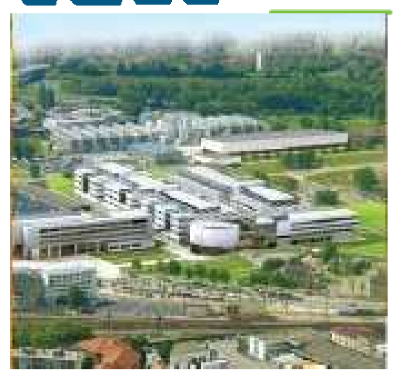
Nonlinear vibrations of M/NEMS resonant sensors

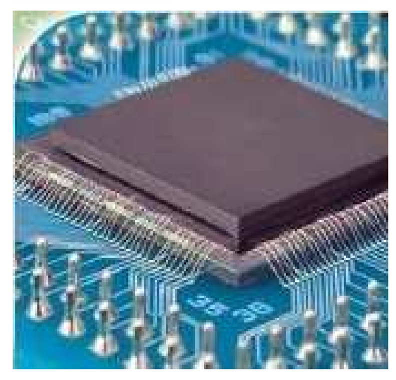
Najib KACEM[1;2], Sébastien BAGUET[1], Régis DUFOUR[1] , Sébastien HENTZ[2]

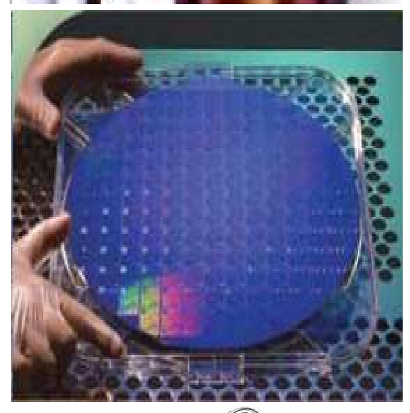
[1] LaMCoS, INSA-Lyon, CNRS UMR5259 [2] CEA/LETI - MINATEC, Grenoble

Context

- Collaboration with CEA LETI, applied research center for microelectronics.
- M/NEMS (Micro/Nano Electro-Mechanical Systems) sensors are used for GPS navigation, camcorder stabilization, airbag, video games, missile guidance, …
- Scaling MEMS down to NEMS makes the dynamic behavior nonlinear.
- Need for a lightweight and easy-to-use model for MEMS designers.





