NE 211 : MICRO AND NANOMECHANICS

COURSE PROJECT

Simulation of a Z-axis Differential Capacitive Accelerometer

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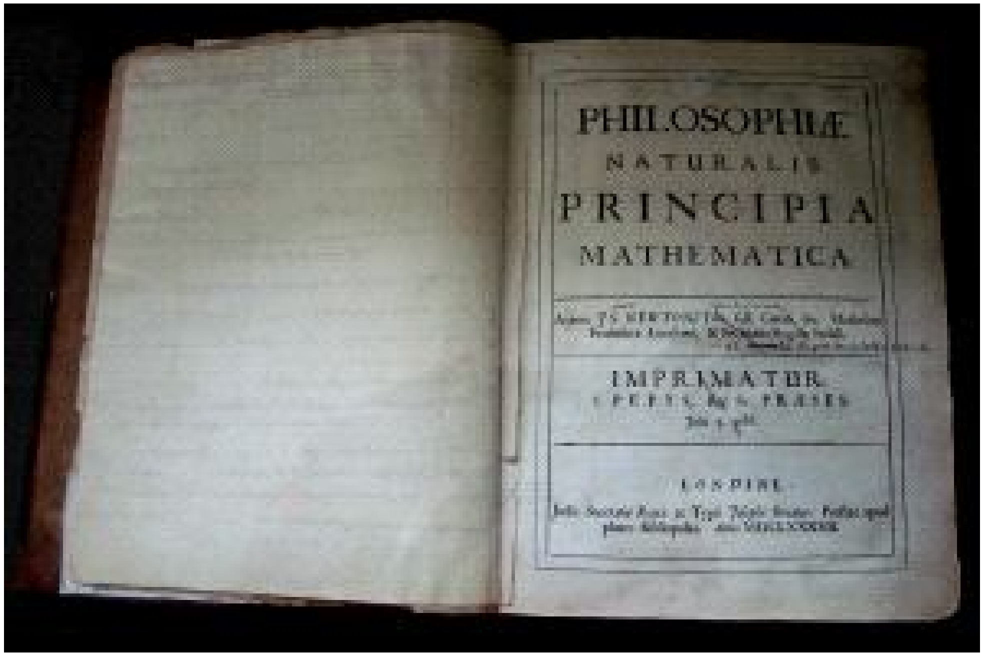
Overview

- ❖ Introduction
- ❖ Accelerometer Model
- ❖ Major Specifications
- ❖ Accelerometer Configuration
- ❖ About the Software
- ❖ Detailed design analyses
    - Static Analysis
    - Modal Analysis
    - Damping Analysis
    - Transient Analysis
    - Sensitivity Analysis
    - Cross Axis Sensitivity
    - Pull-in Analysis
    - Harmonic Analysis
- ❖ Conclusions

What is Acceleration?

- Acceleration - The rate of change of velocity.
- It is a vector quantity with dimension $L\ T^{-2}$.
- In SI units, acceleration is measured in meter per second squared (m/s^2).



Principia (1687): **Newton published his studies about the gravitational force that he developed in 1665/66 at the age of 23.**

"... all matter attracts all other matter with a force proportional to the product of their masses and inversely proportional to the square of the distance between them."

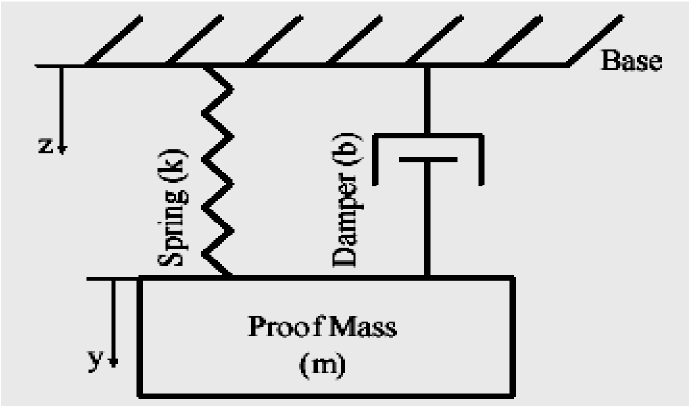
Accelerometer Model

Equation of motion of simple spring mass system: $$m\frac{d^2x}{dt^2} + kx = 0$$

Equation of motion of spring mass system with damping: $$m\frac{d^2x}{dt^2} + b\frac{dx}{dt} + kx = 0$$

Equation of motion of forced vibration

$$F = ma = m\frac{d^2x}{dt^2} + b\frac{dx}{dt} + kx$$ **Where, x = y-z**



Mass-spring-damper system

By taking the Laplace transform

$$ma(s) = ms^2X(s) + bsX(s) + kX(s)$$

$$\frac{X(s)}{a(s)} = \frac{1}{s^2 + \frac{b}{m}s + \frac{k}{m}}$$

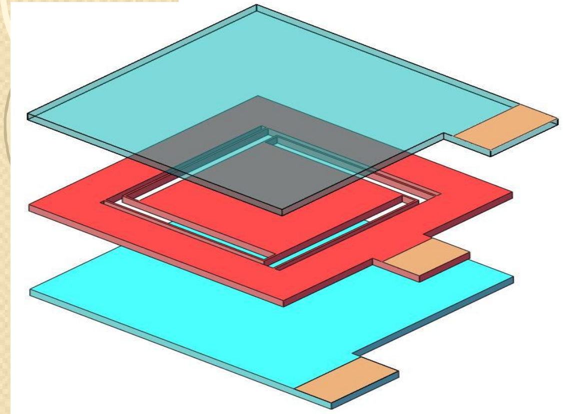
where ω_0 is the resonance frequency of the accelerometer and Q is the quality factor.

$$\omega_0 = \sqrt{\frac{k}{m}} \qquad Q = \frac{\omega_0 m}{b}$$

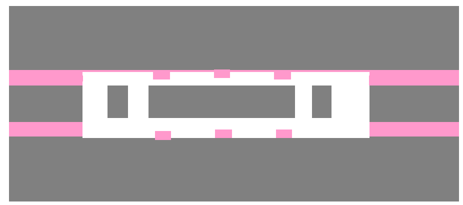
Major Specifications

Parameter	Value
Input Range	±30g
Sensitivity	100 mV /g
Non Linearity	< 1% of FS
Resolution	20 mg
Cross axis sensitivity	< 1% of FS
Operating Temp range	0 – 80^{o}C
Bandwidth	100 Hz

