Design of Reliable MEMS for Space Applications Using Multiphysic Simulation Tools

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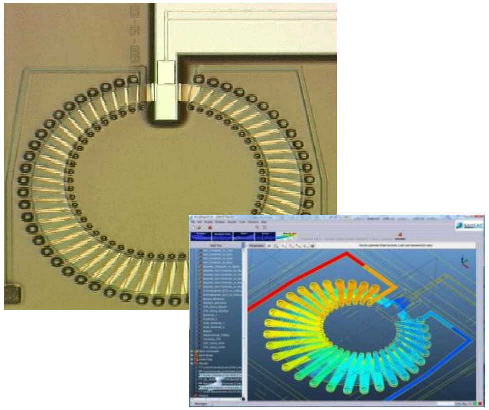
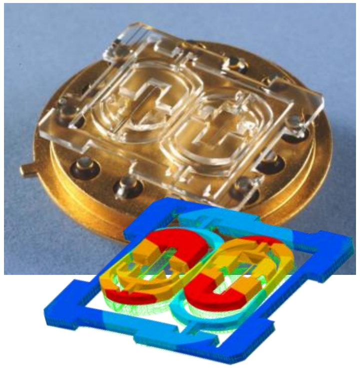
Scope of the presentation

- **Introduction**
  - Open Engineering & OOFELIE::Multiphysics
  - Uncertainties quantification
  - General microsystems applications
- **Detailed applications**
  - Accelerometers: VIA & DIVA
  - MEMS Electromagnetic actuator
- **Conclusions**



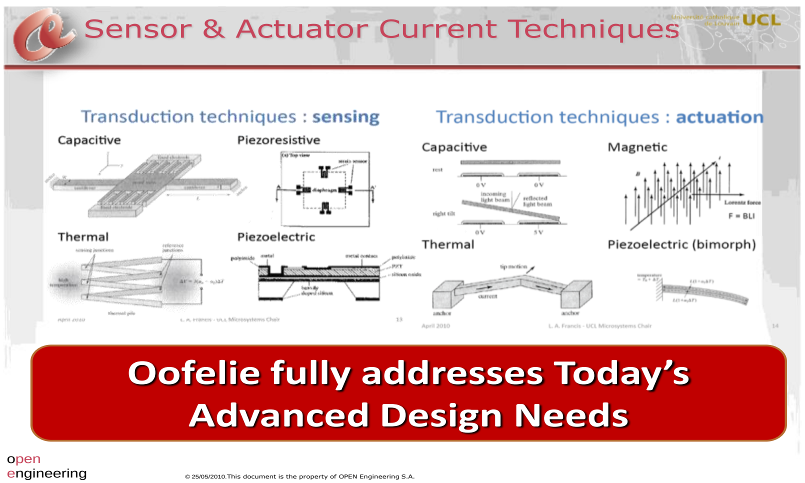


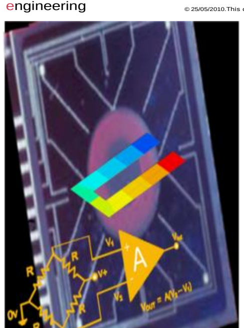
With courtesy of ONERA

Introduction
Open Engineering & OOFELIE::Multiphysics

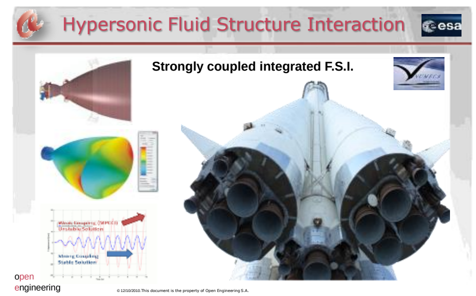
- OE develops and sells simulation software
- OE provides services

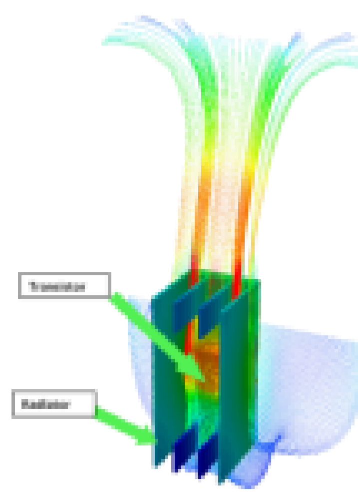
Sensors, Actuators & Optics

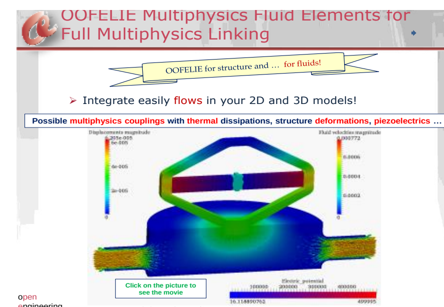




Fluid Structure Interaction





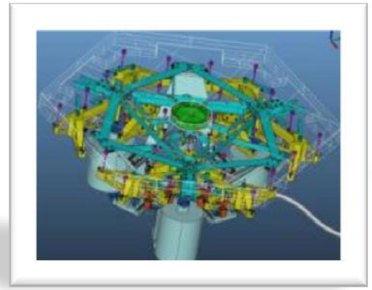


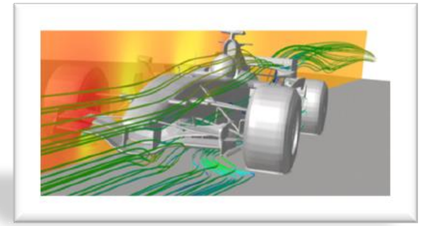
Introduction
OOFELIE::Multiphysics

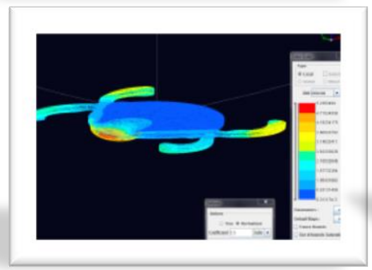
OOFELIE::Multiphysics

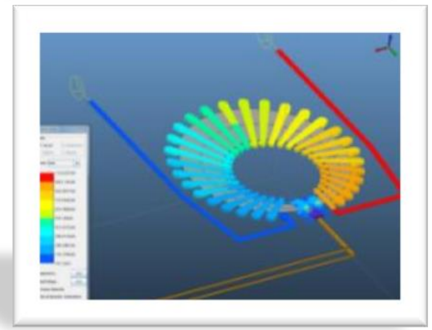
- Mechanics
- Thermics
- Fluids
- Electric
- Acoustics

- Electrostatics
- Piezoresistivity
- Electromagnetics
- Pyro-piezoelectricity
- Thermomechanics
- Electro-thermomechanics
- F.S.I.
- Vibro-Acoustics









Moldex3D MOLDING INNOVATION — Injection Analysis and Coupling

Radiant Zemax — Optics Analysis and Coupling

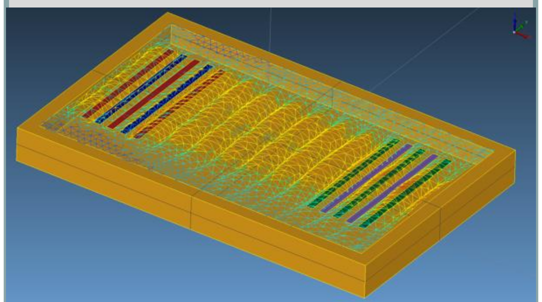
NUMECA INTERNATIONAL — CFD Analysis and Coupling