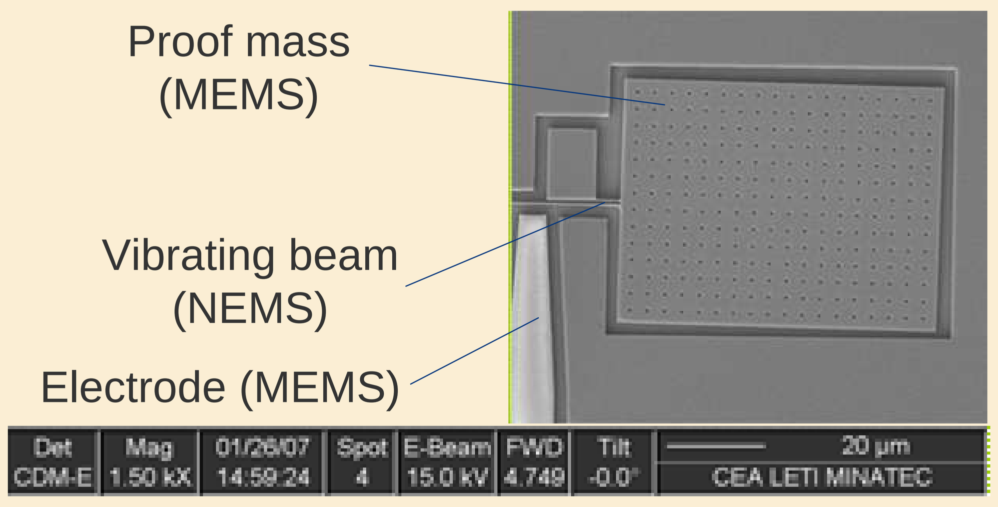



Objectives

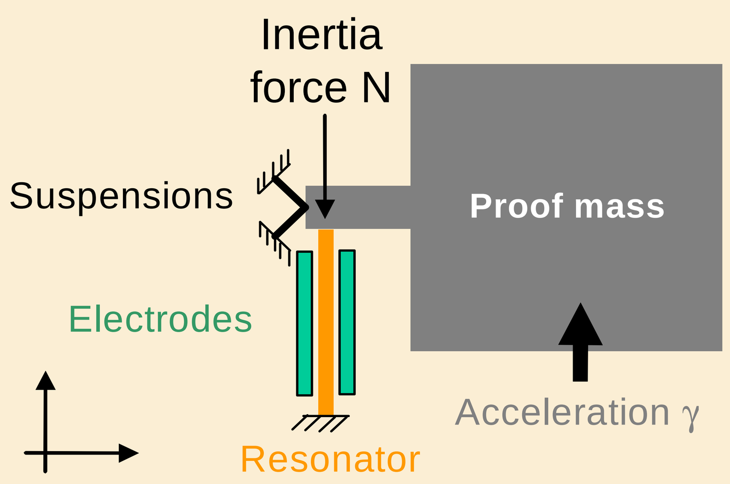
- Nonlinear dynamics of MEMS resonators (numerical and analytical solutions).
- Strategies for enhancing the performances.

MEMS accelerometer sensor

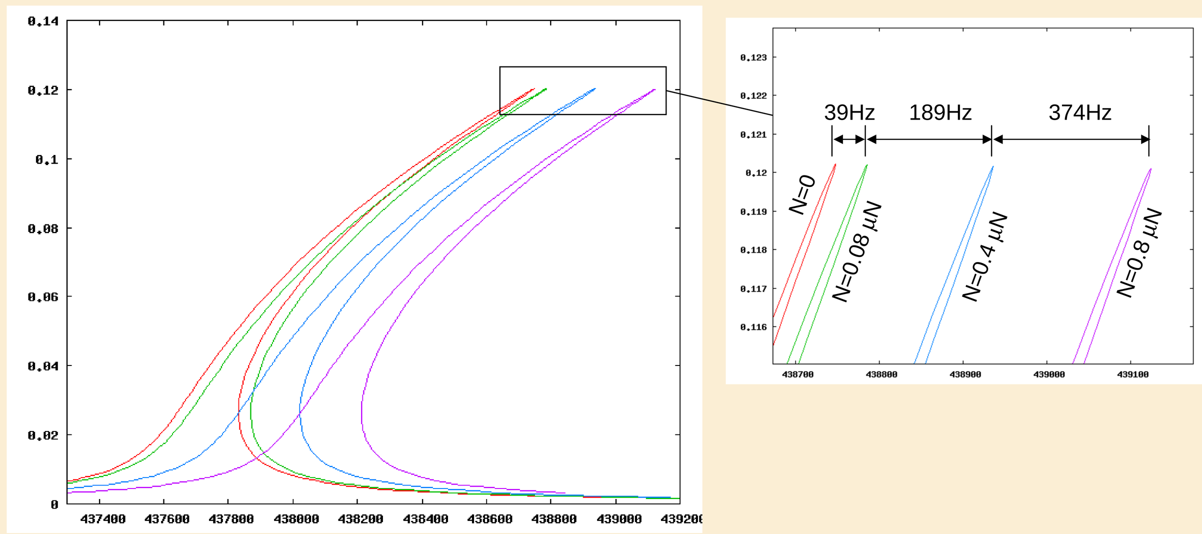
- Resonator = vibrating beam + activation/detection electrodes.
- Continuous voltage Vdc for bending + alternating harmonic voltage Vac at fundamental frequency
- The variation of the axial load (inertia of the mass subjected to acceleration) induces a variation of the fundamental frequency of the resonator
- The measurement of the variation in frequency leads to the axial load (ie acceleration)