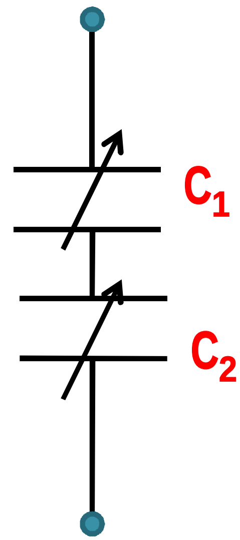
Accelerometer Configuration

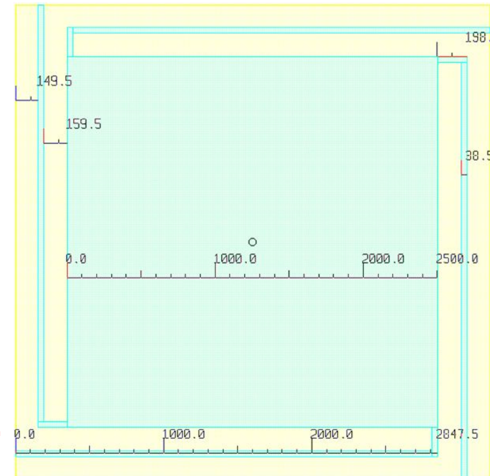


Exploded View of the Chip



Cross Section of the Chip

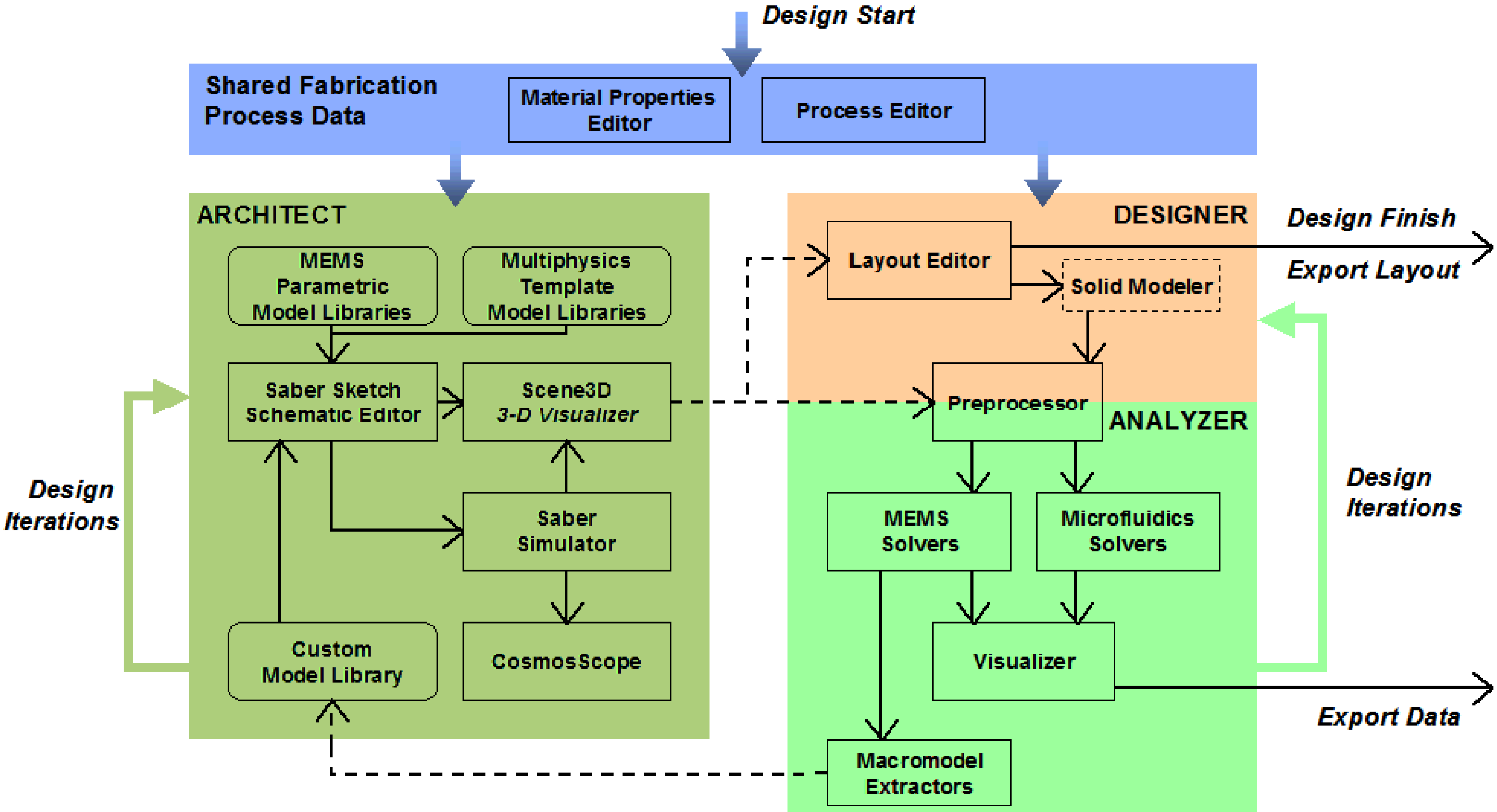




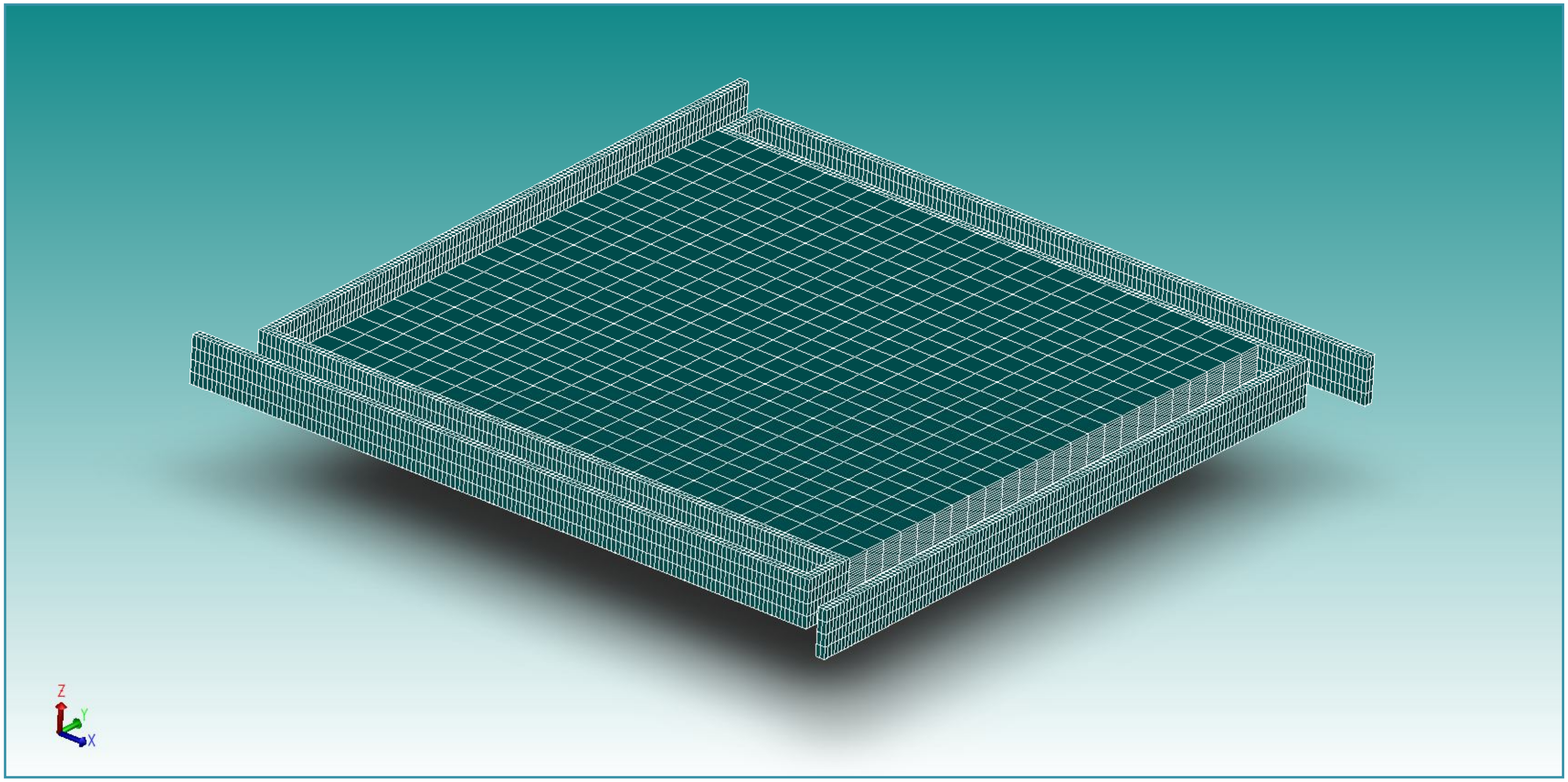
Top View of Sensing element

- The accelerometer is a Three wafer Si-Si-Si structure fabricated using fusion bonding
- A 2µm thickness SiO_2 isolates the PM layer from top electrode and bottom electrode. Al metallisation is done on the contact pads to take out the electrical connections
- The sensing element consists of a PM suspended by 4 L-shaped beams anchored on to the frame
- The PM structure is sandwiched between the two electrodes (top and bottom) to measure the differential capacitance
- The contacts to the three layers are taken out by means of projections coming out of the bonded area

About the Software



Solid Model of the Sensing Element



- **Meshing Type : Manhattan Bricks**
- **Mesher Settings for Proof Mass : 100 x 100 x 10 (μm^3)**
- **Mesher Settings for Beams : 20 x 20 x 50 (μm^3)**

