open
engineering

Piezo-Thermo-Mechanical FEM analysis applied to vibrating inertial microsensors

ONERA

THE FRENCH AEROSPACE LAB

retour sur innovation

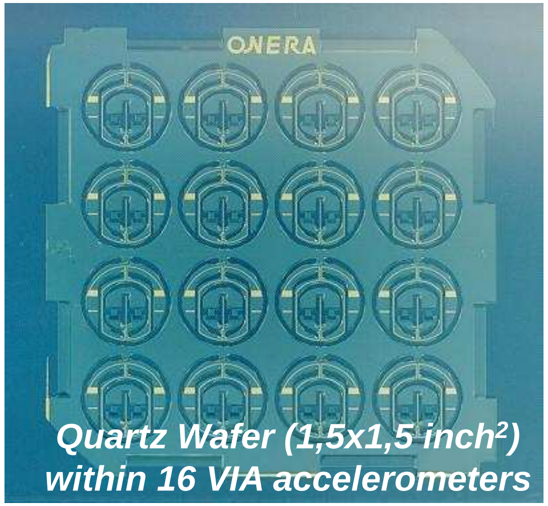
Q1/2009

Inertial microsensors at ONERA

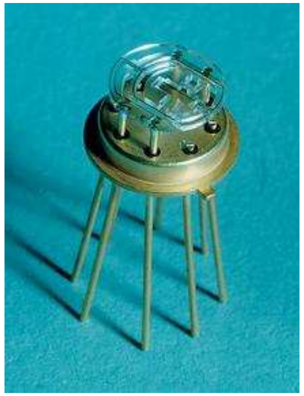
- **2 kinds of inertial microsensors**
  - Accelerometers VIA & DIVA
  - Rate gyro VIG

- **Application**
  - Inertial Measurement Unit
    - 3 accelerometers
    - 3 gyros

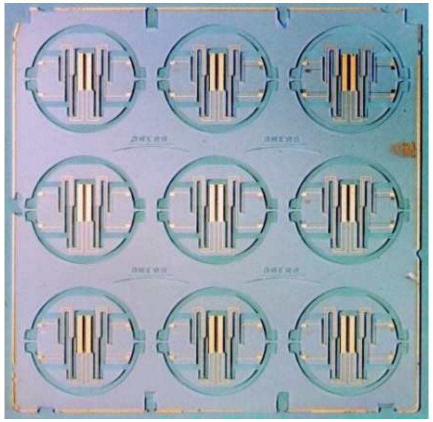
- **Quartz**
  - Piezoelectricity
  - Thermal stability



Quartz Wafer (1,5x1,5 inch^2) within 16 VIA accelerometers



VIA Accelerometer

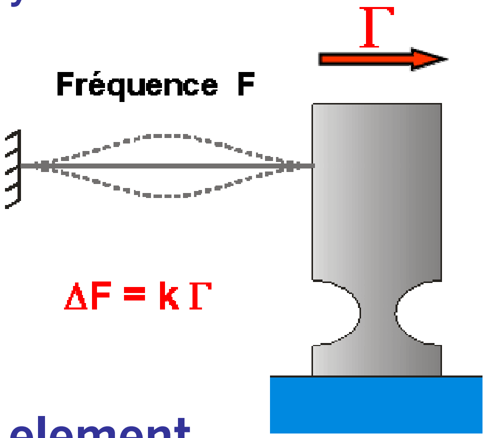


Quartz Wafer (1,5x1,5 inch^2) within 9 VIG Gyros

VIG Gyro

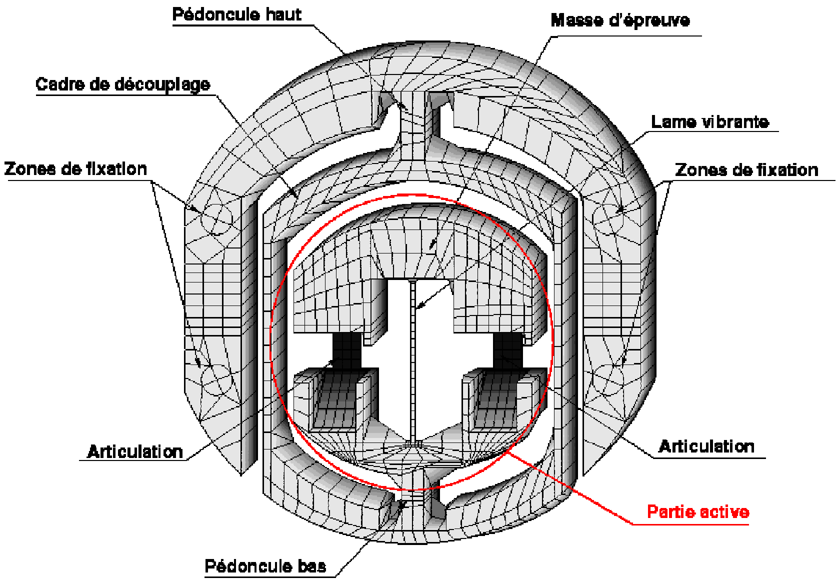
Accelerometers VIA & DIVA

- Vibrating Beam Accelerometer
  - Frequency shift due to axial stresses

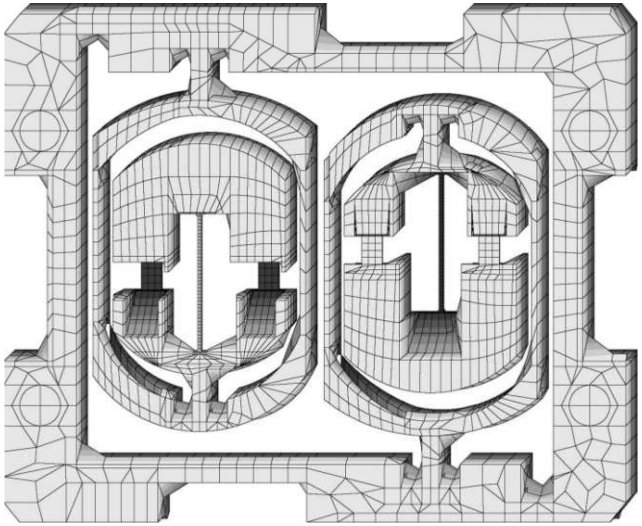


- Sensitive element
  - Beam : 60 µm x 30 µm x 2.2 mm
  - Proof mass : 5 mg
  - Sensitive to orthogonal acceleration
- Detection system
  - Piezoelectric excitation
  - Electronic oscillator
- Monolithic differential accelerometer
  - DIVA