SEM image of the resonant accelerometer



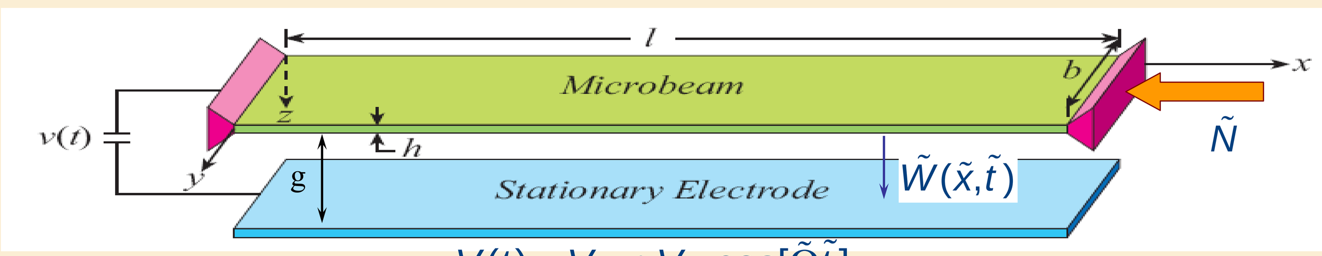
Schematic representation



Variation of fundamental frequency due to axial load N

Multiphysics model

- Euler-Bernoulli beam
- Mechanical and electrostatic nonlinearities



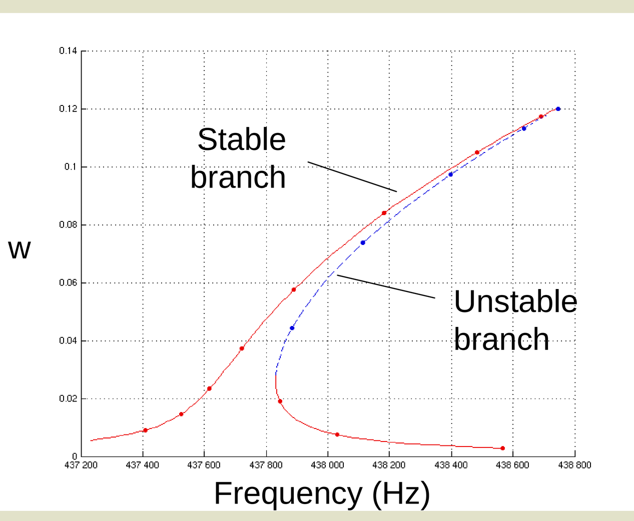
$$V(t)=V_{dc}+V_{ac}\cos[\tilde{\Omega}\tilde{t}]$$

$$EI\frac{\partial^4\tilde{w}}{\partial\tilde{x}^4}+\rho bh\frac{\partial^2\tilde{w}}{\partial\tilde{t}^2}+\tilde{c}\frac{\partial\tilde{w}}{\partial\tilde{t}}-\left[\tilde{N}+\frac{Ebh}{2l}\int_0^l\left(\frac{\partial\tilde{w}}{\partial\tilde{x}}\right)^2 d\tilde{x}\right]\frac{\partial^2\tilde{w}}{\partial\tilde{x}^2}=\frac{1}{2}\varepsilon_0 b\frac{\left[V_{dc}+V_{ac}\cos(\tilde{\Omega}\tilde{t})\right]^2}{(g-\tilde{w})^2}$$

Elastic force | Inertia force | Dissipative force | Axial force | Geometric nonlinearity Large deformations | Nonlinear Electrostatic force