SoftMEMS Bringing MEMS to the Mainstream — EDA link and coupling

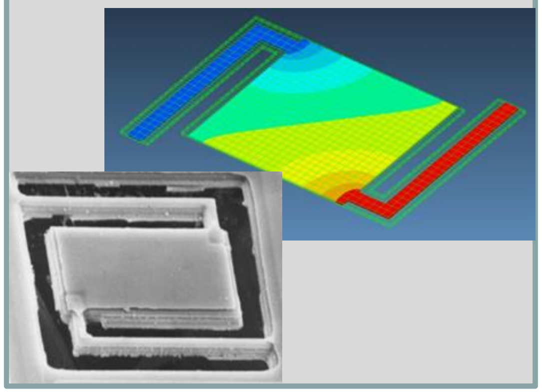
OOFELIE::Multiphysics

Introduction
General microsystems applications

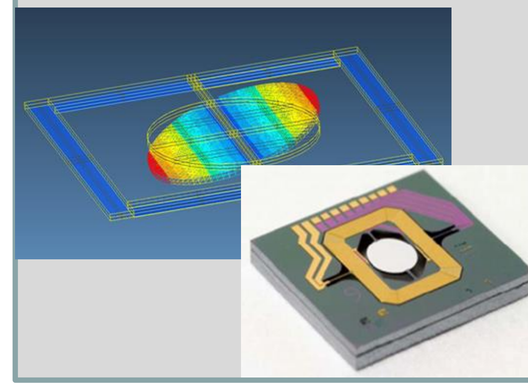
Gyrometer (SAW)



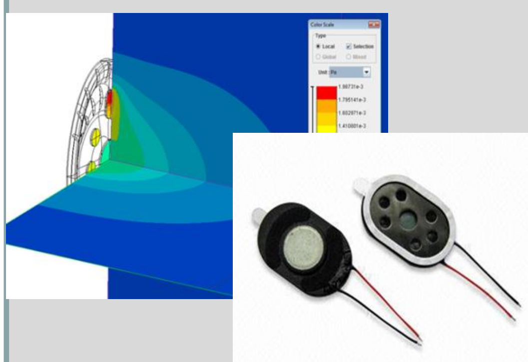
IR sensor



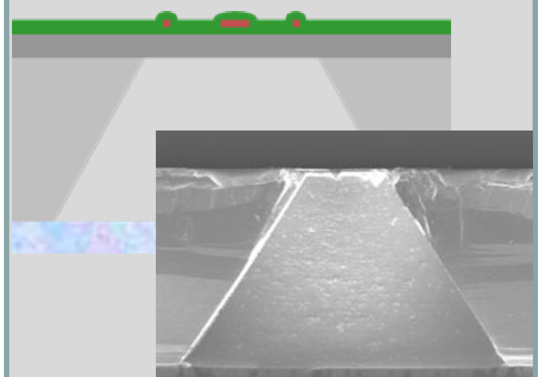
Micro-mirror



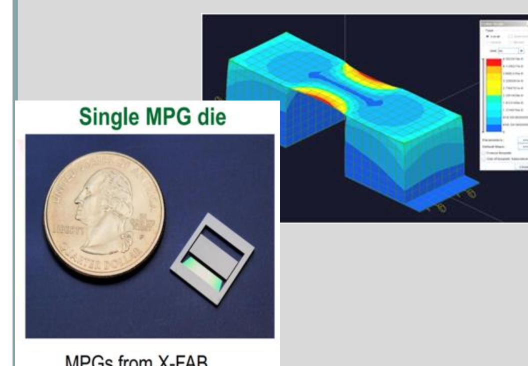
Micro-loudspeaker



Pressure sensor

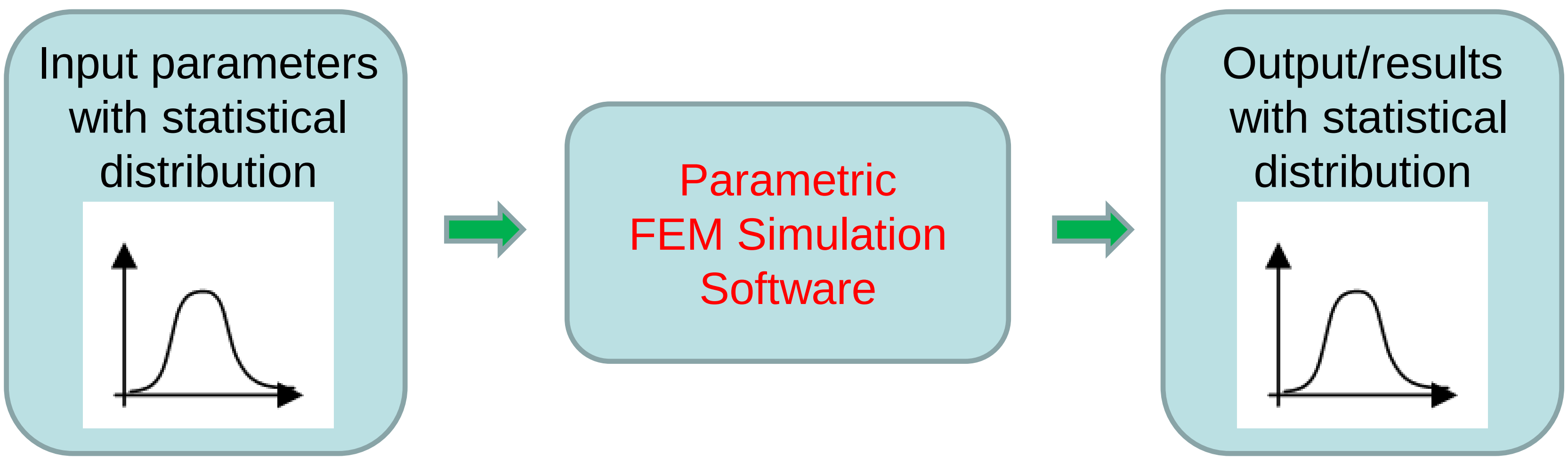


Energy harvester



Uncertainties quantification (1/2)

- **Source of uncertainties in microsystems**
  - Material properties
  - Dimensions
  - Roughness
  - Prestress from fab process
  - …
- **General principle**



Uncertainties quantification (2/2)

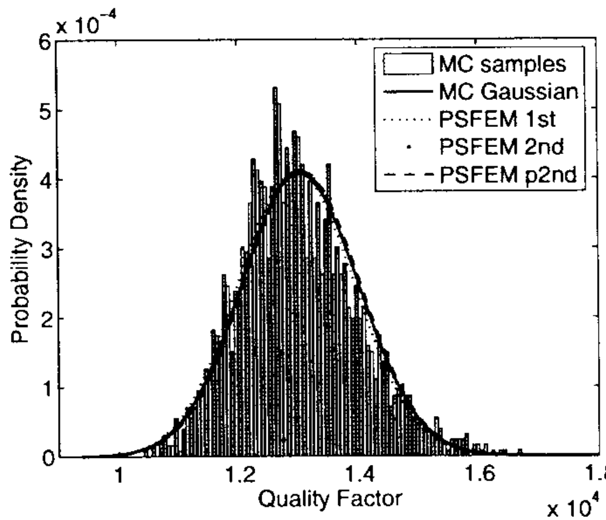
- **How to deal with these uncertainties in FEM software**
  - Non-intrusive methods
    - General and easy to implement : like Monte Carlo methodology
      … but CPU time expensive
  - Intrusive methods
    - Difficult to implement: like Stochastic FEM
      … but CPU time efficient

