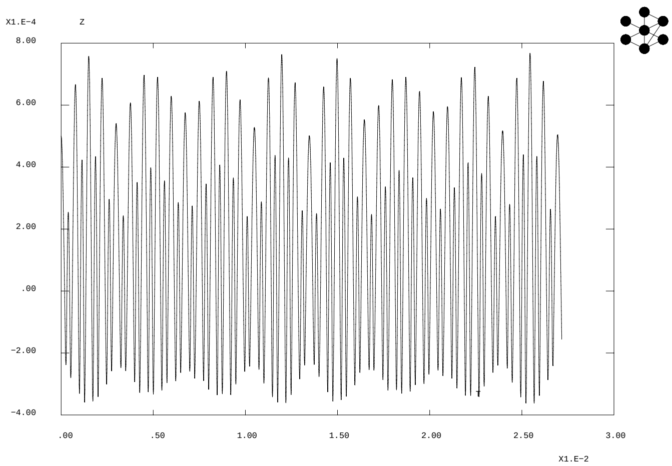
Liste des exposés

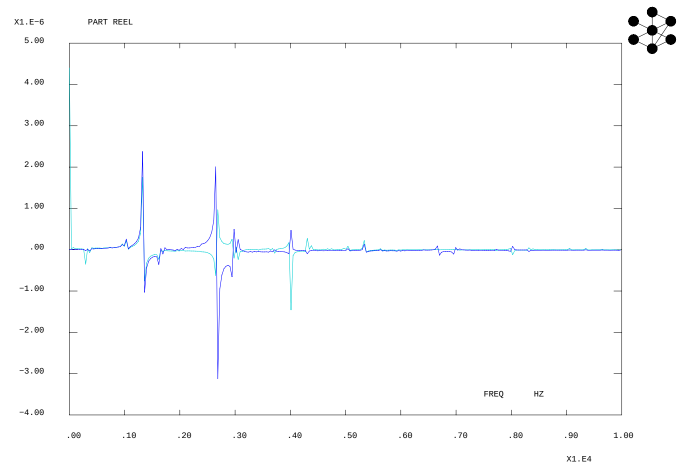
BEATING REED (2)
results

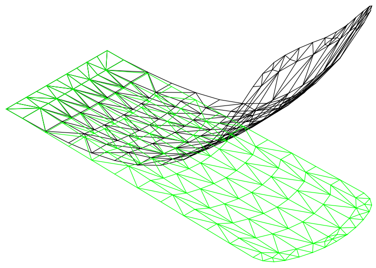
displacement signals of a point of the reed









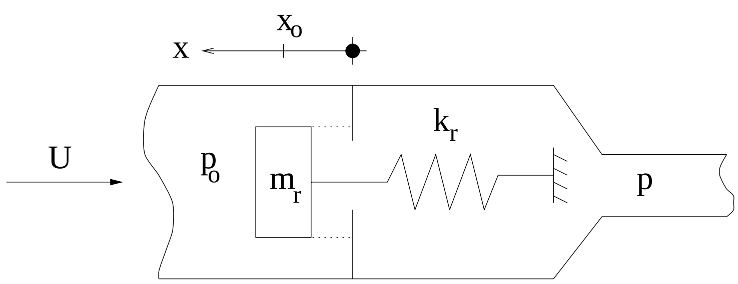


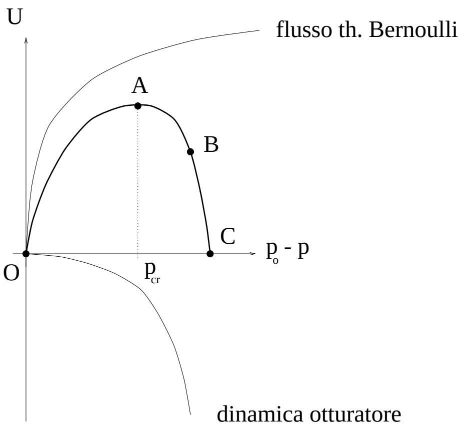
effects
- deformation: asymetric $\rightarrow$ symetric
- displacements $\sim$ mouthpiece lay curvature
- "enriched" spectrum

Liste des exposés

SOUND EMISSION (1)
model

reed = pressure-controlled flux valve

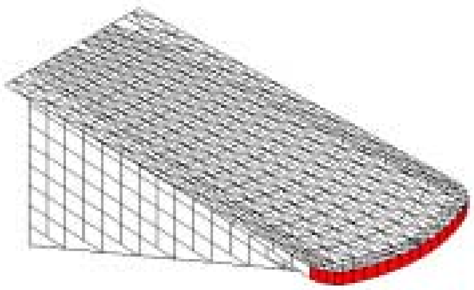


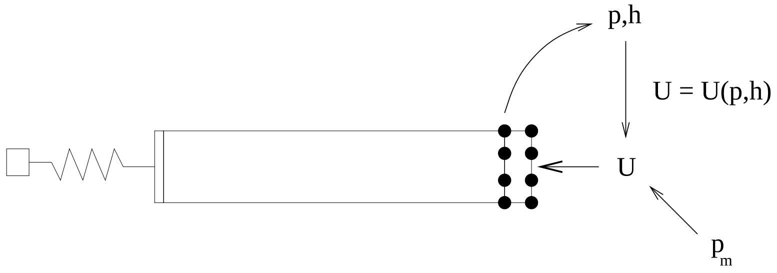


acoustic admittance $\quad Y_r = -\dfrac{\partial U}{\partial p} = +\dfrac{\partial U}{\partial (p_0 - p)}$