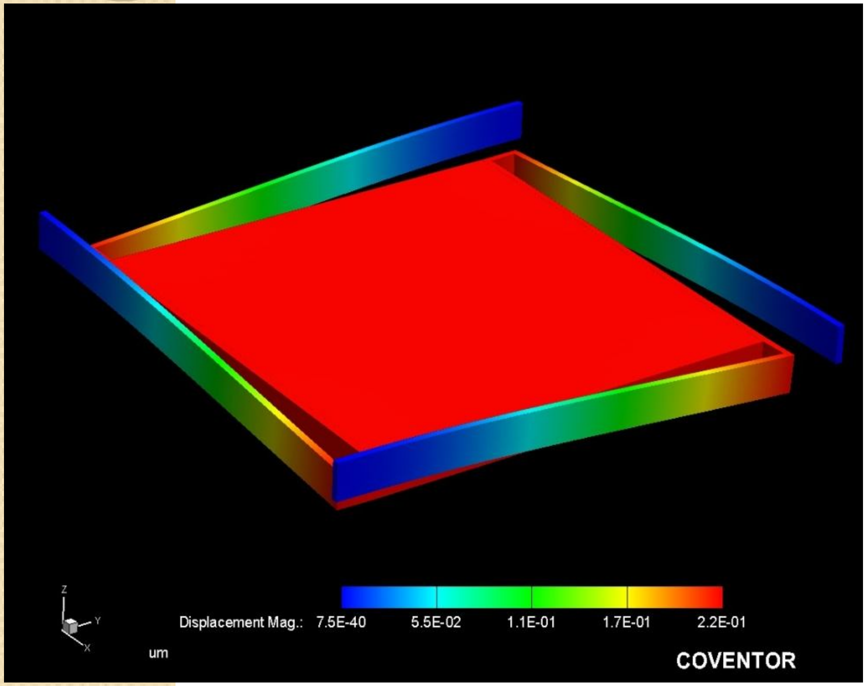
Solid Model of the Sensing Element

Manhattan Meshing

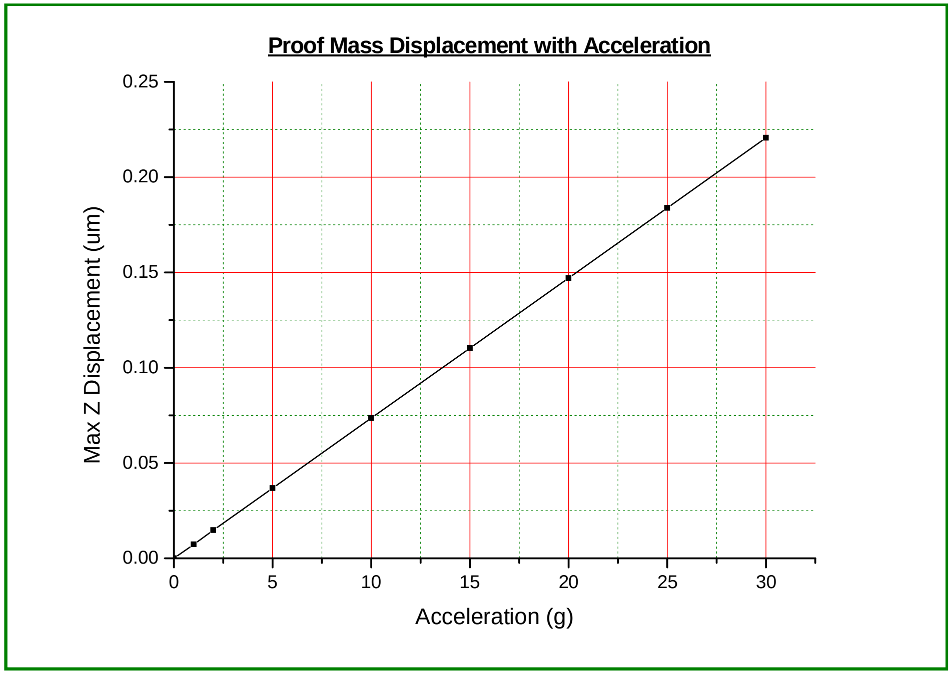
- **The Manhattan bricks mesh option creates orthogonal or nearly orthogonal hexahedral (brick) elements.**
- ***The mesher* subdivides the geometry of the entity to be meshed at concave intersections of faces, and then further subdivides the entity using planes that are parallel or nearly parallel to the faces.**
- **<u>This type of meshing is used for models with orthogonal or nearly orthogonal geometry.</u>**
- **The model does not need to be aligned with the principal axes of the global coordinate system.**
- **This mesher supports sloped sidewalls.**

Static Analysis

- **Applied Input acceleration (in g) : 1 , 2 , 5, 10 , 15 , 20 , 25 , 30**
- **Parametric Analysis to get the static displacement**



Deformed Structure @ 30g

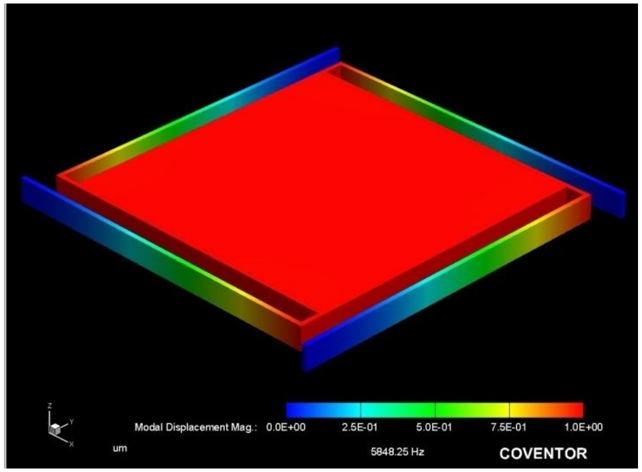


Parametric Analysis for Static Displacement

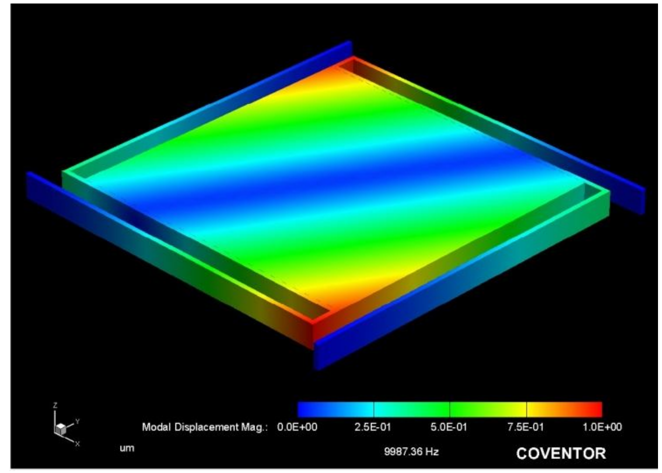
- **Proof mass displacement @ 30g : 0.22065 µm**
- **Analytical value of Proof mass deflection @ 30g : 0.19042 µm**