VIA



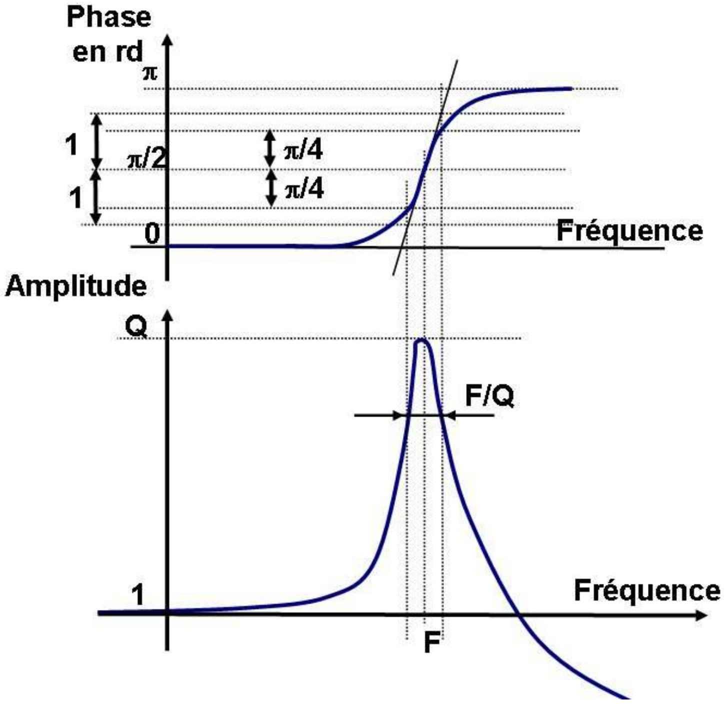
DIVA



High-Q resonators

- **Oscillator accuracy**
  - High Q-factors required

$$\Delta F = \frac{F}{2.Q}\Delta\varphi$$



- **Energy dissipation**
  - Gas damping (neglected)
    - Vacuum (10^{-2} mbar)
  - Thermoelastic damping
  - Clamp losses

$$Q = 2\pi \cdot \frac{W_{stockée}}{W_{dissipée}} \quad \Rightarrow \frac{1}{Q} = \frac{1}{Q_i} + \frac{1}{Q_s} + \frac{1}{Q_d}$$

- **FEM Analysis**
  - Multiphysic approach required

Multiphysic FEM

Needs

- Mechanical behavior
  - Anisotropic material
  - 3D structure
  - Quality Factor prediction
    - Thermoelastic damping
- Resonator behavior
  - Electrical parameters
    - Piezoelectric coupling
- Sensor
  - Scale factor

$$\begin{cases} T_i = C_{ij}^E.\left(S_j - \alpha_i\theta\right) - e_{ki}^t.E_k \\ D_i = \varepsilon_{ij}^S.E_j + e_{ijk}.S_{jk} + p_i\theta \\ \sigma = \left(C_{ij}^E\alpha_i\right)^t S_i + p_i^t E_i + \dfrac{C_P}{T_0}\theta \end{cases}$$

Multiphysic approach

- Piezo-thermo-elastic FEM
  - OOFELIE (Open Engineering)
  - Samcef Field (Samtech)

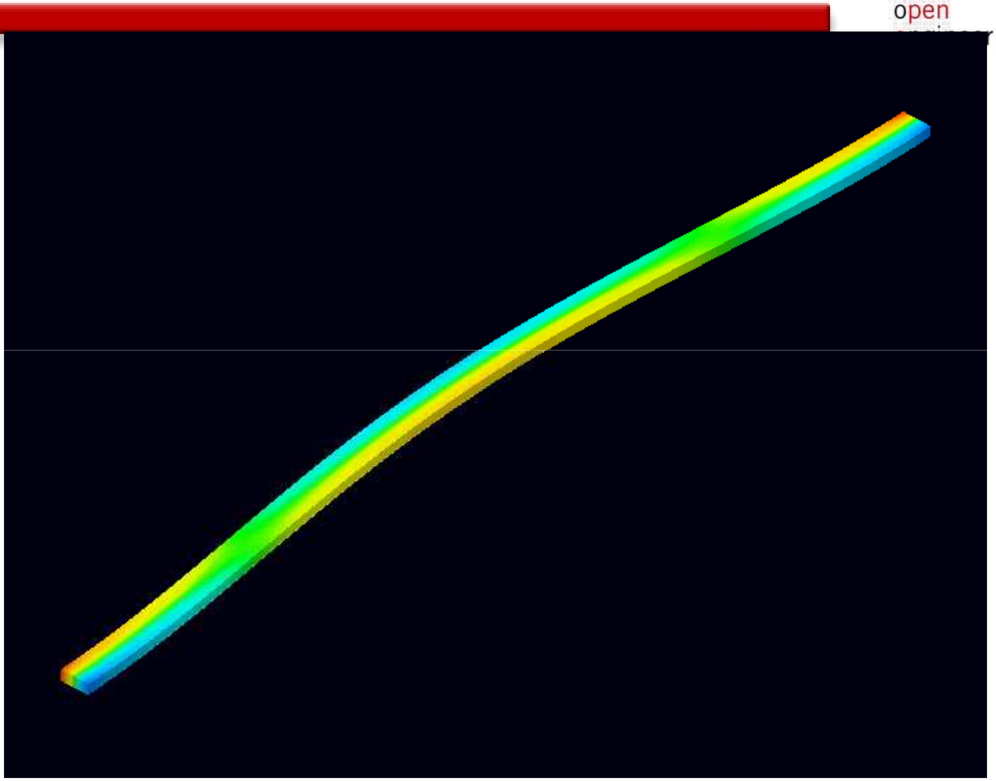
$$\begin{cases} \rho\dfrac{\partial^2 u_i}{\partial t^2} = \dfrac{\partial T_{ik}}{\partial x_k} + f \\ \dfrac{\partial D_i}{\partial x_i} = \rho_e \\ \left(T_0 + \theta\right)\dot{\sigma} = \lambda\Delta\theta + u_{th} \end{cases}$$