R & D on intrusive methods are performed at the present time in OOFELIE::Multiphysics software in the framework of several research projects

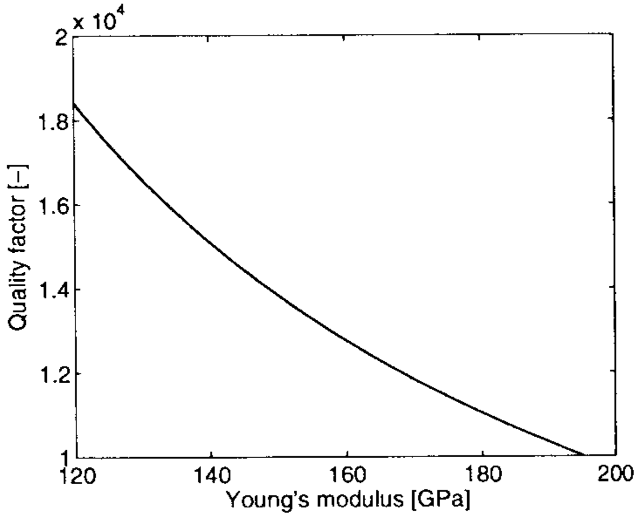
PSFEM - Application

Monte Carlo simulation vs Stochastic FEM

Method	Mean (Q)	σ (Q)	CPU Time*
MC	13035	980	2005
PSFEM 1st	12967	971	1,02
PSFEM 2^{nd}	13037	971	1.16
PSFEM p2nd	13069	971	1.04



(a)

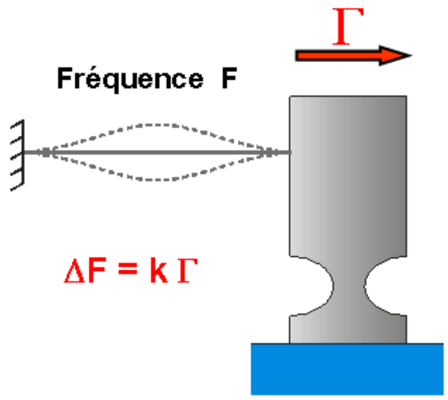


(b)

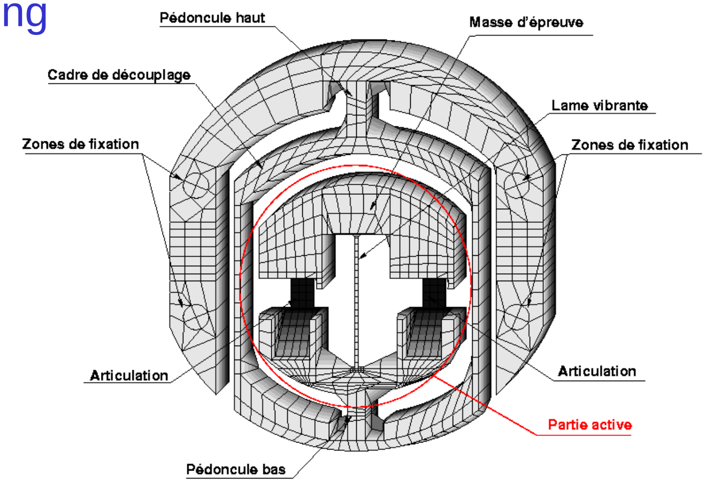
Detailed Applications
Accelerometer: VIA & DIVA

❑Vibrating Inertial Accelerometer

- ❑ Frequency shift due to axial stresses (guitar string effect)



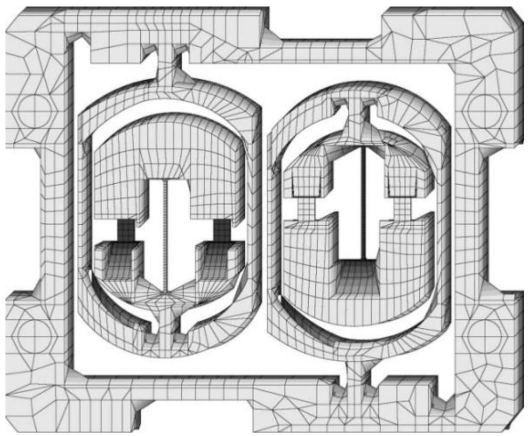
VIA



❑Sensitive element (Quartz)

- ❑ Beam : 60 µm x 30 µm x 2.2 mm
- ❑ Proof mass : 5 mg
- ❑ Sensitive to orthogonal acceleration

DIVA



❑Detection system

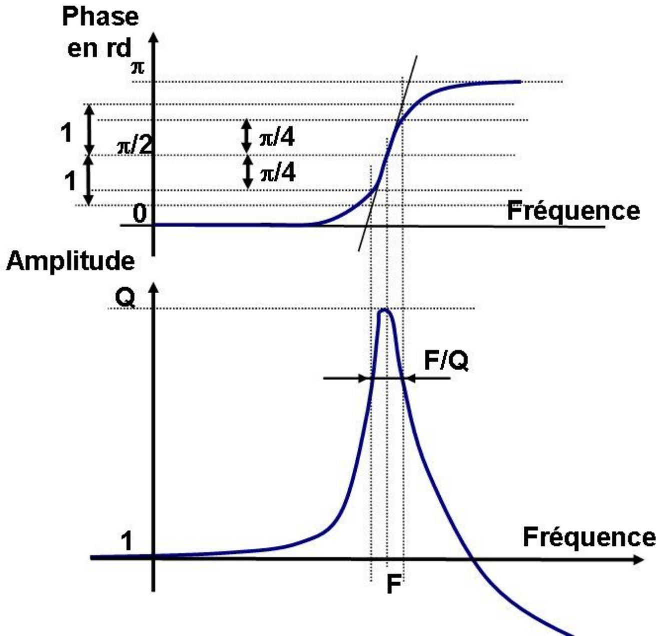
- ❑ Piezoelectric excitation
- ❑ Electronic oscillator

❑Monolithic differential accelerometer

- ❑ DIVA

Detailed Applications – VIA & DIVA
High-Q resonators

- **Oscillator accuracy**
  - High Q-factors required
- **Energy dissipation**
  - Gas damping
    - Vacuum (10^{-2} mbar) → neglected
    - Could be considered using
      - BEM Stokes formulation
      - PLM viscous acoustic elements
  - Thermoelastic damping
    - Main source of damping since monolithic structure
  - Clamp losses
- **Multiphysic analysis**
  - Mechanical, Electrical & thermal fields
  - Piezoelectric, thermo-mechanical couplings (+pyro)