Modal Analysis

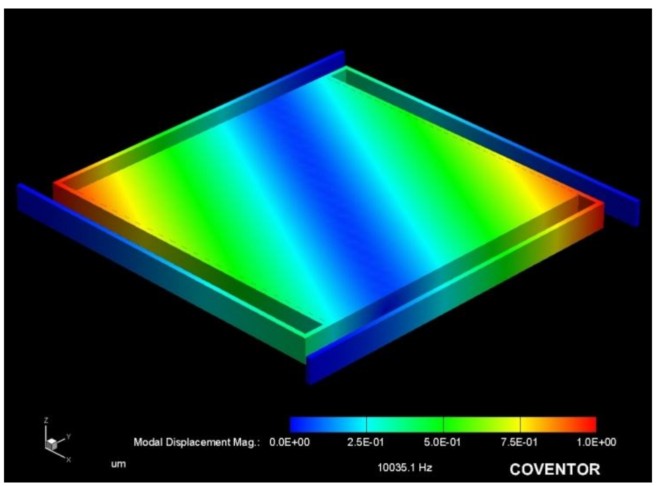
- To get the First 4 Modes of Vibration



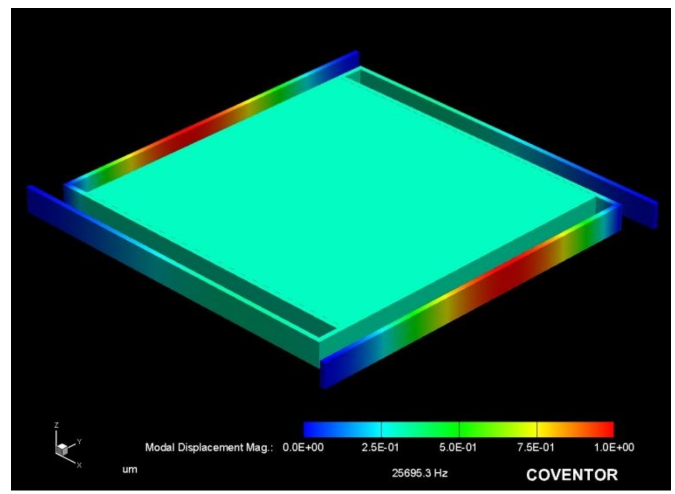
Mode 1 : 5848.25 Hz



Mode 2 : 9987.36 Hz



Mode 3 : 10.0351 KHz



Mode 4 : 25.6953 KHz

Analytical value of Mode 1 Frequency : 6253.73 Hz

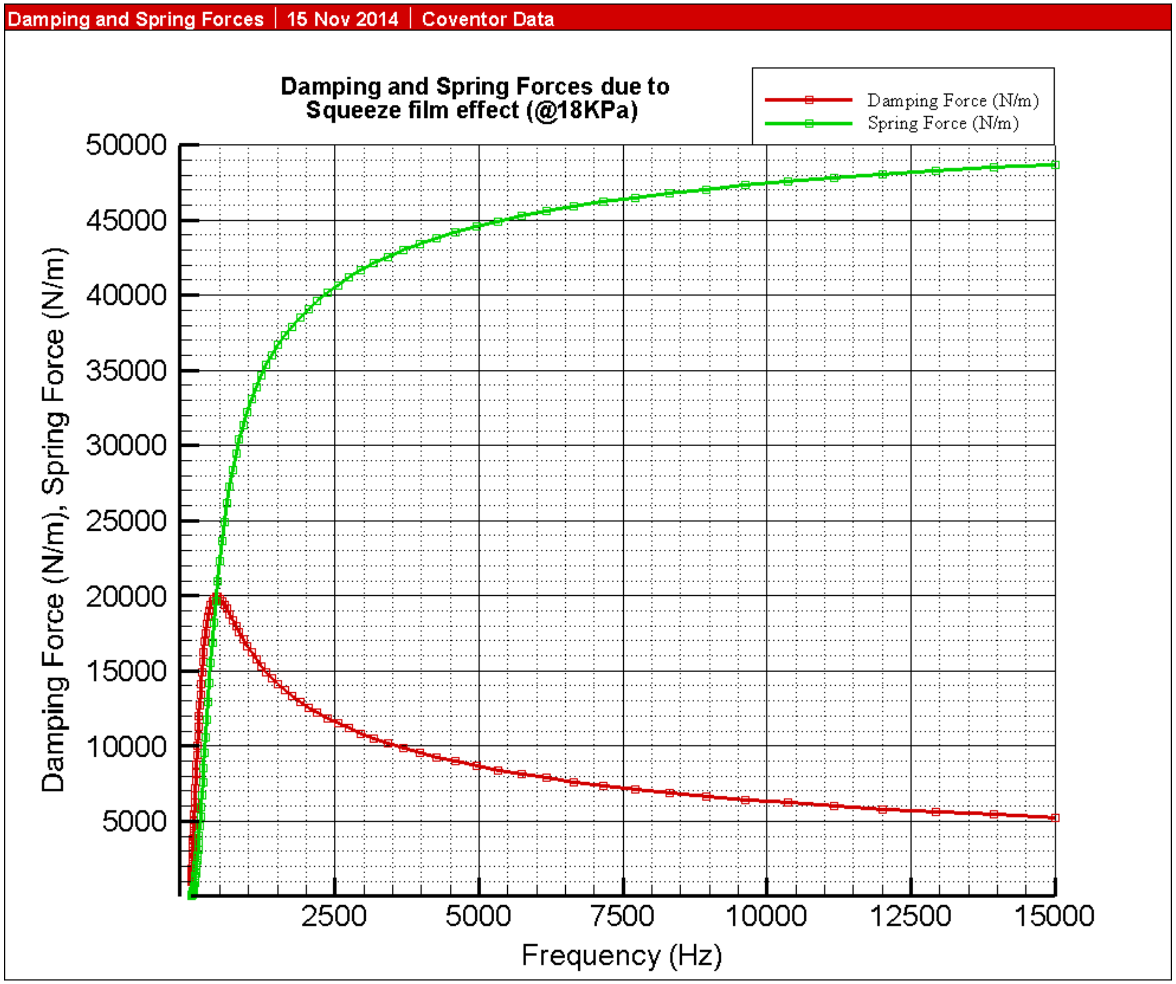
Damping Analysis

Linearized Reynolds Equation

$$\frac{p_o h_o^2}{12\mu_{eff}}\nabla^2\left(\frac{\Delta p}{P_0}\right) - \frac{\partial}{\partial t}\left(\frac{\Delta p}{P_0}\right) = \frac{\partial}{\partial t}\left(\frac{h}{h_o}\right)$$

- **Coventor uses the Damping MM Module to do damping analysis**
- **The Squeezed Film solver uses flow resistance models to set up a finite-element representation of the linearized Reynolds equation for a given input geometry.**
- **Damping MM then applies the Arnoldi algorithm to reduce the order of the system matrix required to adequately model the squeezed film flow.**
- **From this reduced-order model, the damping and spring forces can be calculated over a predefined frequency range.**
- **Damping MM, not only solves for damping due to viscous effects, but also for spring effects due to the compressibility of a fluid.**