Thermoelastic Damping

- Bending mode
  - Compression -> heating
  - Extension -> cooling
- Irreversible heat flow
  - Energy dissipation
  - Damping
- Limitation of analytical model
  - Anisotropic material
  - Complex 3D structure

$$Q_{thermo} = \frac{\rho \cdot C}{\alpha^2 \cdot T \cdot E} \cdot \frac{F_o^2 + F^2}{F_o F} \quad \text{avec } F_o = \frac{\pi \cdot D}{2 \cdot e^2}$$

- Modeling using Oofelie
  - Harmonic response analysis
  - Influence of piezoelectricity
  - Good agreement with experimental results



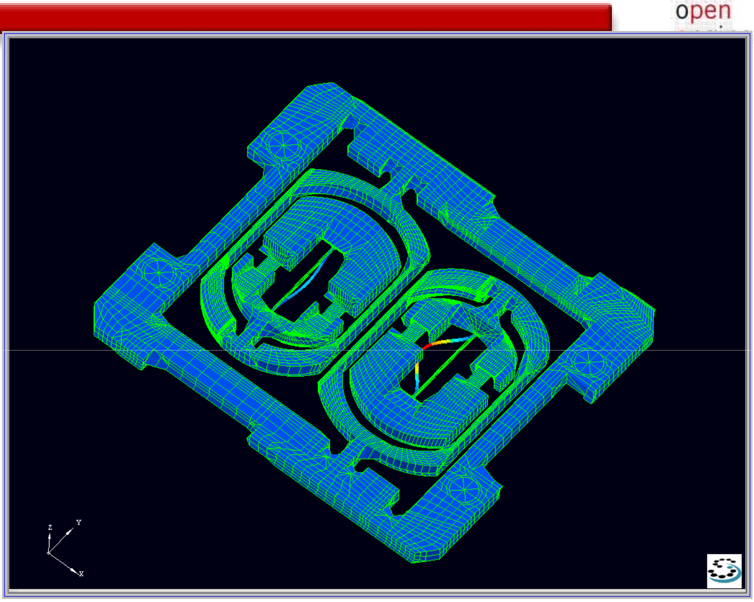
	Q factor
Zener theory	16 580
Oofelie : thermo-elastic	13 700
Oofelie : piezo-thermo-elastic	13 090
Experimental characterisation	~13 000

S. Lepage et al., CANEUS 2006, Toulouse, France

Insulating Frame

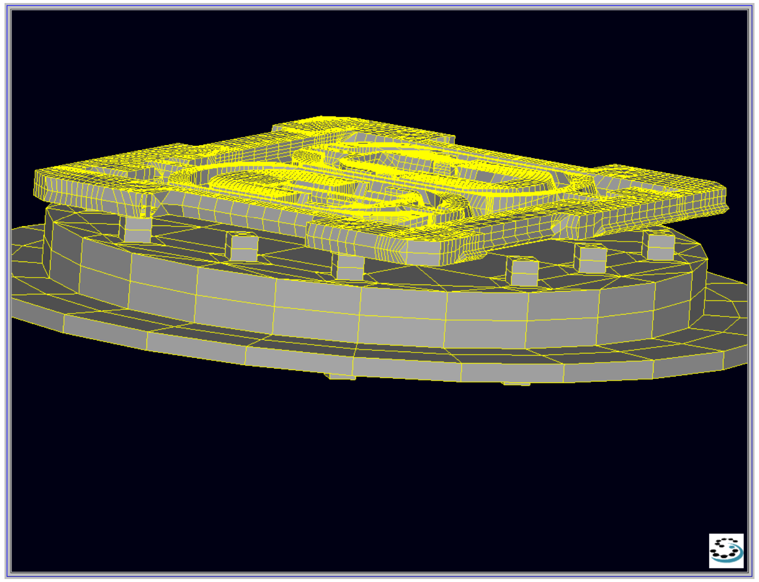
❑Goal

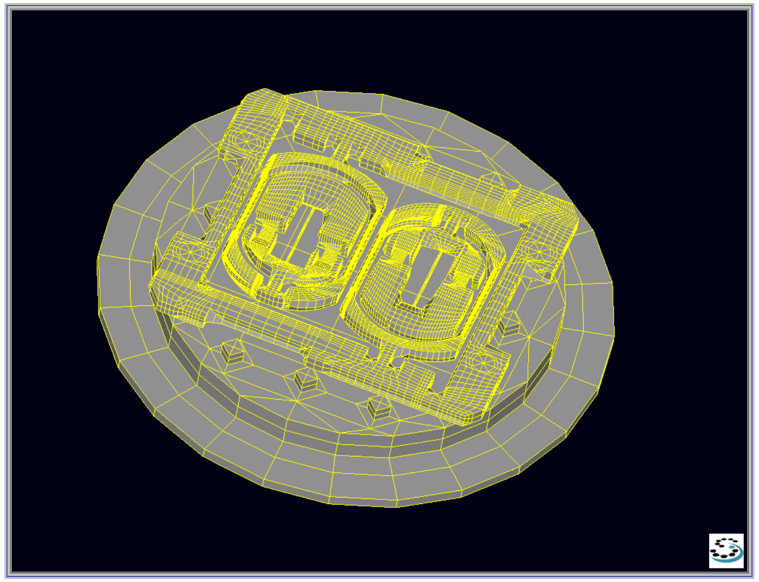
- ❑ Limit energy losses through mounting parts
- ❑ Preserve resonance quality
- ❑ Protect resonance frequency from thermal stresses