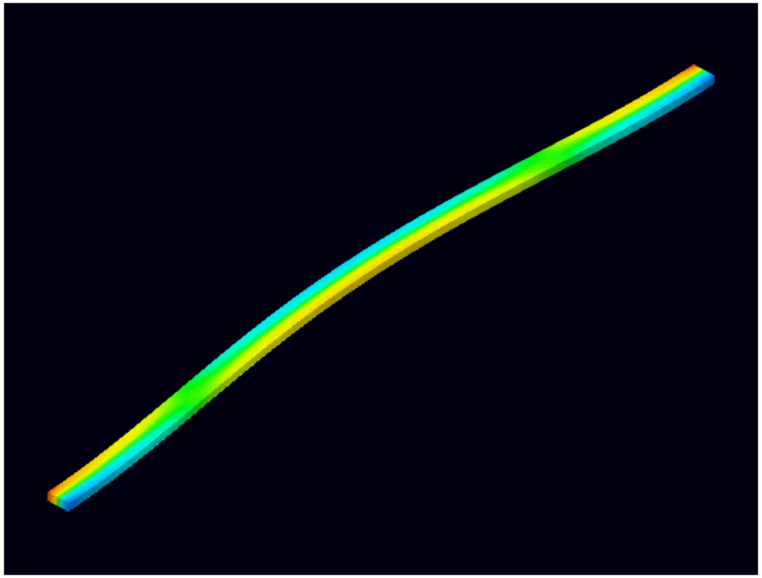


$$Q = 2\pi \cdot \frac{W_{Stored}}{W_{Dissipated}}$$

$$\Rightarrow \frac{1}{Q} = \frac{1}{Q_{gd}} + \frac{1}{Q_{ted}} + \frac{1}{Q_{cl}}$$

Detailed Applications – VIA & DIVA
Thermoelastic Damping

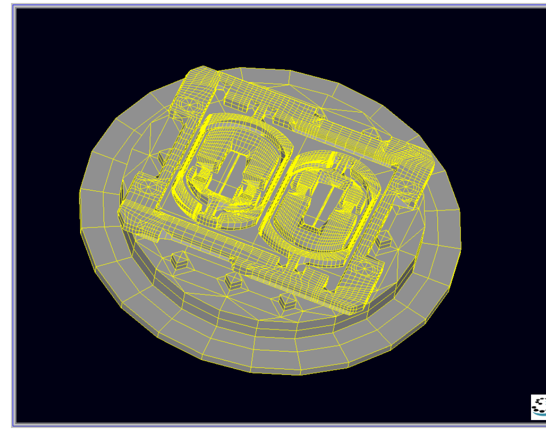
- Bending mode
  - Compression -> heating
  - Extension -> cooling
- Irreversible heat flow
  - Energy dissipation
  - Damping
- Limitation of analytical model
  - Anisotropic piezoelectric material
  - Complex 3D structure
    - Electrodes
    - …
- Modelling using OOFELIE
  - Harmonic response analysis or complex modal analysis
  - Influence of piezoelectricity, electrodes
  - 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

Detailed Applications – VIA & DIVA
Insulating frame



❑ Goals

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

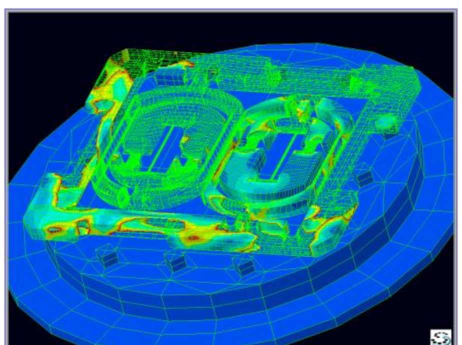
❑ Modal FEM Analysis

- ❑ Model quartz structure + TO8 base
- ❑ Evaluation of the strain energy dissipated in the base

→ Less than 10^{-8} of total vibrating energy in mounting parts

→ $Q_{decoupling} > 10^8$

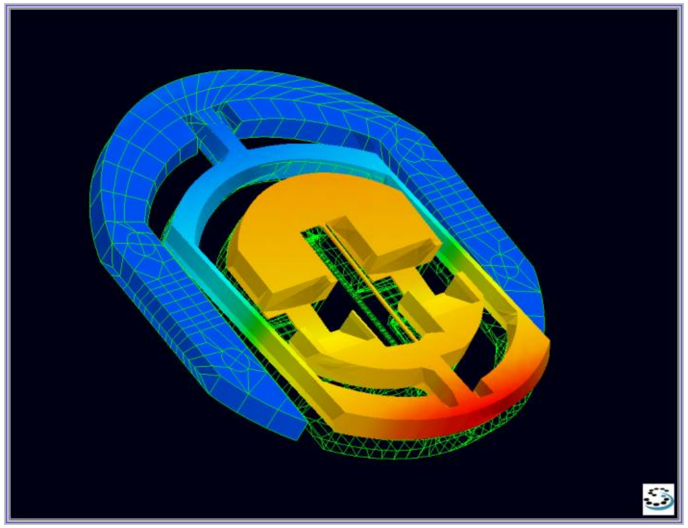
→ Can be neglected because Q_{ted} =13000



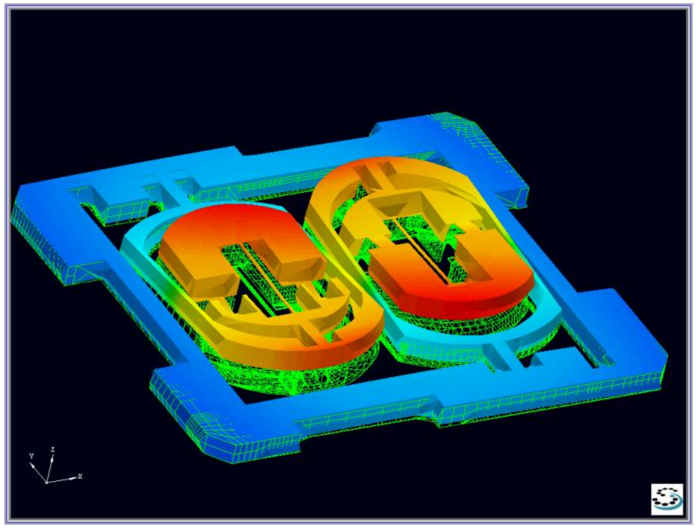
NOTE: more accurate computation of Q_{cl} could be performed using PML elements