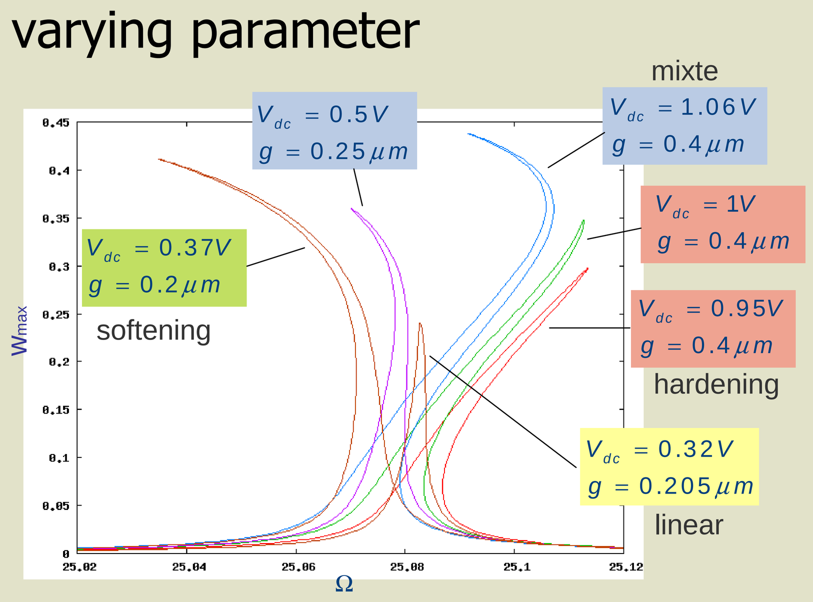
Numerical simulations

- Modal decomposition
- Harmonic Balance (HBM) : decomposition in Fourier series
  Nonlinear differential problem ⇨ Nonlinear algebraic problem
- Asymptotic Numerical Method (MAN) : robust continuation of Nonlinear solutions with respect to a varying parameter



$l = 200\,\mu m$, $b = 4\,\mu m$, $h = 2\,\mu m$, $g = 1\,\mu m$, $N = 15\,MPa$, $E = 169\,MPa$, $\rho = 2330\,kg/m^3$, $Q = 10000$, $V_{dc} = 100 V_{ac}$

Response curve of the resonator : transverse displacement vs. frequency



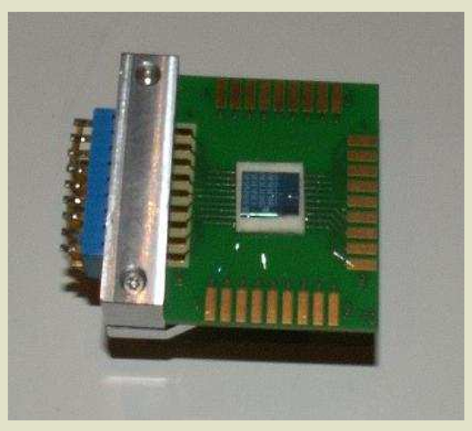
Influence of the electrostatic force on the nonlinear dynamic behavior

Analytical solution

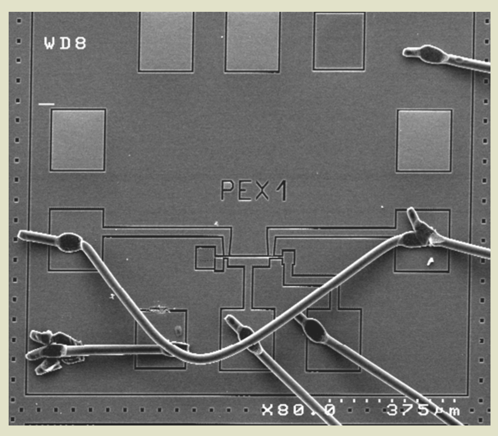
- Perturbation technique : averaging
- Closed-form expressions of the critical amplitude and the dynamic pull-in amplitude
- Simplified model for fast M/NEMS design

Experimental validation

SEM



Test card with sample resonators



SEM image of the resonator

Performance enhancement

- The resonator can be driven beyond the critical amplitude by cancelling out the nonlinearities
- Pull-in retarding under superharmonic excitation

Future work

- Resonator with 2 electrodes for actuation and sensing
- Extension to resonant gyroscope with axial parametric excitation
- Cantilever beam for mass detection

Sebastien.baguet@insa-lyon.fr
LaMCoS, Université de Lyon, CNRS, INSA-Lyon UMR5259
18-20 rue des Sciences - F69621 Villeurbanne Cedex

Laboratoire de Mécanique des Contacts et des Structures