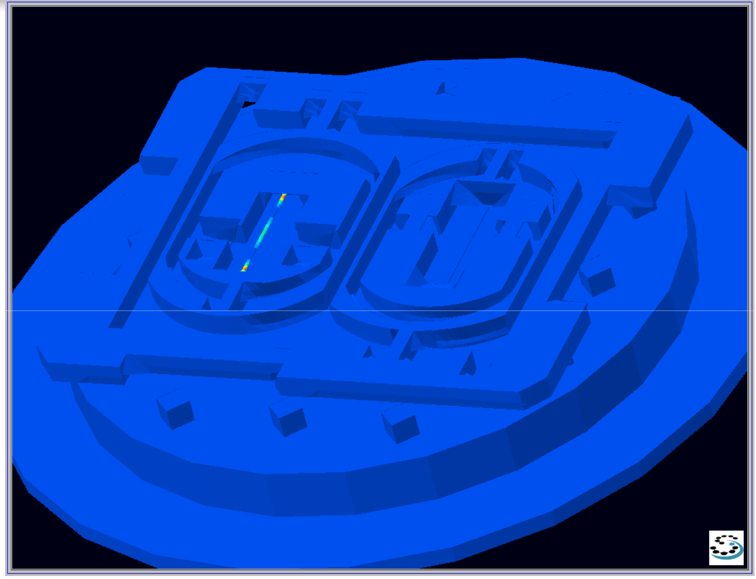
❑FEM Analysis

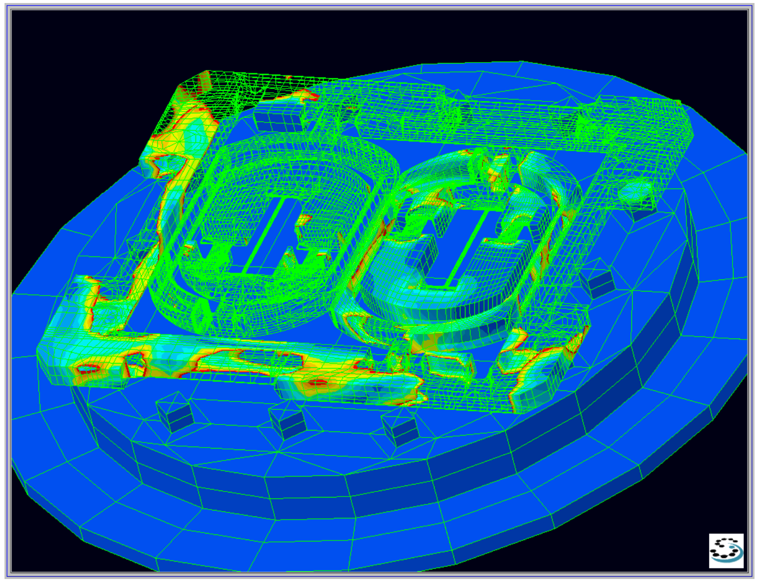
- ❑ Model quartz structure + TO8 base





Insulating Frame



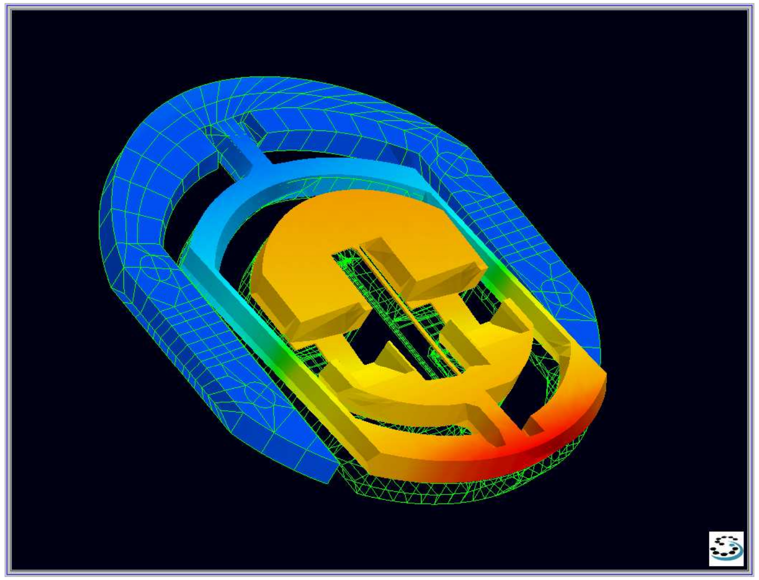


- ☐ Prediction of the frame efficiency
  - ☐ Modal Analysis
  - ☐ Evaluation of the strain energy dissipated in the base

- ☐ Less than 10^{-8} of total vibrating energy in mounting parts
  - ☐ $Q_{decoupling} > 10^8$
  - ☐ Compatible with thermoelastic damping
    ($Q_{th} = 13000$)

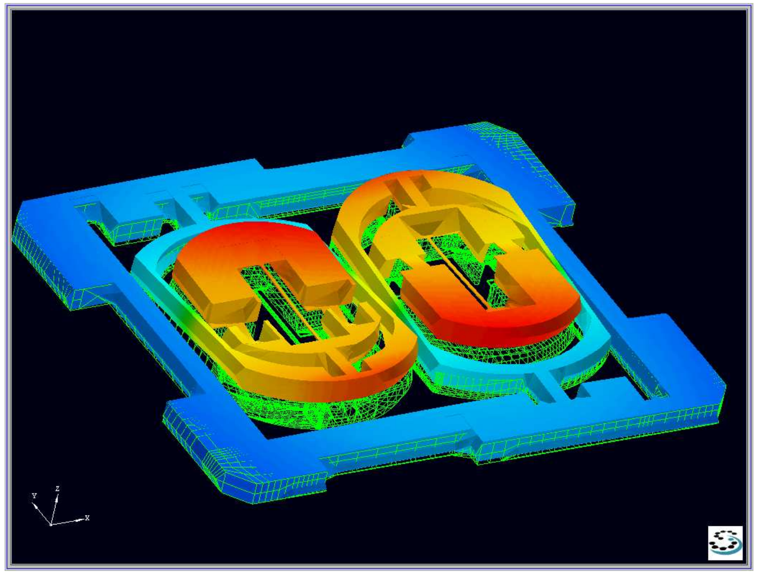
Scale Factor Estimation

- Stress generated by static acceleration
- Modal analysis with static pre-stress
- Evaluation of the frequency shift due to acceleration