$$\textbf{regime} \begin{cases} \text{reed dissipator:} & p_0 < p_{cr} \quad \rightarrow \quad Y_r > 0 \\ \text{reed generator:} & p_0 > p_{cr} \quad \rightarrow \quad Y_r < 0 \end{cases}$$

- □ *Bernoulli flux* $\rightarrow$ modified EF comportement law
- □ *cap dynamic* $\rightarrow$ numeric integration





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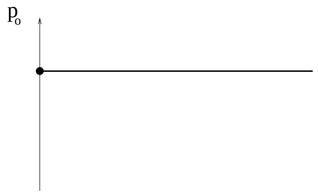
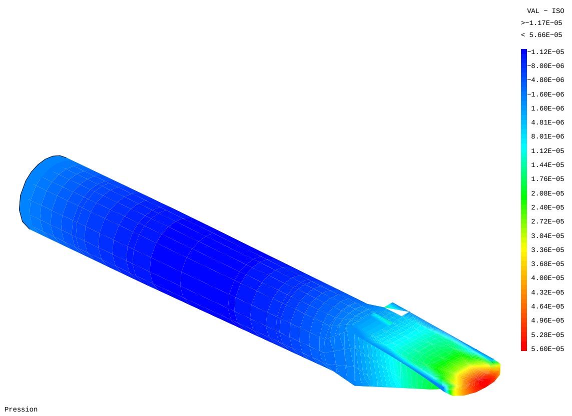
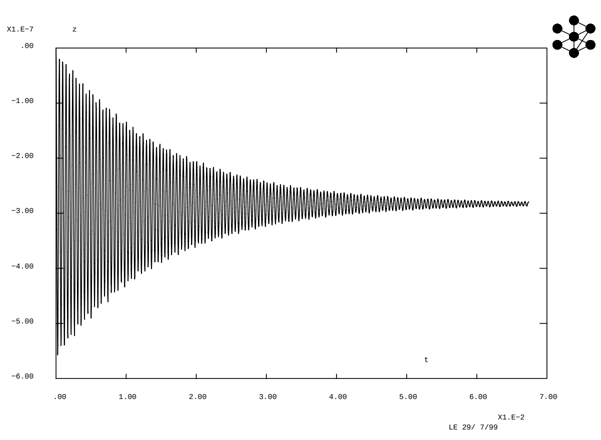
SOUND EMISSION (2)
results

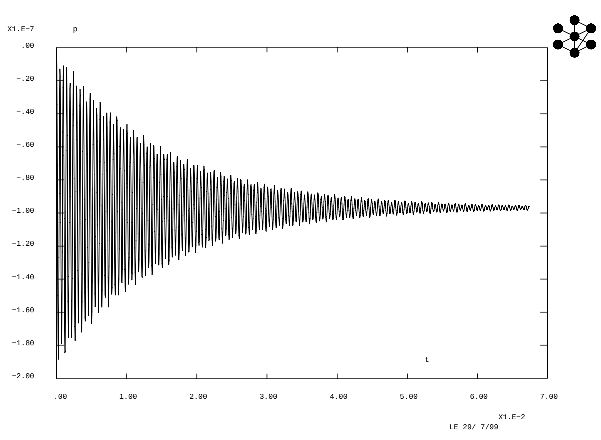




dissipative regime: $p_0 < p_{cr}$

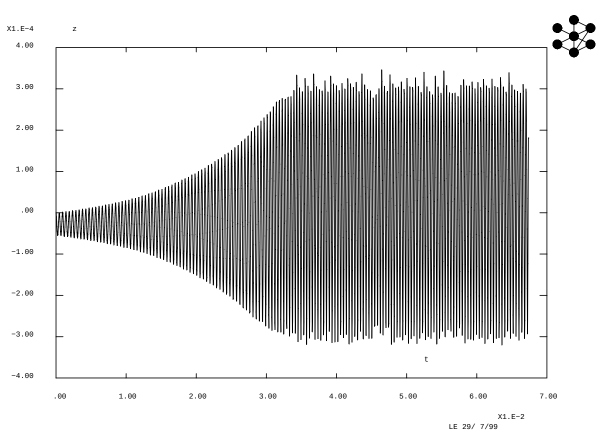
displacement and acoustic pressure signals