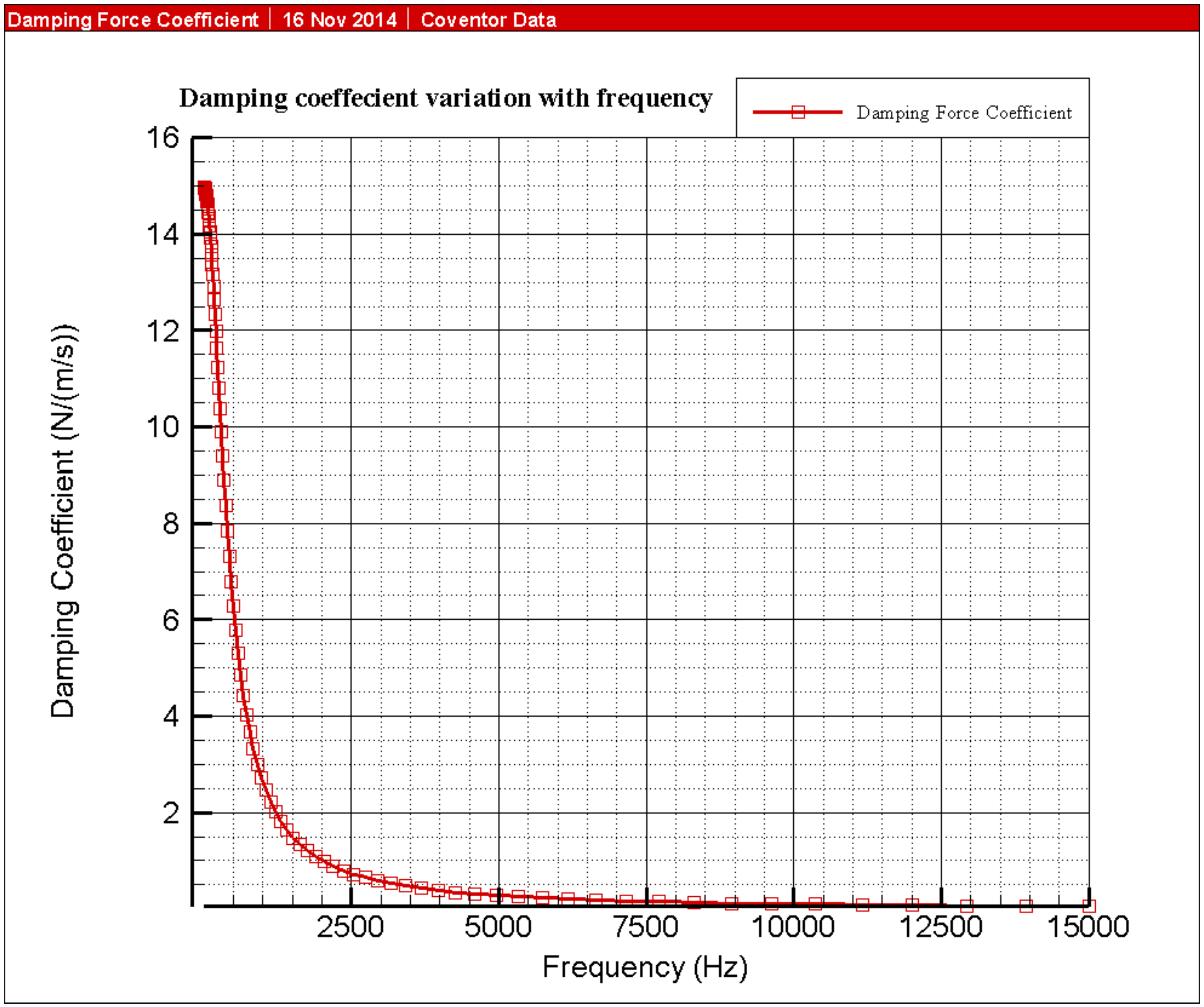
Damping Analysis



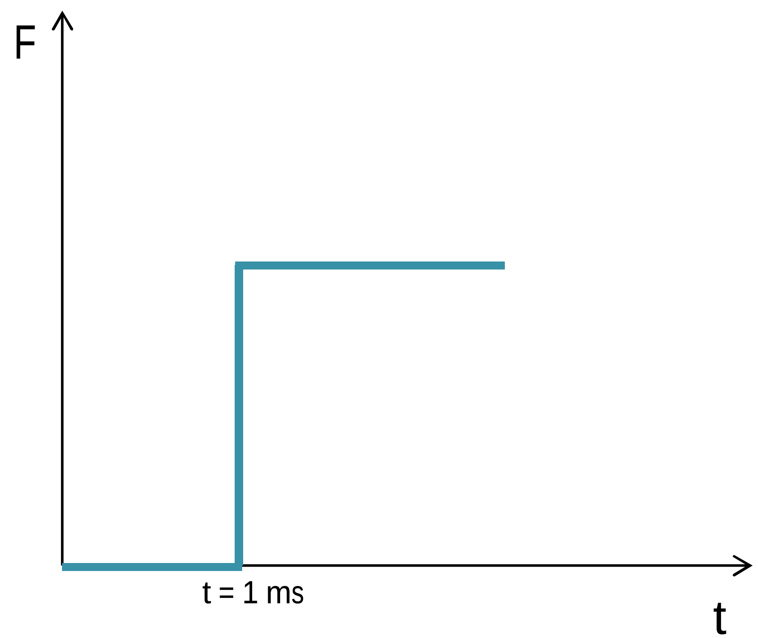
- **Cut-off frequency from simulation : 440 Hz**
- **Cut-off frequency from analytical lumped modeling : 474 Hz**

Damping Analysis

- **At a Pressure of 18KPa**



Transient Analysis



- **The response of the Accelerometer to a step input is studied**
- **The input is a step force function at time t = 0.001 s**
- **The Transient analysis is studied at different values of encapsulation pressure of P = 500 Pa, 1 KPa, 2 Kpa, 5 KPa, 10 Kpa, 15KPa, 20 KPa, 40 Kpa to study the under damped, critically damped and over damped cases**

Transient Analysis

- CoventorWare's MemMech uses Rayleigh Damping parameters α and β to take into account various damping effects in dynamic simulations.

- The general dynamic vibration equation can be described as

$$[M][\ddot{x}] + [C][\dot{x}] + [K][x] = [F]$$

- On orthogonal transformation using eigenvectors instead of individual translations and rotations, this dynamic vibration equation can be reduced to the form

$$[m_j][\ddot{z}_j] + [c_j][\dot{z}_j] + [k_j][z_j] = [F_j]$$

- In this form, the equation represents a collection of uncoupled eigenvector equations for a multi-degree of freedom system.

$$[\ddot{z}_j] + 2\zeta_j\omega_j[\dot{z}_j] + \omega_j^2[z_j] = [f_j]$$

- Rayleigh or proportional damping uses a convenient mass and spring-dependent relationship to describe the overall damping:

$$[C] = \alpha[M] + \beta[K]$$

Transient Analysis

- With orthogonal transformation reduces to the damping relationship

$$2\zeta_j\omega_j = \alpha + \beta\omega_j^2$$

- For the first and second modes :

$$2\zeta_1\omega_1 = \alpha + \beta\omega_1^2$$

$$2\zeta_2\omega_2 = \alpha + \beta\omega_2^2$$

- The solution to this system of simultaneous equations is

$$\alpha = 2\omega_1\omega_2\frac{(\zeta_1\omega_2 - \zeta_2\omega_1)}{(\omega_2^2 - \omega_1^2)} \quad \text{and} \quad \beta = 2\frac{(\zeta_2\omega_2 - \zeta_1\omega_1)}{(\omega_2^2 - \omega_1^2)}$$

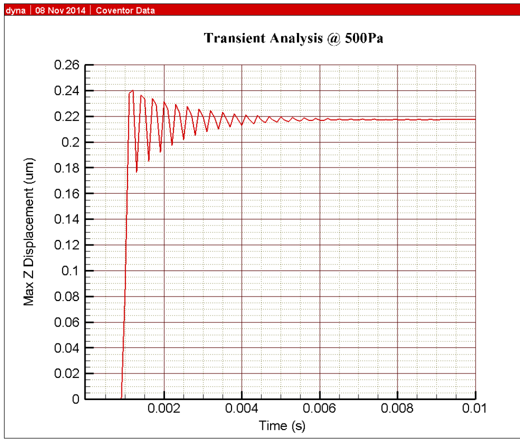
Where

$$\zeta_1 = \frac{c_{resonance,1}}{(2m_1\omega_1)} \quad \text{and} \quad \zeta_2 = \frac{c_{resonance,2}}{(2m_2\omega_2)}$$

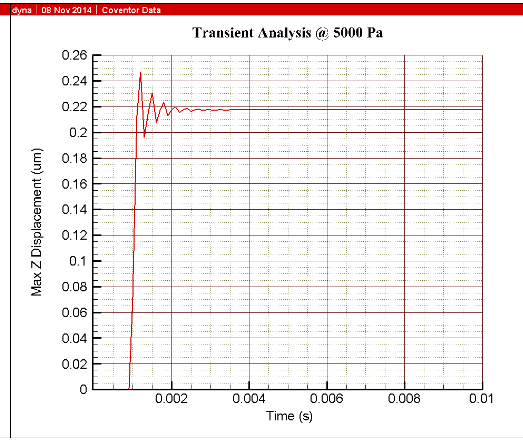
- In CoventorWare, the terms ω_1,ω_2, m_1, and m_2 can be determined from a MemMech modal analysis. The terms $c_{resonance1}$ and $c_{resonance2}$ can then be determined from a DampingMM /mode shape analysis.