Numeric scale factor : 12.6 Hz/g

Experimental S.F. : ~ 12.5 Hz/g

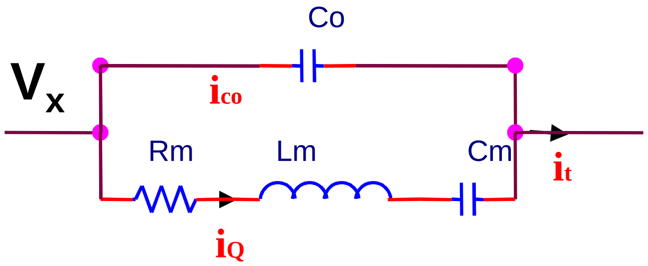


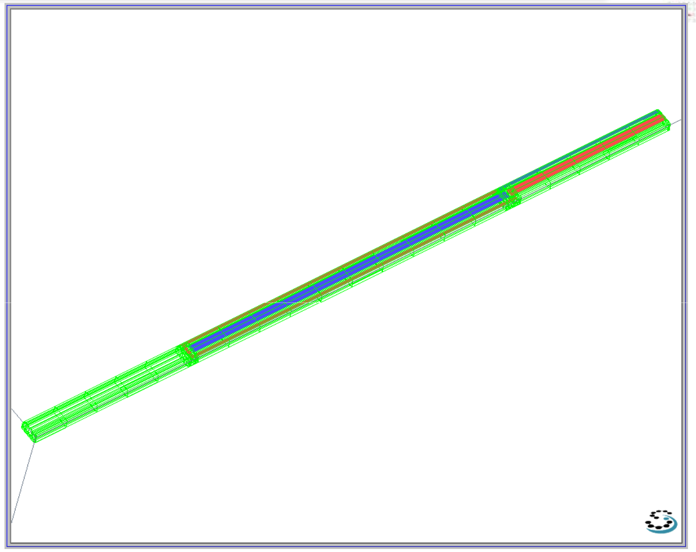
Numeric scale factor : 31.9 Hz/g

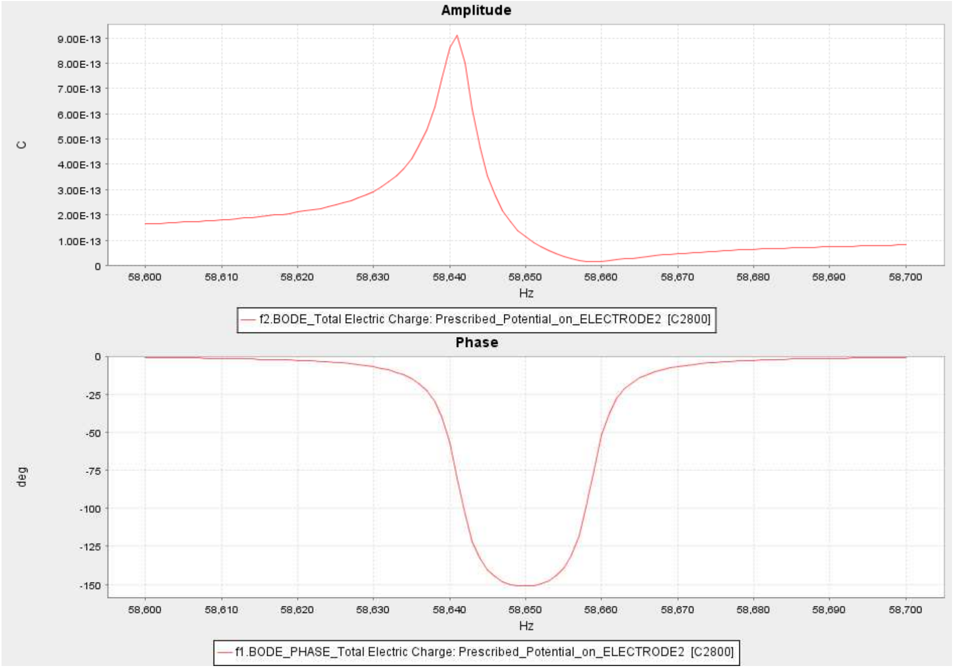
Experimental S.F. : ~ 30.5 Hz/g

Electric behavior (1/2)

- Equivalent electric model
  - C_0 : Capacitance
  - R_m, L_m, C_m : motionnal parameters.
- Influence on electronic oscillateur
- Piezoelectric FEM analysis
  - Electric response of the transducer
  - Motionnal parameters
    - C_0 # 1 pF
    - R_m # 3 MΩ
    - Très bon accord avec l'expérience
- Phase shift induced by C_0