Detailed Applications – VIA & DIVA
Scale factor estimation

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

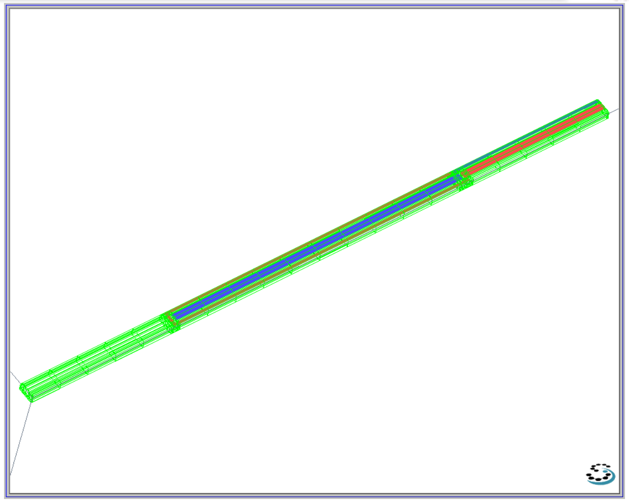


Numerical scale factor : 12.6 Hz/g
Experimental S.F. : ~ 12.5 Hz/g



Numerical scale factor : 31.9 Hz/g
Experimental S.F. : ~ 30.5 Hz/g

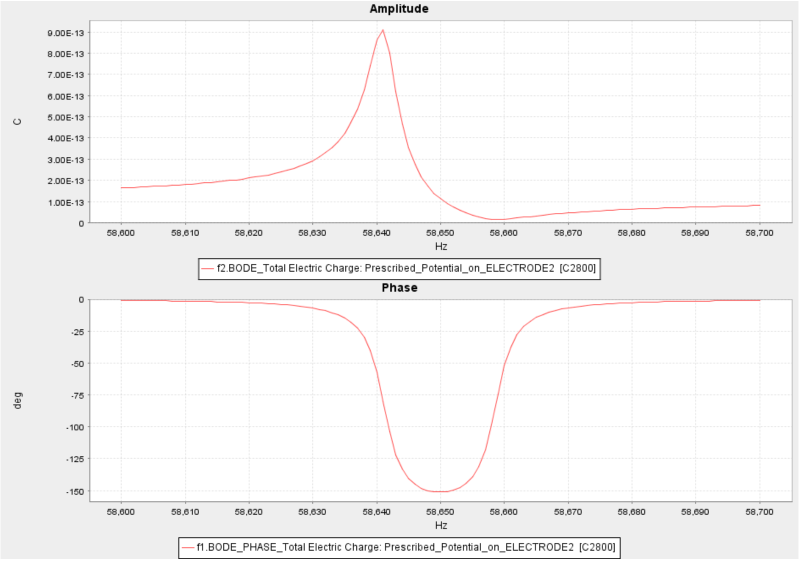
Detailed Applications – VIA & DIVA
Electrical behaviour (1/2)



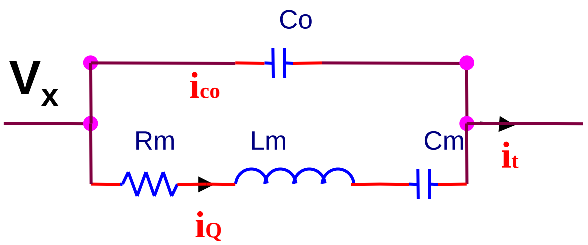
❑ Equivalent electrical model
- ❑ C_0 : Capacitance
- ❑ R_m, L_m, C_m : motional parameters.

❑ Influence on electronic oscillator

❑ Piezoelectric FEM analysis
- ❑ Electrical response of the transducer
- ❑ Motional parameters
  - ❑ C_0 # 1 pF
  - ❑ R_m # 3 MΩ
  - ❑ Good agreement with experiment

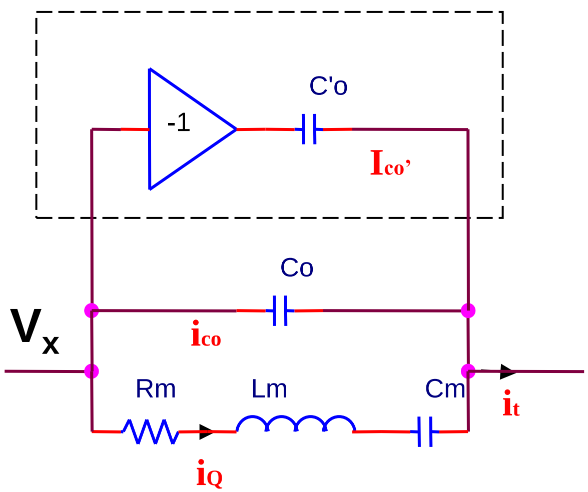


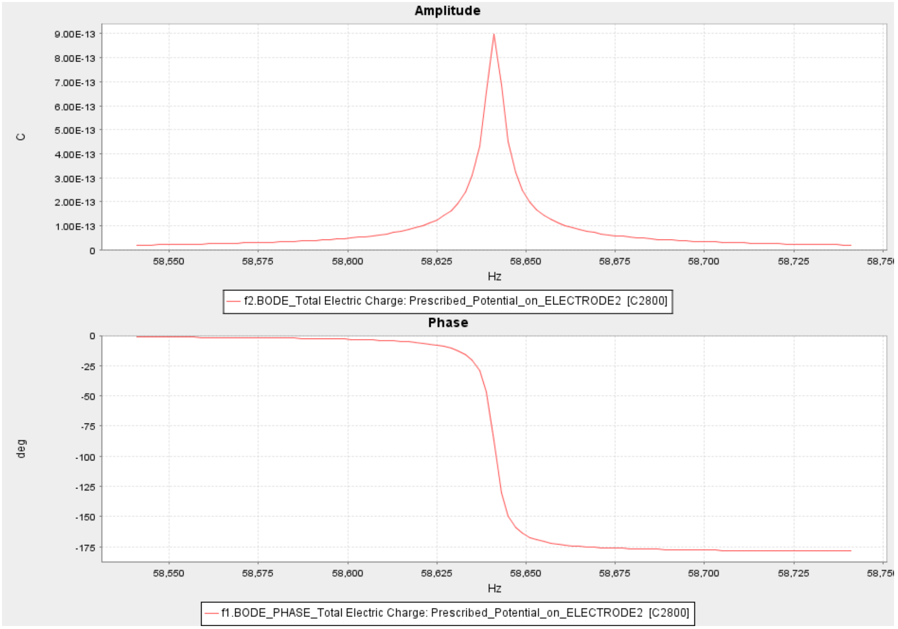
❑ Phase shift induced by C_0



Detailed Applications – VIA & DIVA
Electrical behaviour (2/2)

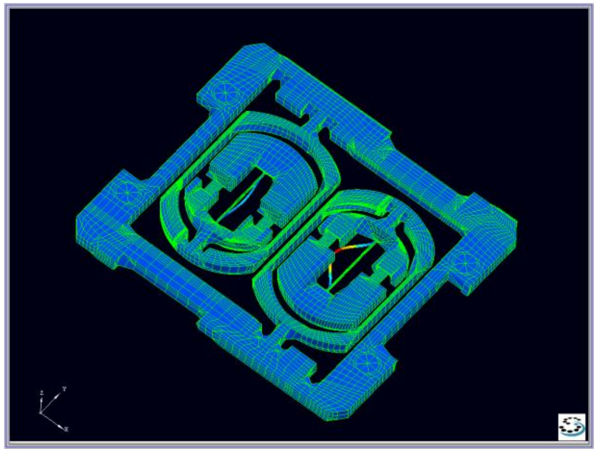
- **Influence of external electrical impedance**
  - Inter electrode capacitance cancellation
- **Impact of the electronic circuit on the transducer behavior**
  - Phase shift cancelled
  - Same quality factor
- **Better response of the transducer**