Transient Analysis

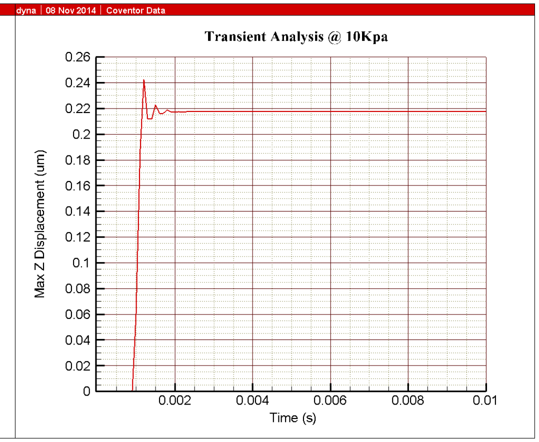
Results



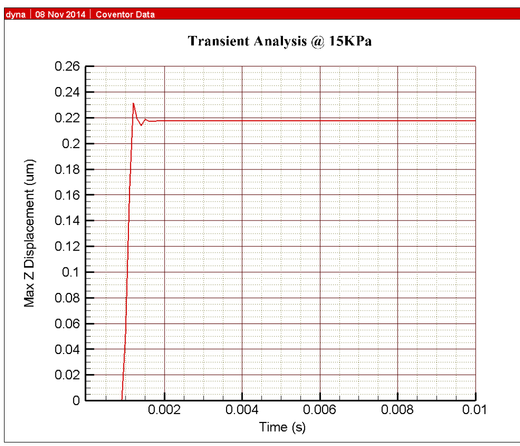
Response @ 500Pa UD



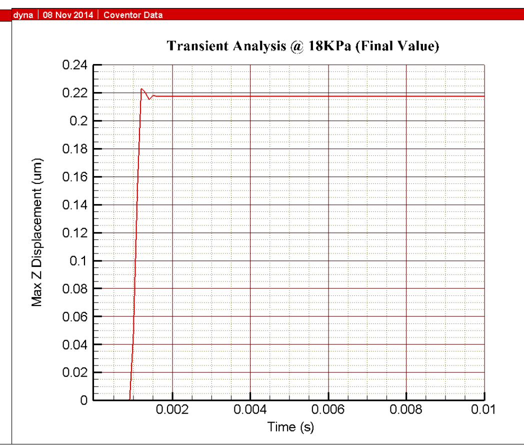
Response @ 5 KPa UD



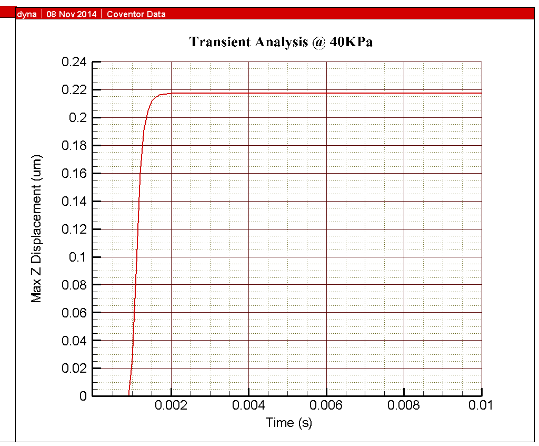
Response @ 10 KPa UD



Response @ 15 KPa UD



Response @ 18 KPa CD



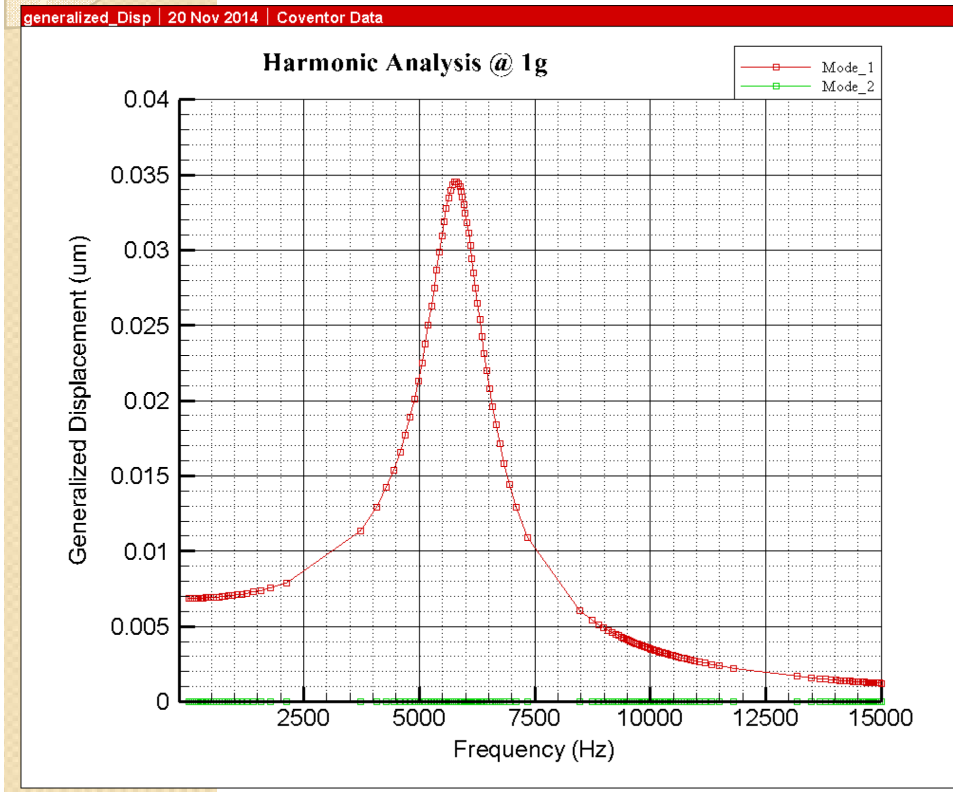
Response @ 40 KPa OD

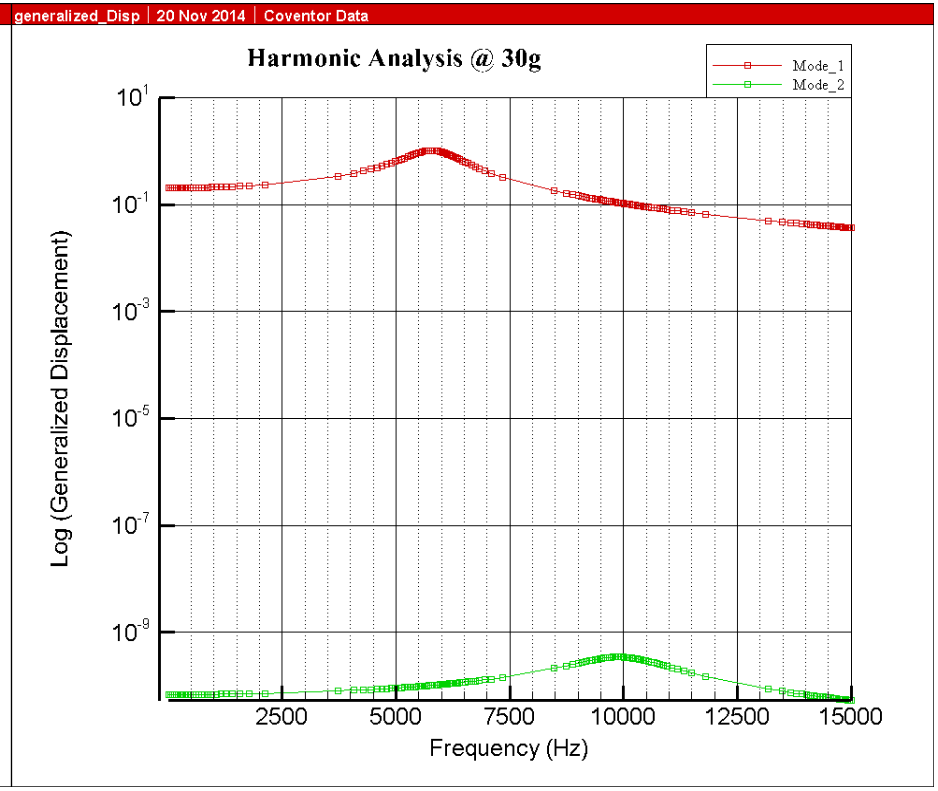
UD – Under Damped

CD – Critically Damped

OD – Over Damped

Harmonic Analysis





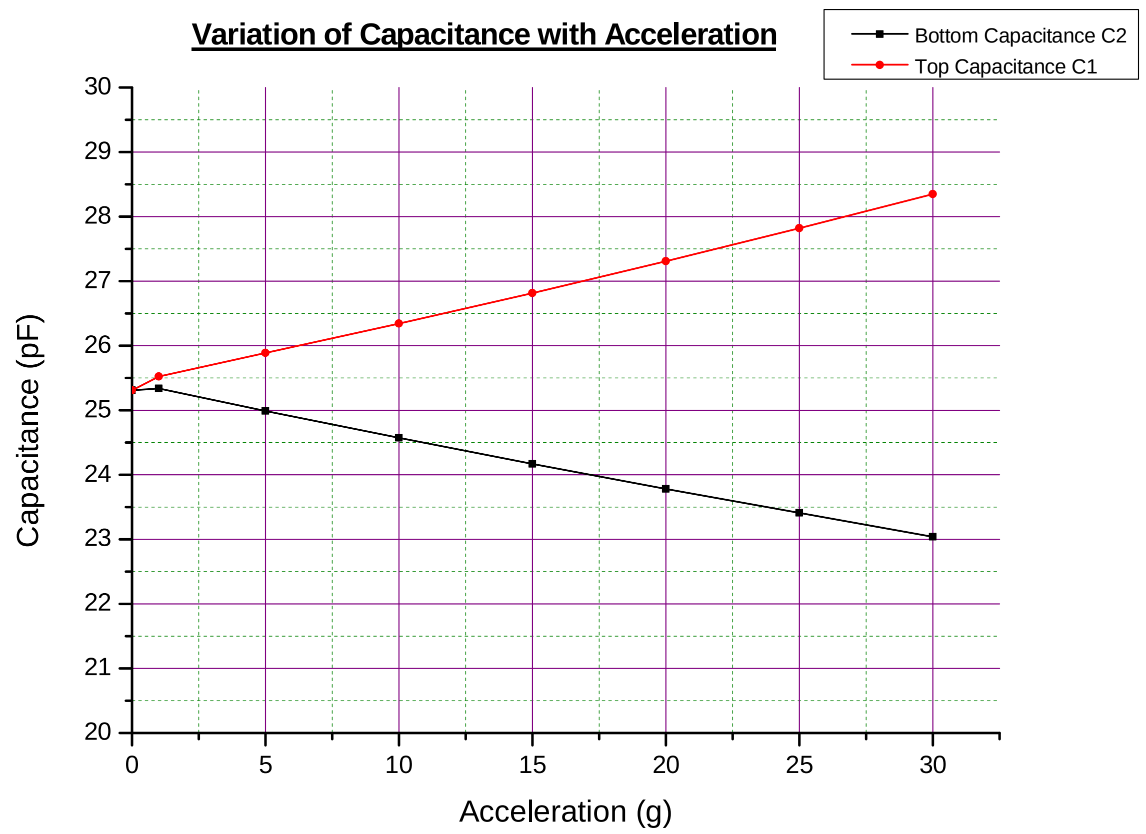
Harmonic Analysis @ 1g

Harmonic Analysis @ 30g (Log Plot)