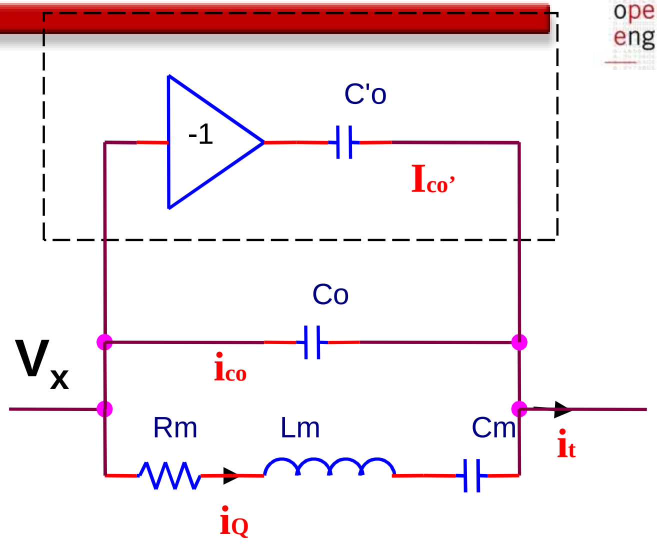






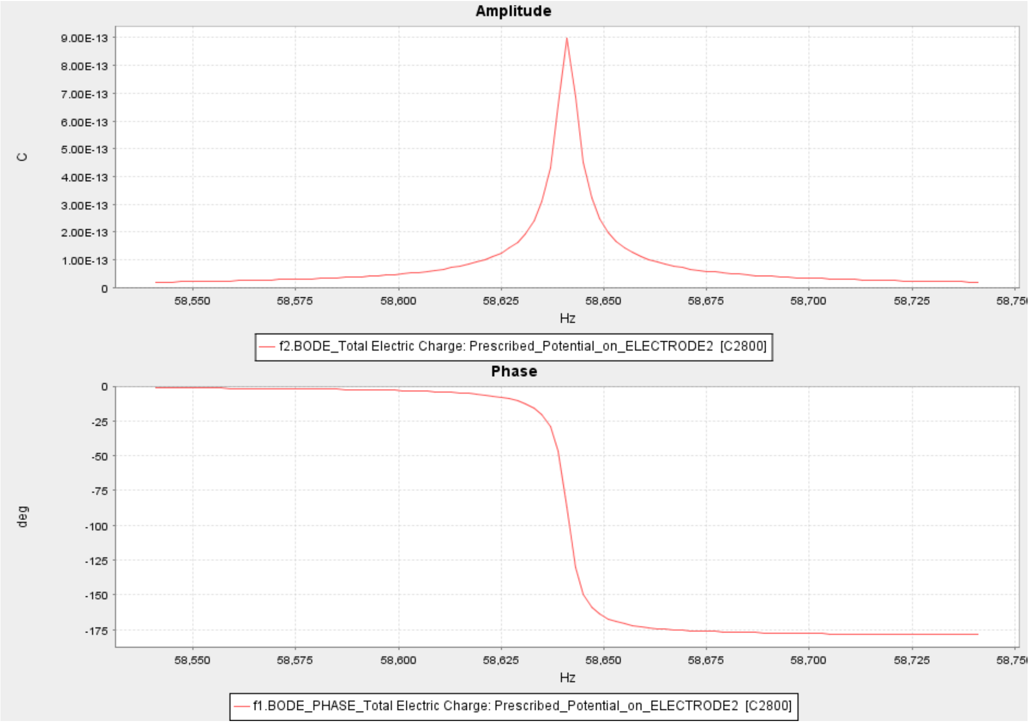
Electric behavior (2/2)

- **Influence of external electric impedance**
  - Inter electrode capacitance cancellation



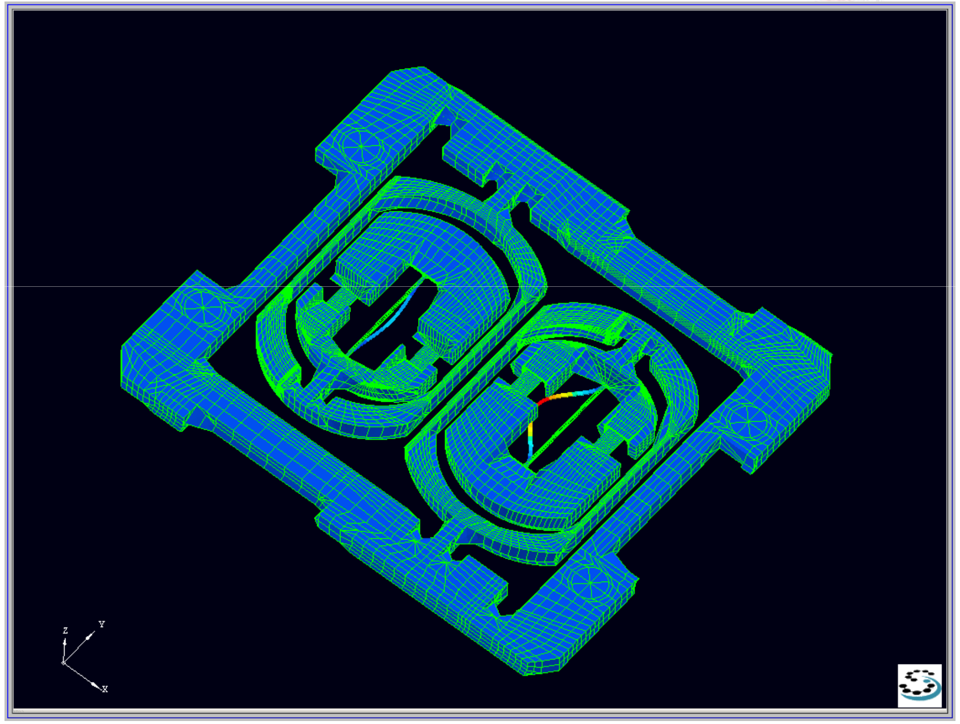
- **Impact of the electronic circuit on the transducer behavior**
  - Phase shift cancelled
  - Same quality factor

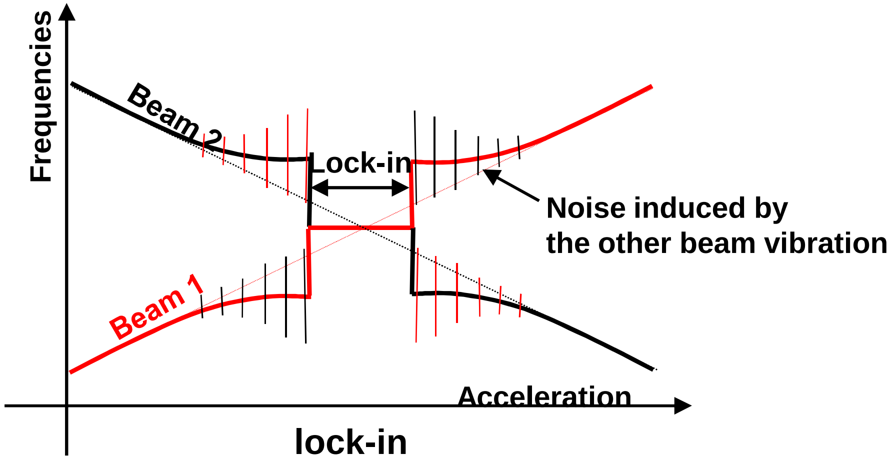
- **Better response of the transduce**



DIVA : Lock-in phenomena

- ❑Lock-in
  - ❑ Mechanical coupling between resonators
  - ❑ Same resonance frequencies
  - ❑ Blind zone
- ❑Specific optimization by FEM
  - ❑ Decoupling frame optimization
  - ❑ Reduce vibrating energy transfer between resonators
- ❑Reduction of the blind zone to 1 mg