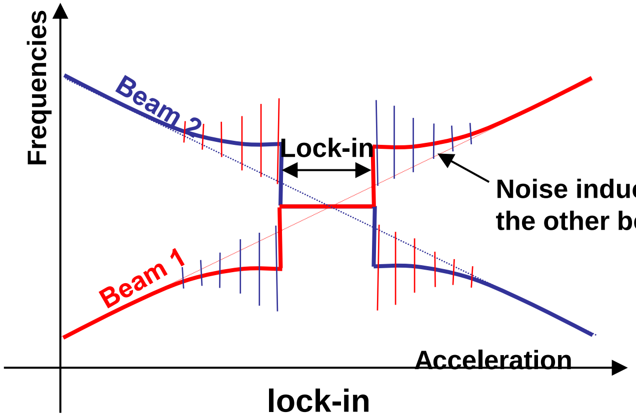




Detailed Applications – VIA & DIVA
DIVA: Lock-in phenomena

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

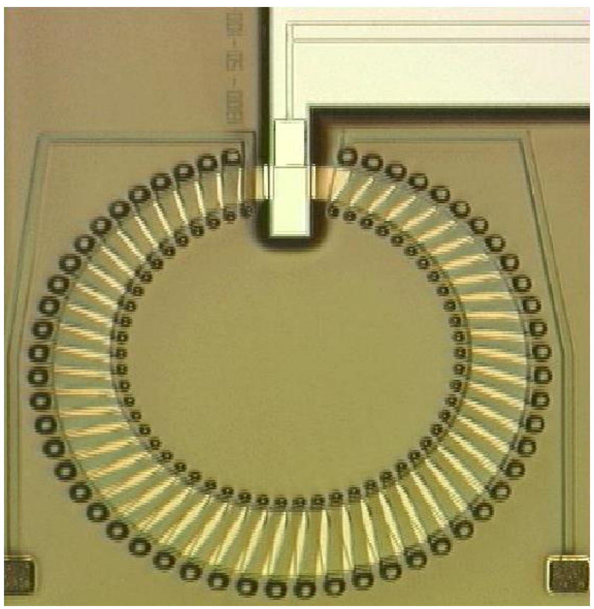


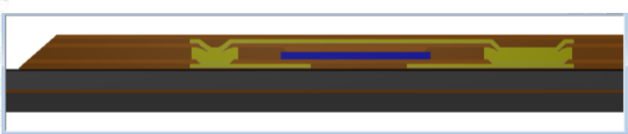


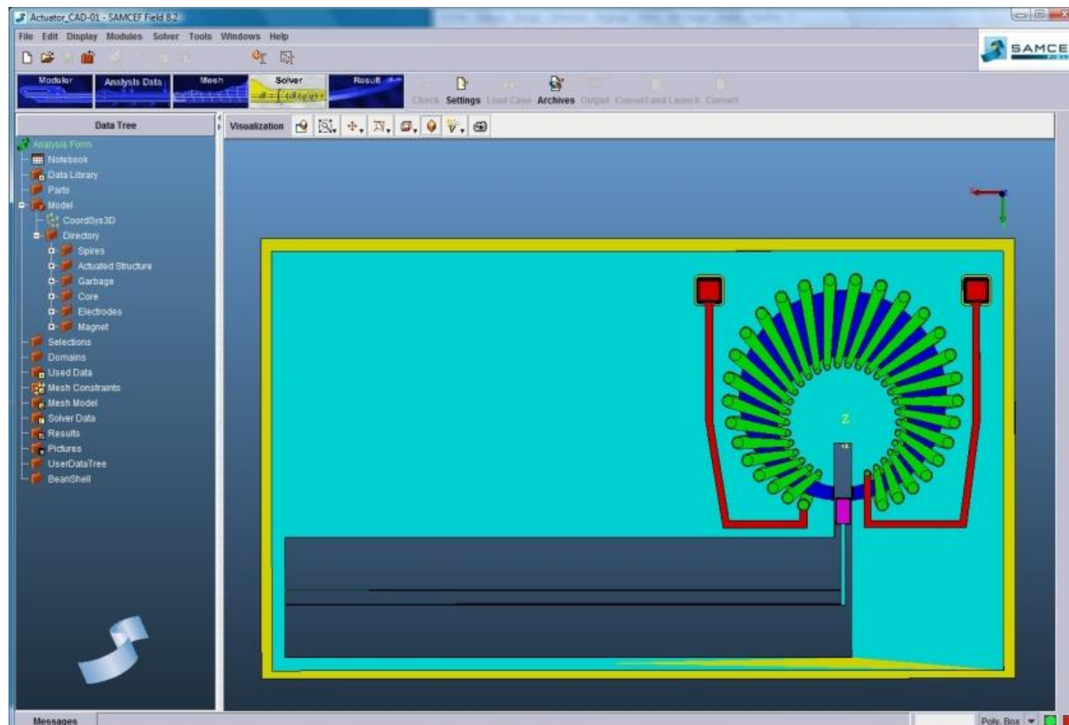
Detailed Applications
MEMS Electromagnetic actuator

❑ Electromagnetic Actuator

- ❑ Based on 25 µm thick SOI
- ❑ Magnetic core and plunger made of 4 µm electroplated soft magnetic permalloy - NiFe (80/20)
- ❑ Windings are realized by electroplating 2 µm of Copper.
- ❑ Isolation and planarization based on polymer deposition







Detailed Applications – MEMS Electromagnetic actuator
Simulation methodology

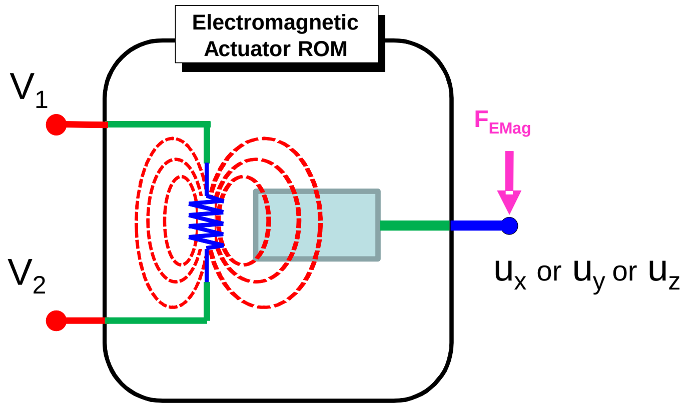
- **Basic mutiphysic analysis**
  - Non linear fully coupled analysis
    - → CPU time expensive
  - Large displacement of the plunger
    - → remeshing → CPU time expensive
- **Hypothesis**
  - no eddy current in the system
- **New efficient simulation strategy**
  - Reduced Order Model (ROM) construction of the electromagnetic actuation part with a succession of magnetostatic analyses
  - Use of generated ROM in a full 3D structural model
    - NL Static analysis
    - NL Transient analysis

Electromagnetic actuation ROM generation

- Construction of an EM parametric model in OOFELIE
  - u: position/displacement of the plunger in the considered direction
  - i: current injected in the coil

+ extraction of resistivity of « coil » : R

- Performing several NL magnetostatic analyses
  - Batch computation for a grid of values for u and i
  - For each couple (u,i)
    - Extraction of electromagnetic force on the plunger: F(u,i)
    - Extraction of secant inductance at the coil: L(u,i)
- Construction of polynomial expressions for F(u,i) and L(u,i) that will be used in the 3 nodes emag actuation ROM

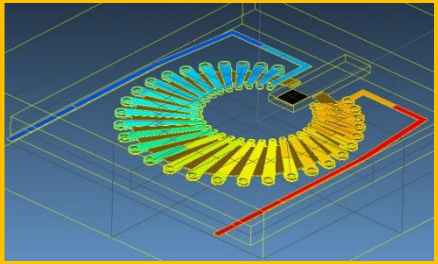


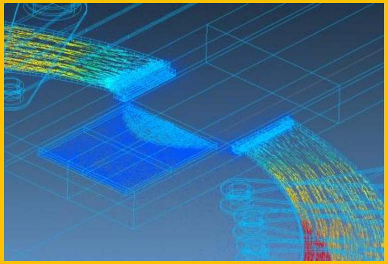
$$F(u,i)$$

$$V_1 - V_2 = R\,i + \frac{d(L(u,i)\,i)}{dt}$$

Detailed Applications - MEMS Electromagnetic actuator
Electromagnetic ROM generation

