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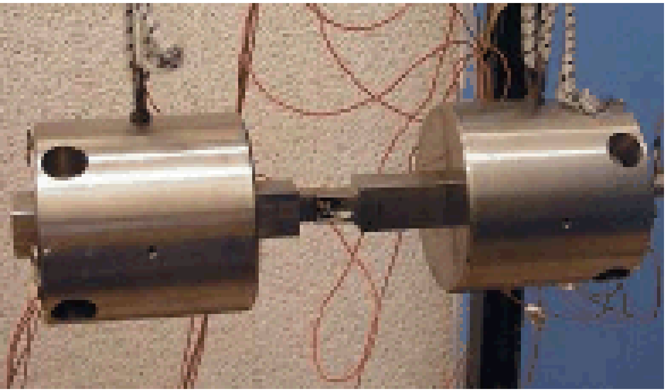
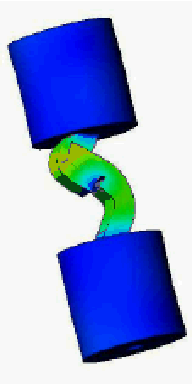
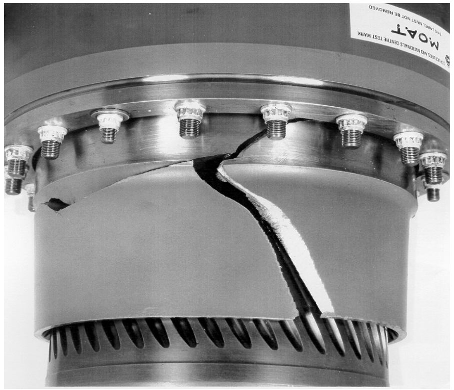
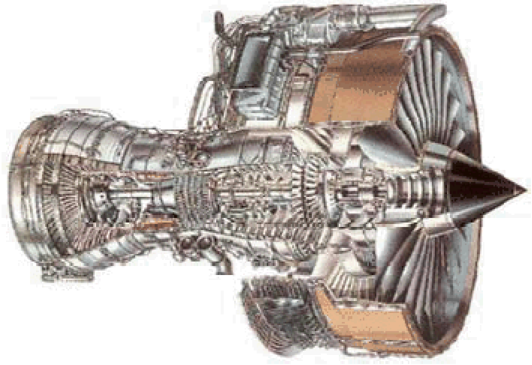








# Project 3: Numerical Round Robin for Prediction of Dissipation in Joints

Loic Salles, Christian Swacek, Robert Lacayo, Matt Brake

# Project 03 - Participants

- Loic Salles (France) – Imperial College, London – Research Associate
- Christian Swacek (Germany) – University of Stuttgart – Student
- Robert Lacayo (USA) – University of Wisconsin, Madison – Bachelor of Science
- Matt Brake (USA) – Sandia National Labs, Albuquerque – PhD, Mechanical Engineering

# Motivation

- Accurate prediction and measurement of single components
- Joints to put together different structures will introduce nonlinear behavior of jointed system
- Introduced level of nonlinearity may not be negligible for the structural dynamical behavior
- Different methods have been developed to model dissipation in joints.
- There is no benchmark to compare different models

# Project 03 - Numerical Round Robin

- Developing a benchmark model to compare different numerical routines
- Comparison of different methodologies to predict nonlinear dissipation behavior in joints
- Comparison of results obtained by different solvers
- Comparison of performance of different solvers
- Application of a high fidelity model and comparison to experimental data

# Numerical Methods

Stuttgart Method

Salinas

Imperial College: FORSE

# Approach Stuttgart

- Equation of Motion with nonlinear friction force

$$\boldsymbol{M}\ddot{\boldsymbol{x}} + \boldsymbol{D}\dot{\boldsymbol{x}} + \boldsymbol{K}\boldsymbol{x} + \boldsymbol{f}_{\mathrm{T}}(\dot{\boldsymbol{x}}, \boldsymbol{x}) = \boldsymbol{f}_{\mathrm{exc}}$$

- Linearize friction force using Harmonic Balance Method

$$\boldsymbol{f}_{\mathrm{T}}(\dot{\boldsymbol{x}}, \boldsymbol{x}) \approx \boldsymbol{D}_{\mathrm{hbm}}\dot{\boldsymbol{x}} + \boldsymbol{K}_{\mathrm{hbm}}\boldsymbol{x}$$

- Linearized equation of motion in frequency domain

$$\underbrace{\Big((\boldsymbol{K} + \boldsymbol{K}_{\mathrm{hbm}}(\hat{\boldsymbol{x}})) - i\omega(\boldsymbol{D} + \boldsymbol{D}_{\mathrm{hbm}}(\hat{\boldsymbol{x}})) - \omega^2 \boldsymbol{M}\Big)}_{\boldsymbol{H}_{\mathrm{hbm}}(\hat{\boldsymbol{x}})}\hat{\boldsymbol{x}} = \hat{\boldsymbol{f}}_{\mathrm{exc}}$$