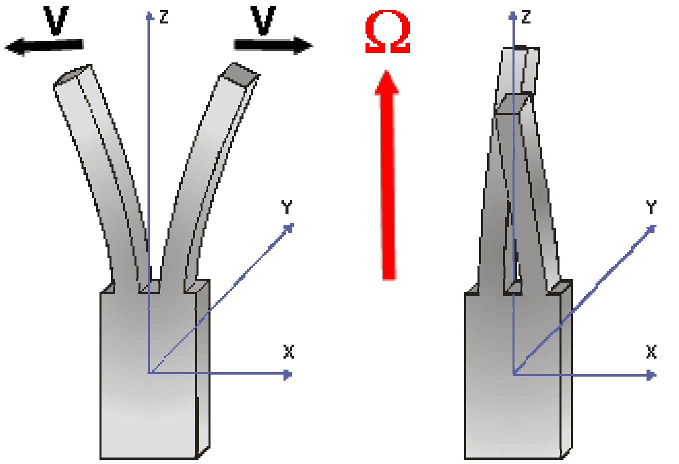
Noise induced by
the other beam vibration

lock-in

Gyro VIG

Coriolis Vibrating Gyro

- Sensitive element: tuning fork
  - 500 µm * 500 µm * 2 mm
- Driving mode : in-plane bending resonance (~ 35 kHz)
- Sensing mode : orthogonal bending mode induced by coriolis acceleration
- Angular rate measured by the amplitude of the sensing mode



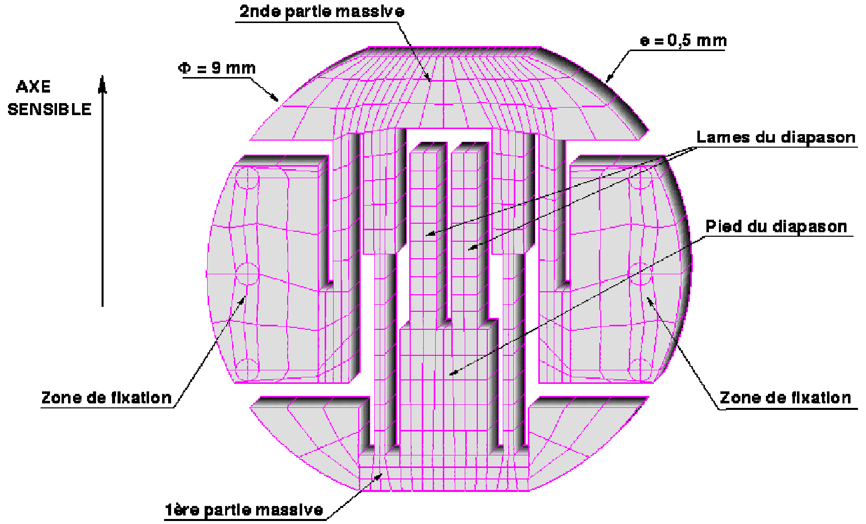
$$\vec{\Gamma}_c = 2\,\vec{\Omega} \wedge \vec{V} \Rightarrow \frac{Y}{X} = \frac{\Omega}{(w_x - w_y)}$$

Excitation

- Piezoelectric excitation by electrodes on the stem

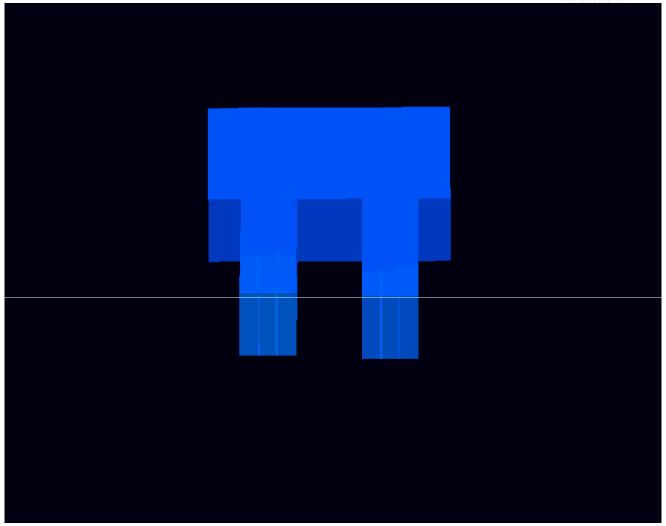
Detection

- Electrical charges collected on each blade

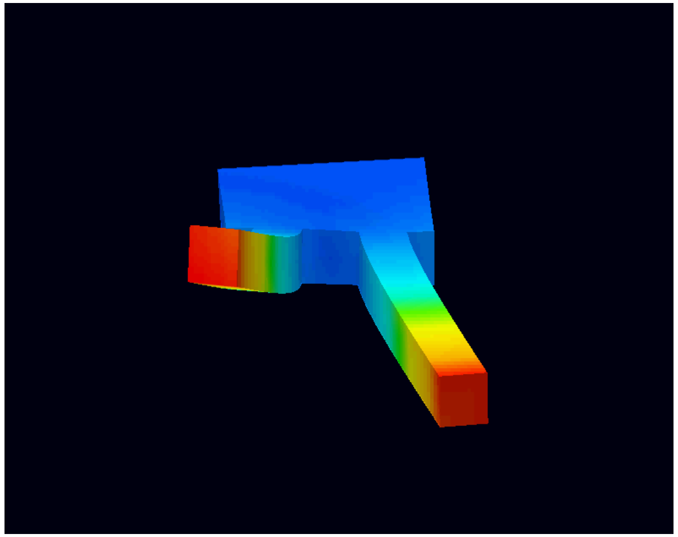


Coriolis Acceleration

- ☐ **Coriolis coupling FEM analysis with Oofelie**
  - ☐ **Harmonic response analysis**
  - ☐ **Complex modal analysis**
  - ☐ **Driving mode excitation by piezoelectricity**
    - ☐ Electric potentiel : 1V
    - ☐ Frequency : # 35 kHz
    - ☐ Driving amplitude : ~ 1 μm
  - ☐ **Orthogonal vibration due to Coriolis acceleration**
    - ☐ Angular rate : 10 °/s
    - ☐ Sensing amplitude : 0.2 nm