Sampling configuration space ($u=u_1,\ldots,u_N$)



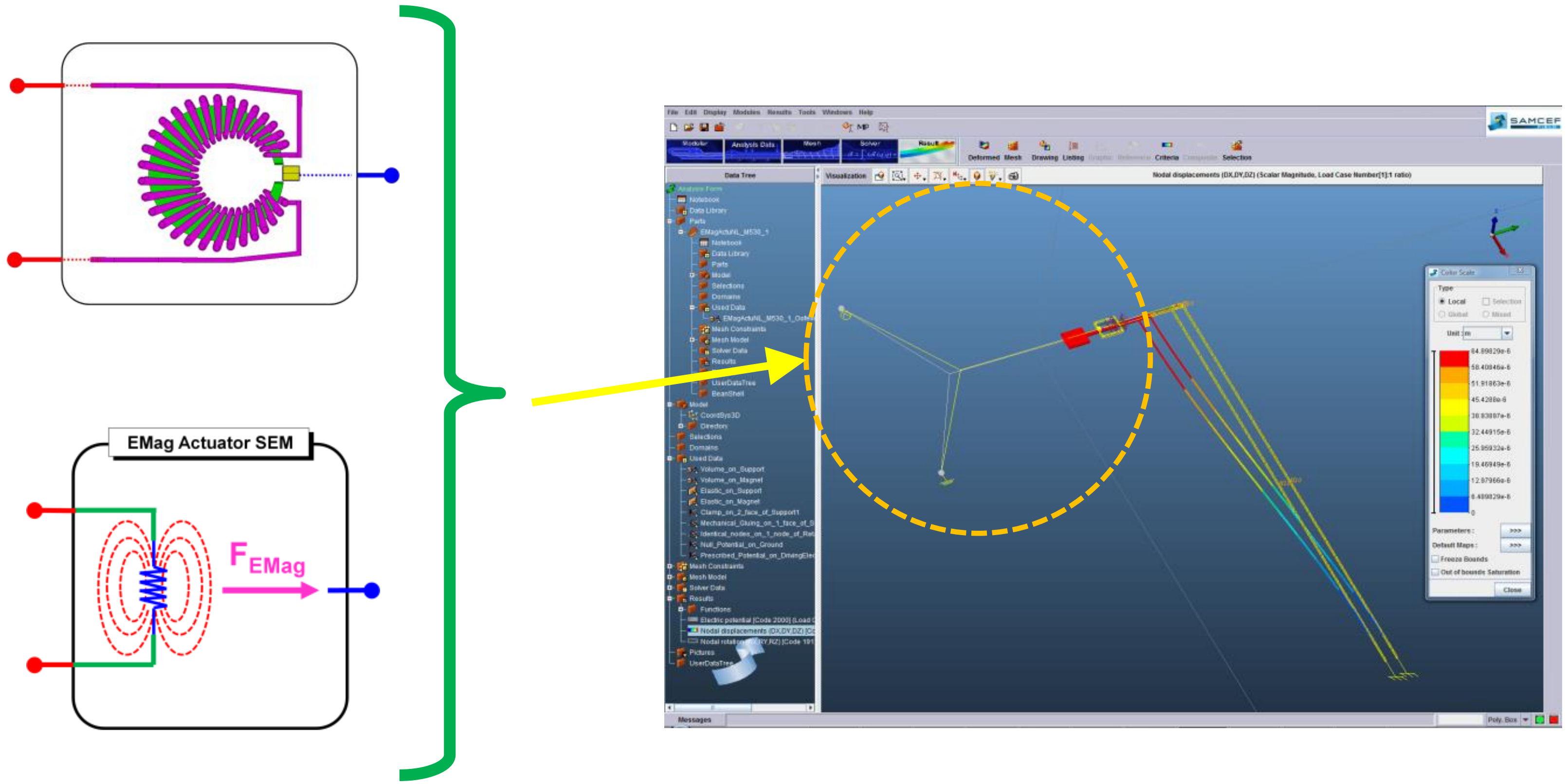


$L(u,i_1)$	$F(u,i_1)$
…	…
$L(u,i_M)$	$F(u,i_M)$

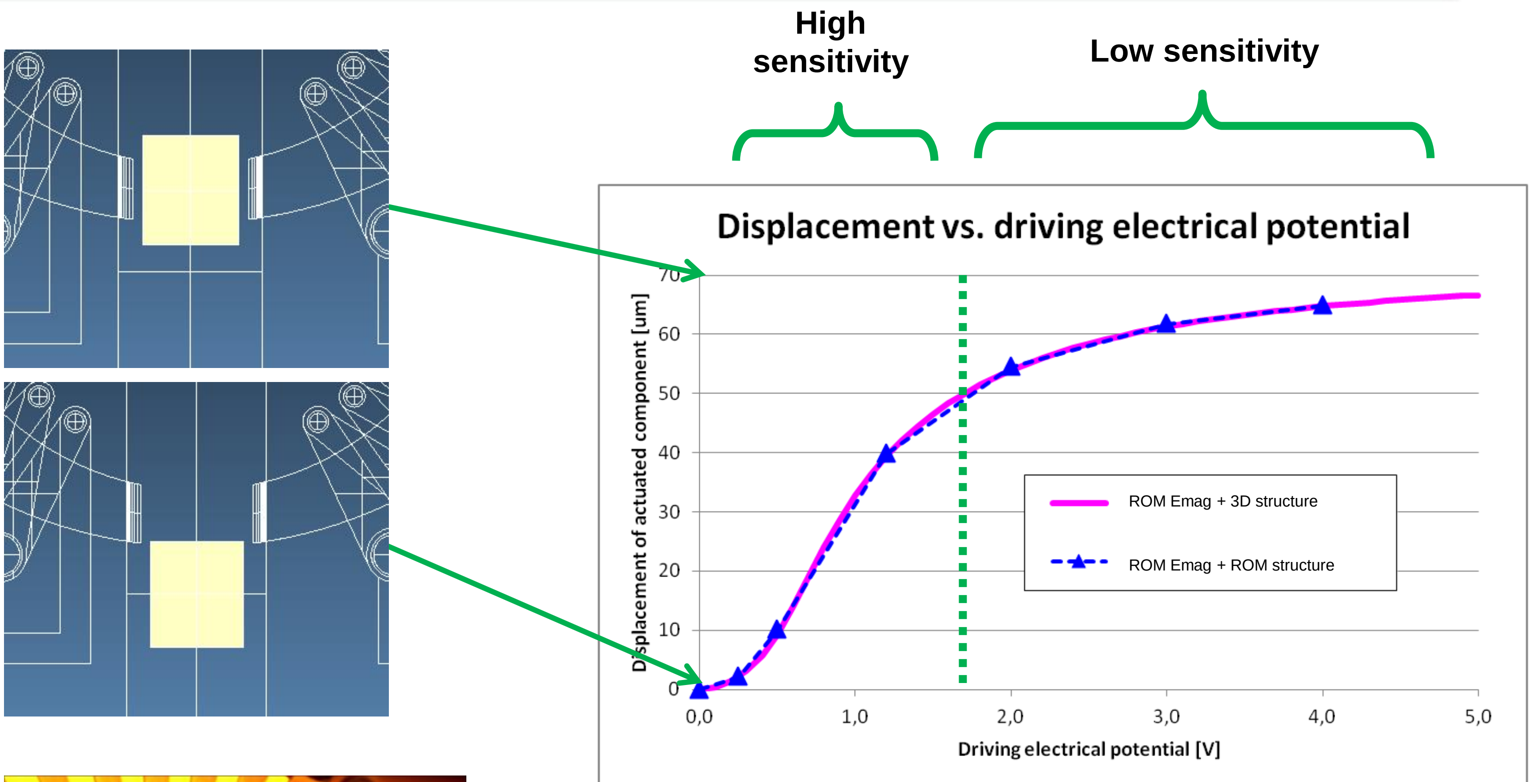
Building polynomial expression of L(u,i) & F(u,i)