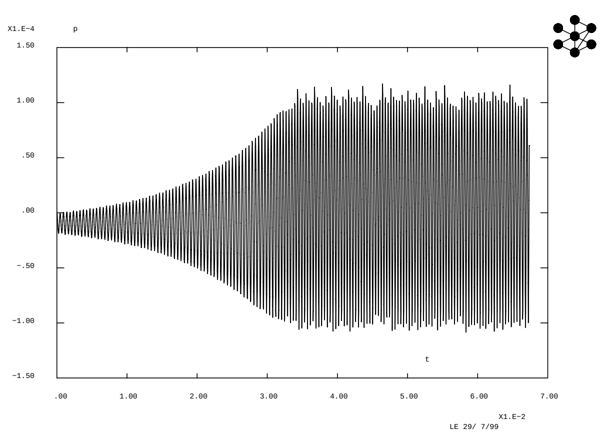




generative regime: $p_0 > p_{cr}$

displacement and acoustic pressure signals





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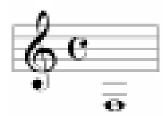
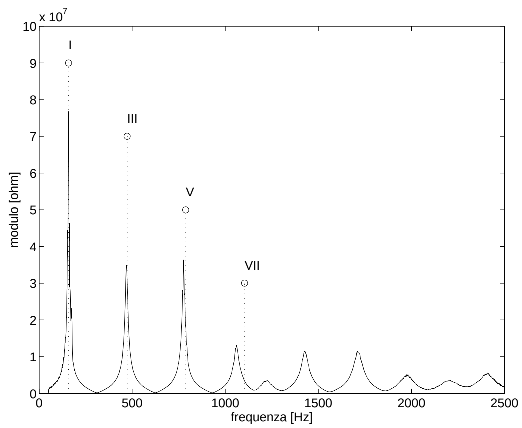
SOUND EMISSION (3)
results

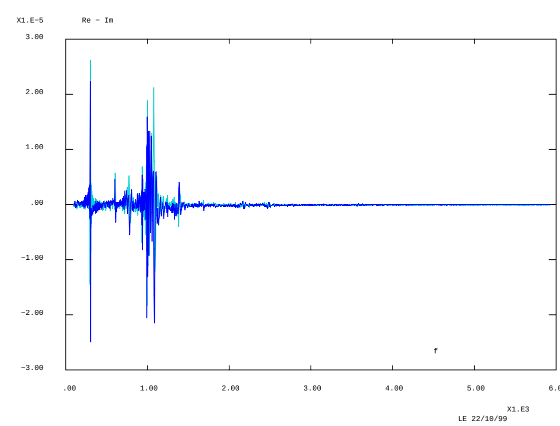
FA low



measured acoustic impedance

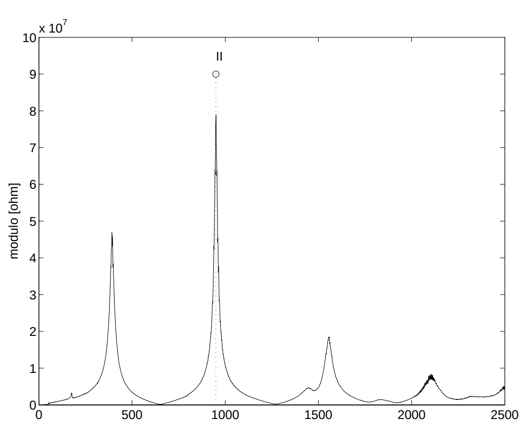


computed sound spectrum

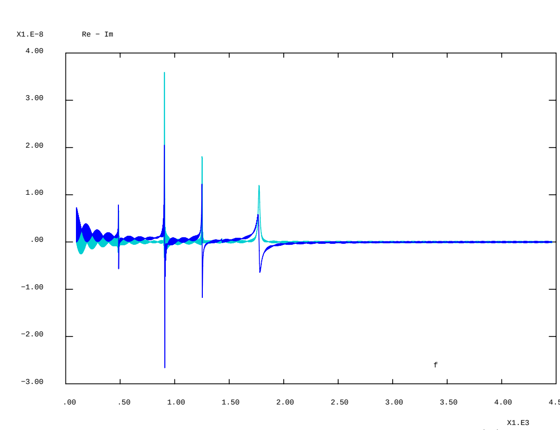


SOL♯ high

measured acoustic impedance



computed sound spectrum



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CONCLUSIONS & PROSPECTS

- **target:** numerical model
  - sound generation
  - beating reed
  - low frequencies

- **widening & development paths**
  - *spectrum*
    - frequencies $\uparrow$
    - “tone” of the clarinet
  - *player*
    - mechanic contact on the reed
    - mouth resonant cavity
  - *reed*
    - wet air $\rightarrow$ wet reed
    - local heterogeneity & anisotropies

- **applications**
  - dynamic behaviuor and sound analysis
  - artificial reeds (composite)

Liste des exposés