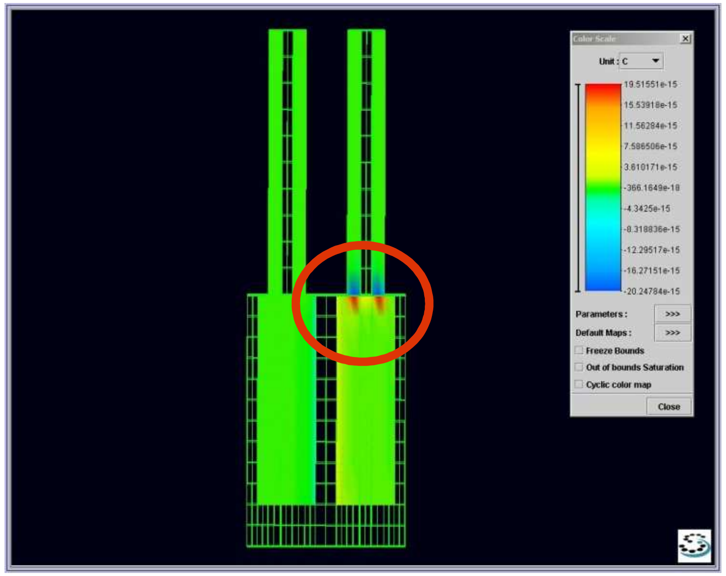
Driving mode

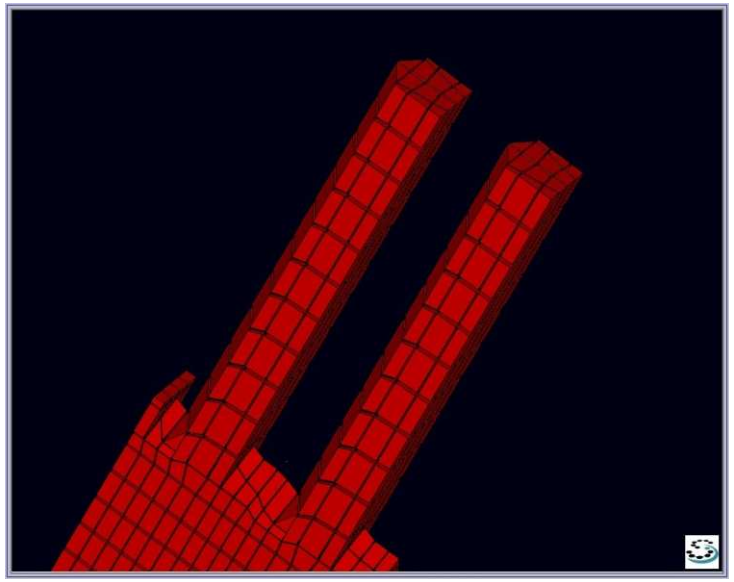


Coriolis coupling

Design Analysis

- ❑ Evaluation of total electrical charges
  - ❑ Capacitive coupling
  - ❑ Influence of dissymmetry due to technological processing
    - ❑ Electrodes misalignment
    - ❑ Anisotropic chemical etching
  - ❑ Electrodes optimization
- ❑ Better understanding of the transducer behavior





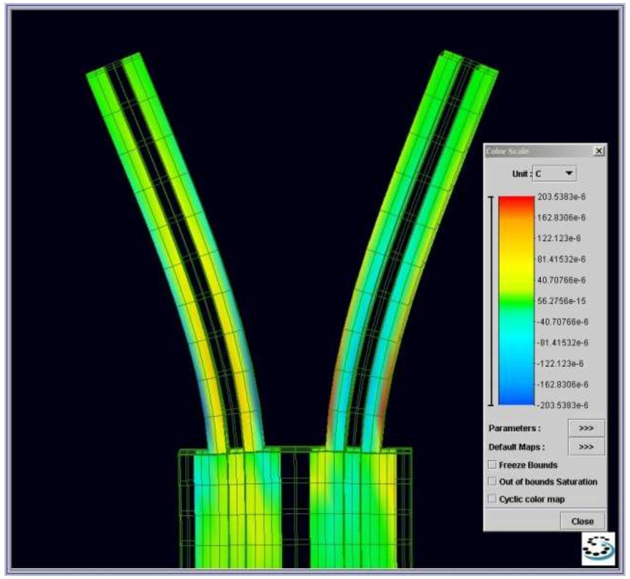
Electrode design

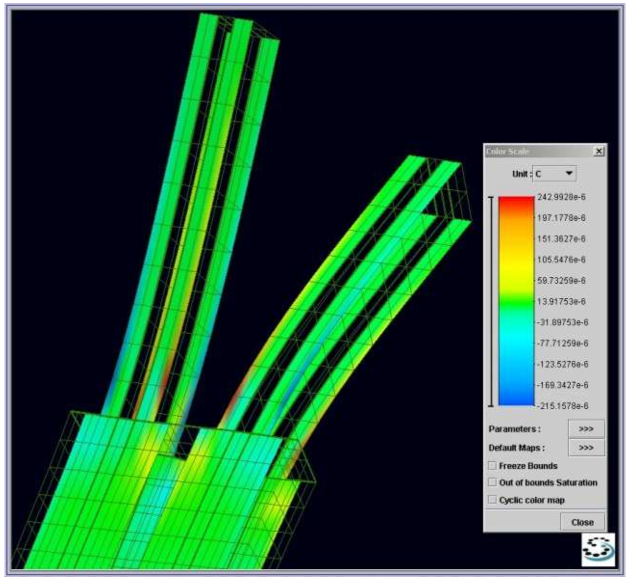
Electrode optimization

- Piezoelectric modal analysis
- Electric charge evaluation
- Electrode efficiency
    - Mode pilote
    - Mode Détecteur
- Optimization of R_m for each mode

Scale factor

- Harmonic analysis with rotation speed
- Numeric Scale factor:
  1.3 10^{-16} C / (°/s)
- Experimental scale factor:
  1.6 10^{-16} C / (°/s)
- Good agreement





Conclusion

❑ FEM analysis for inertial micro-sensors with Oofelie

- ❑ **Multiphysic approach**
  - ❑ Mechanical
  - ❑ Electrical
  - ❑ Thermal
- ❑ **Prediction of the main sensor characteristics**
  - ❑ Quality factor (Thermo-elastic damping)
  - ❑ Accelerometer scale factor (Pre-stress analysis)
  - ❑ Gyro scale factor (Coriolis coupling)
  - ❑ Electric parameters
- ❑ **Good agreement between numeric and experimental results**
- ❑ **Development of accurate inertial microsensors**
  - ❑ Investigation on new materials ($GaPO_4$) and new designs