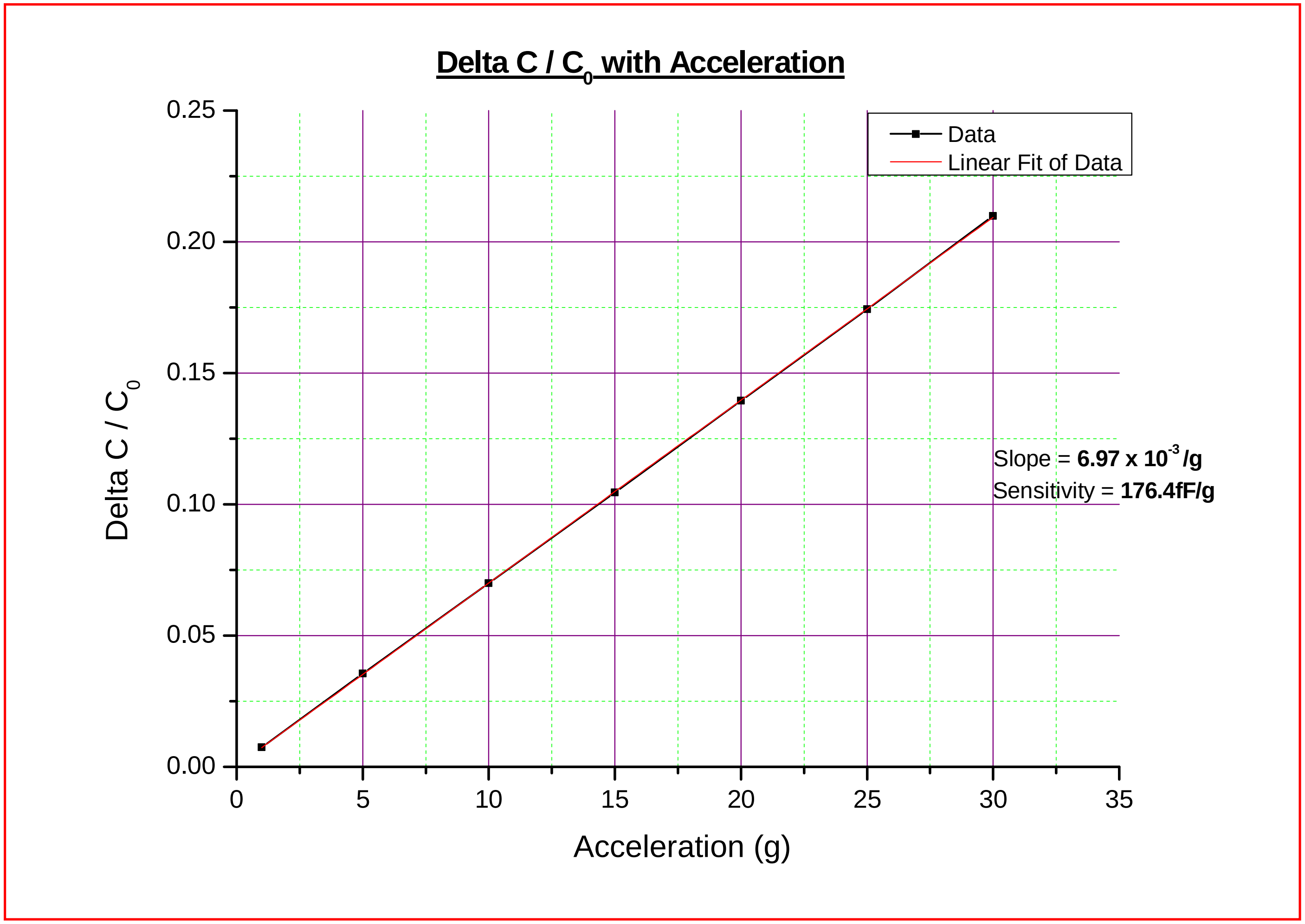
- **The response of the accelerometer to a harmonic force input**
- **The frequency is varied from 10Hz to 15 KHz to cover Modes 1 & 2**
- **The structural bandwidth of the accelerometer : 3700 Hz**

Coupled Mechanical -Electrostatic Analysis

- **The MemMech module in Coventor is used for Mechanical analysis of the structure**
- **The MemElectro module is used to get the capacitance values**
- **The CoSolve EM module combines both these and is used for coupled simulations**



Sensitivity Analysis



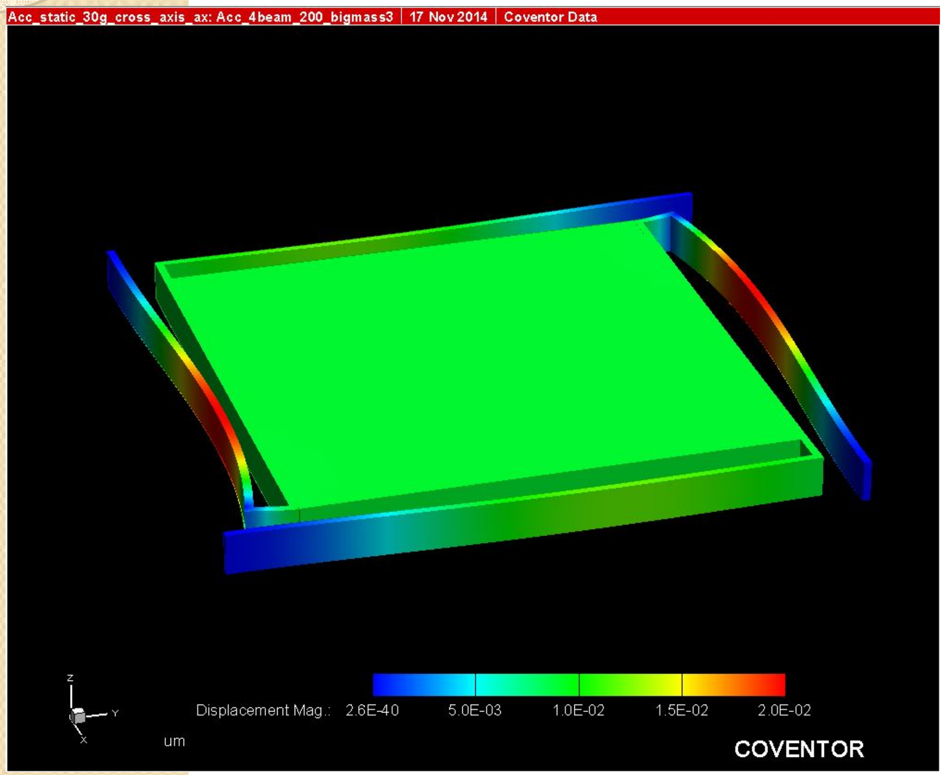
Sensitivity from Simulation : 176.4 fF/g