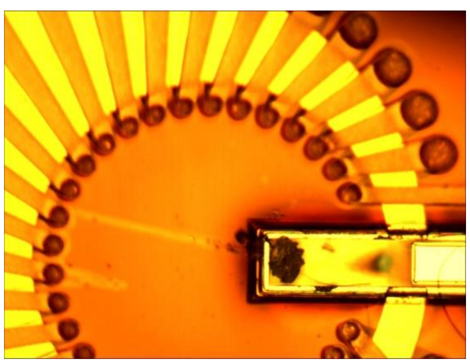
Building 3-nodes emag actuation ROM
+ introduction in a structural FEM model

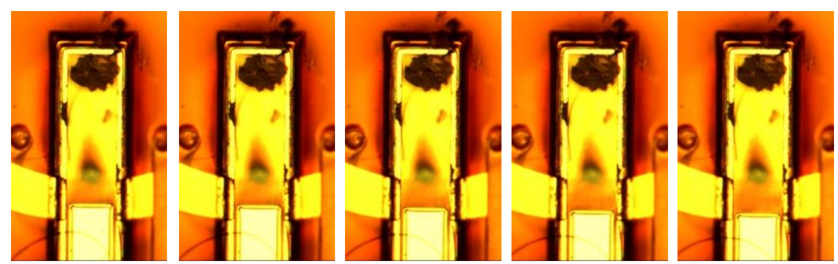
Detailed Applications - MEMS Electromagnetic actuator
Introduction of EMag ROM in structural model



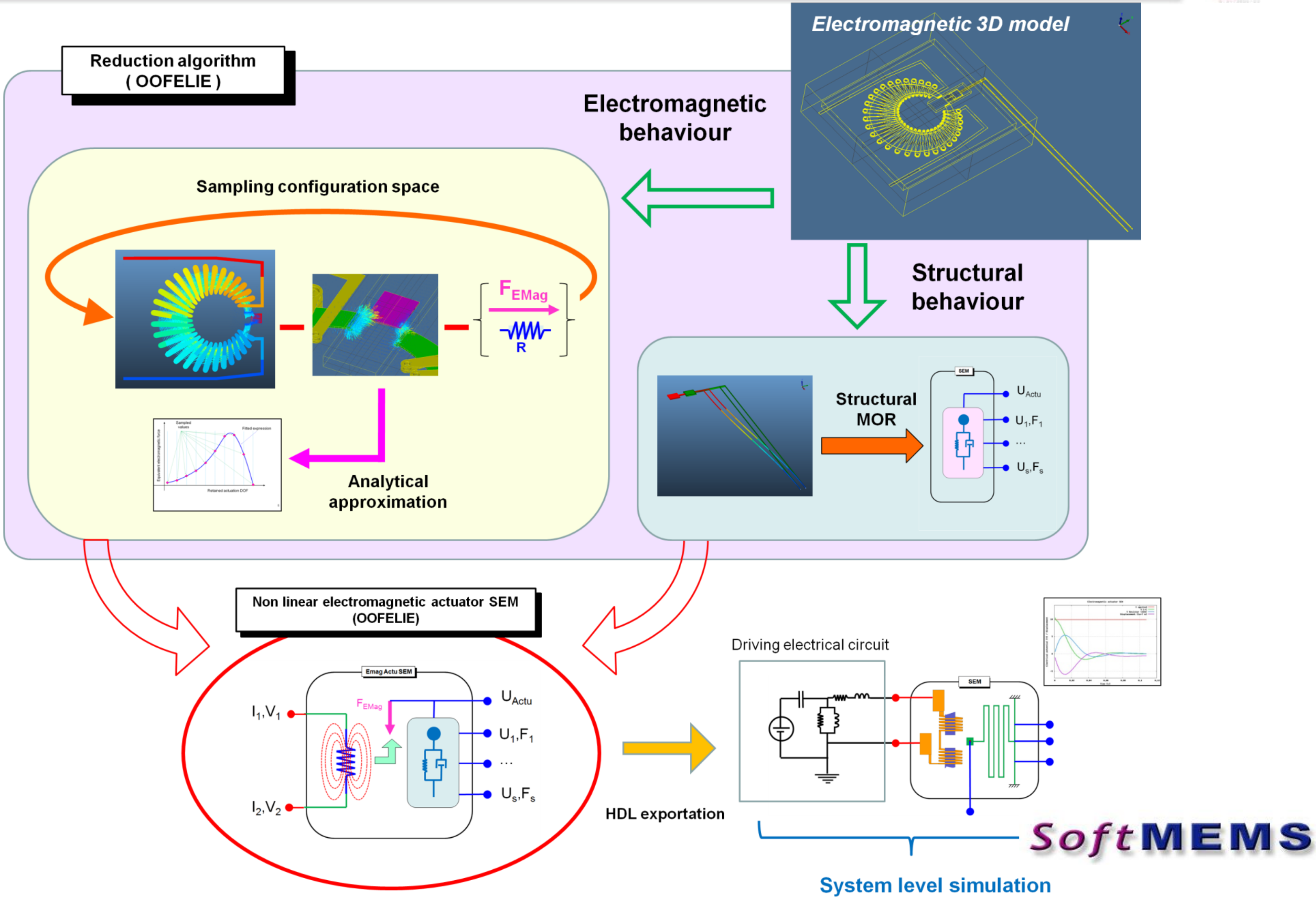
Detailed Applications - MEMS Electromagnetic actuator Application – Static equilibrium







MOR for Electromagnetic Actuators
Co-Simulation with IC



Conclusions

- **OOFELIE::Multiphysics simulation software**
  - Integrated CAE environment
  - Broad transducer domain coverage
  - Strongly coupled multiphysic approach for various MEMS applications
    - Electromagnetism
    - FSI
    - Piezo-thermomechanics (ex: ONERA VIA & DIVA)
    - Piezoresistive
    - …
  - Efficient resolution technique using ROM/SEM with full 3D structural model
    - Strong coupling is conserved (ex: MEMS emag actuator)
  - Multiphysics FEA combined with ZEMAX® for MOEMS design
  - ITAR free

- **New developments in progress**
  - Stochastic FEM to take into account uncertainties aspects at the first stage of design process…

Thank you

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