Sensitivity from Analytical calculations : 177.1 fF/g

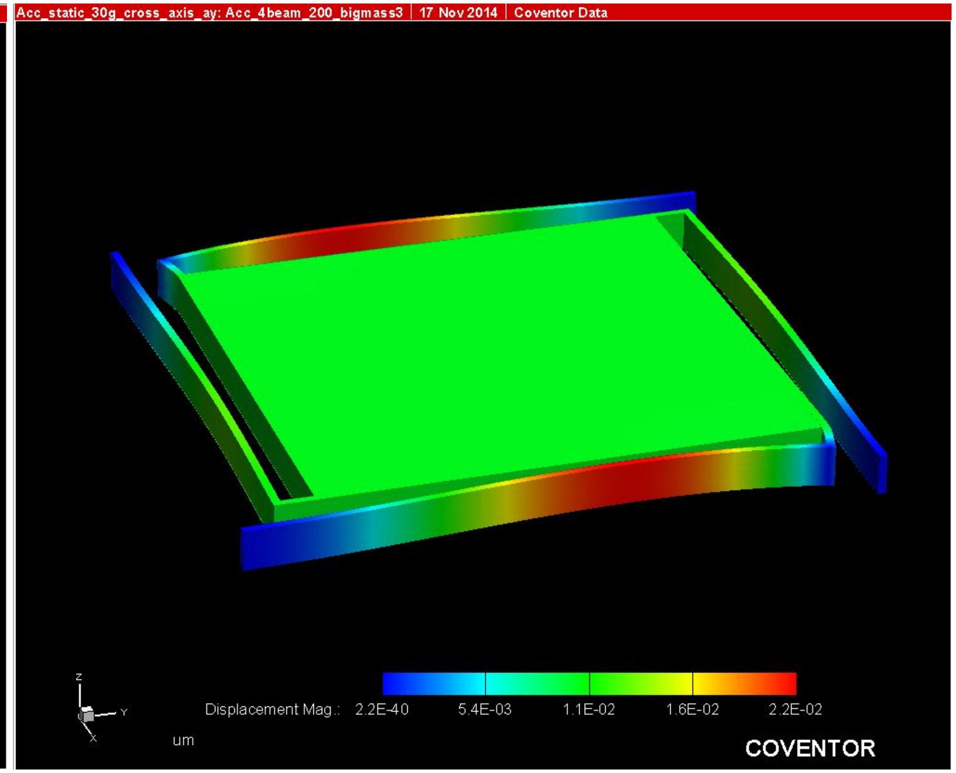
Min acceleration that can be sensed accurately : 6 mg

Max Nonlinearity (observed @ 25 g) : 0.22 %

Cross Axis Sensitivity



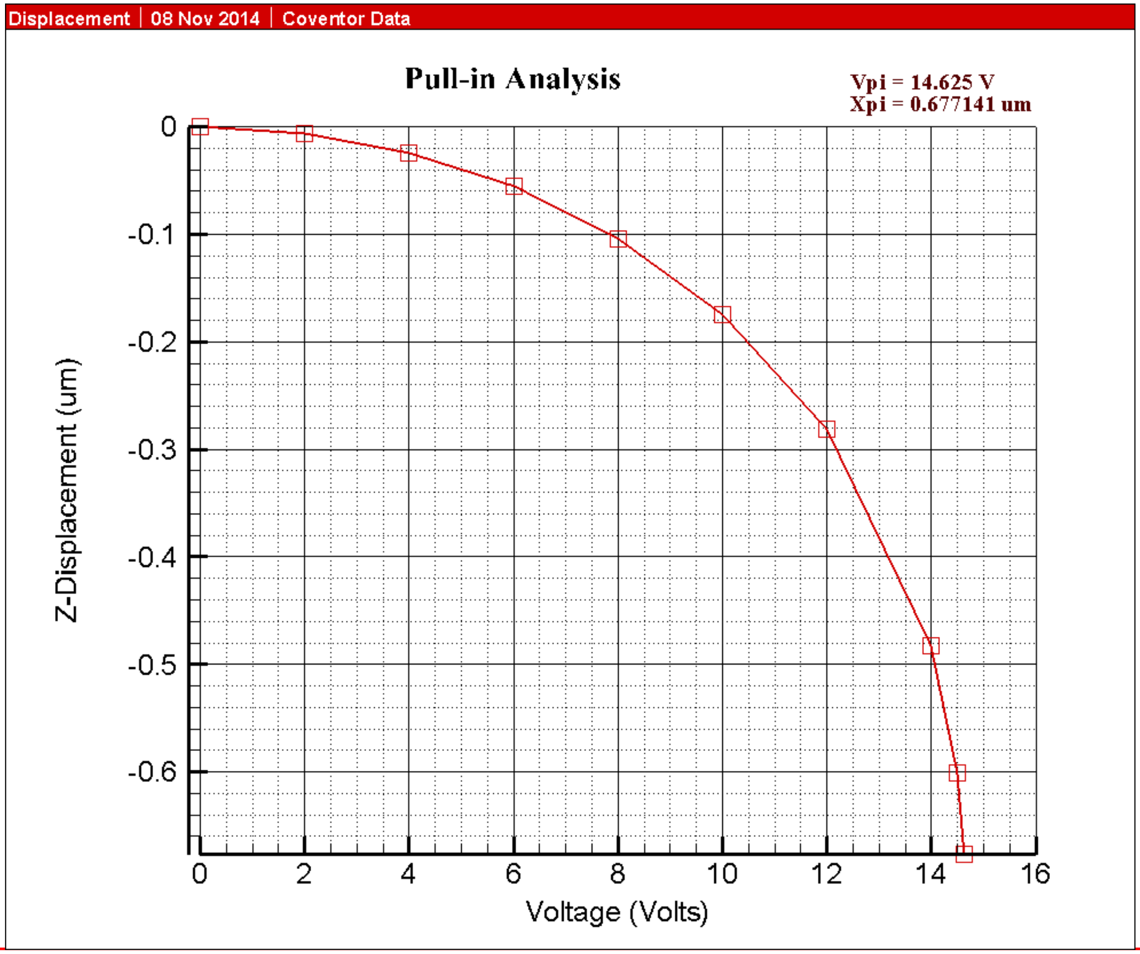
30g applied along X-direction



30g applied along Y-direction

- The Static Analysis in MemMech module is used for studying cross axis sensitivity
- The Cross axis sensitivity of the accelerometer : 0.0736 %

Pull in Analysis



- The CoSolve EM module is used to perform coupled electrostatic and mechanical simulation to determine the pull-in voltage
- The voltage is varied from 0 to 15 V in steps of 2 Volts and when the pull-in is approached, the step value is further refined and the interval is modified further
- The pull-in voltage of the structure : 14.625 V (Analytical Value : 13.8787 V)
- Pull-in displacement : 0.677141 µm

Conclusions

- A 4-beam accelerometer with crab leg suspension is designed for a full scale range of ± 30g and resolution better than 20 mg
- The Final design parameters are tabulated below:

Parameter	Required Value	Achieved Value
Input Range	±30g	±30g
Sensitivity	100 mV /g	176 mV /g
Non Linearity	< 1% of FS	0.22% of FS
Resolution	20 mg	6 mg
Cross axis sensitivity	< 1% of FS	0.0736 %
Bandwidth	100 Hz	3.8 KHz (Structural)

Thank You