$\boldsymbol{H}_{\mathrm{hbm}}(\hat{\boldsymbol{x}})$ ➡ Pseudo-Receptance Matrix

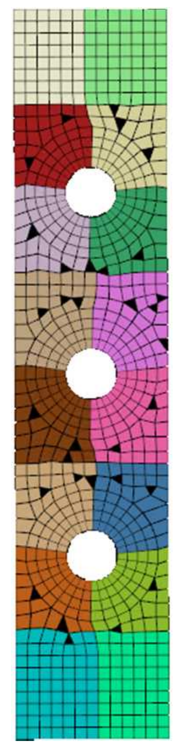
- Problem of the form

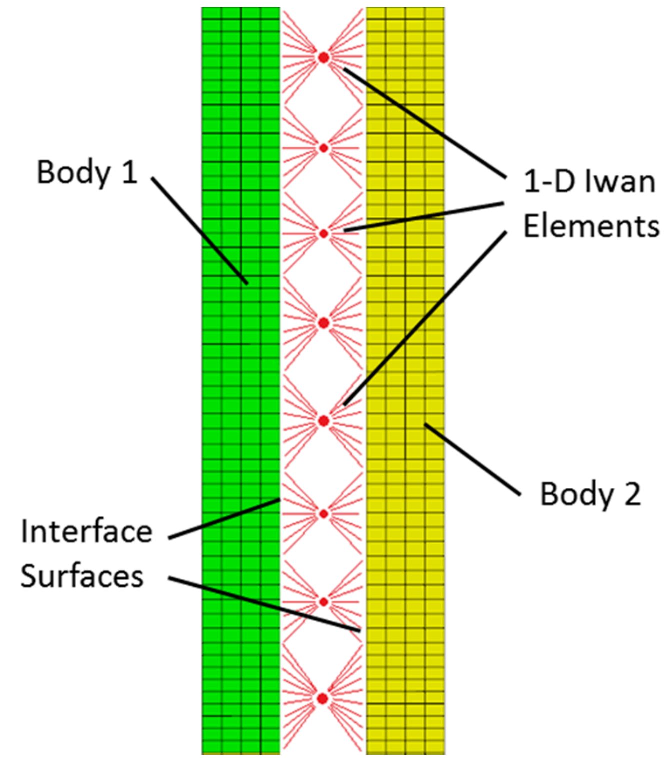
$$\hat{\boldsymbol{x}} = \boldsymbol{H}_{\mathrm{hbm}}^{-1}(\hat{\boldsymbol{x}})\hat{\boldsymbol{f}}_{\mathrm{exc}}$$

# Approach: Salinas - Interface Model

## Model interface using Salinas Tied-Joint Iwan implementation

- Divide interface surfaces into smaller sections.
- Tie interfacing sections to a 1-D Iwan Element.

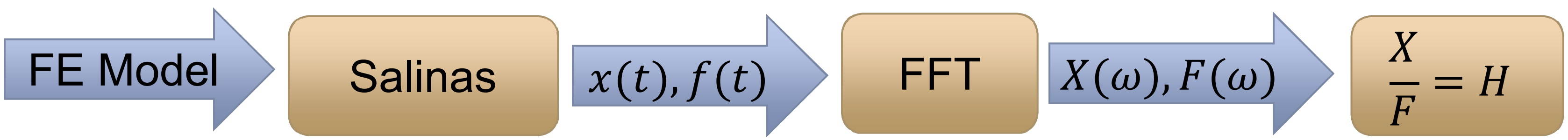




# Approach: Salinas - Getting the FRF

Run transient analysis using Implicit alpha-modified Newmark-Beta method.

Transform time response to frequency response using Fast Fourier Transform.




<u>Pros</u>

- Segalman documents success with Iwan elements.

<u>Cons</u>

- Computationally expensive.
- Time integrator may not converge.

# Harmonic Balance Method

- Truncated Fourier's Series

$$\boldsymbol{U}(\tau) = \tilde{\boldsymbol{U}}_0 + \sum_{n=1}^{Nh} \tilde{\boldsymbol{U}}_{n,c}\cos(n\tau) + \tilde{\boldsymbol{U}}_{n,s}\sin(n\tau)$$

$$\tau = \omega t$$

$$\boldsymbol{f}(\tau) = \tilde{\boldsymbol{f}}_0 + \sum_{n=1}^{Nh} \tilde{\boldsymbol{f}}_{n,c}\cos(n\tau) + \tilde{\boldsymbol{f}}_{n,s}\sin(n\tau)$$

- Galerkin's Procedure

$$\int_0^{2\pi} f(\tau)d\tau = 0 \qquad \int_0^{2\pi} f(\tau)cos(n\tau)d\tau = 0 \qquad \int_0^{2\pi} f(\tau)sin(n\tau)d\tau = 0$$

$$\Downarrow$$

$$\mathbf{M}\ddot{\boldsymbol{U}} + \mathbf{C}\dot{\boldsymbol{U}} + \mathbf{K}_T\boldsymbol{U} = \boldsymbol{F}_{ex}(t) - \lambda$$

$$\Downarrow$$

$$\mathbf{Z}(\omega)\tilde{\boldsymbol{U}} = \tilde{\boldsymbol{F}}_{ex} - \tilde{\boldsymbol{\lambda}}$$

# Harmonic Balance Method

- Algebraic system in frequency domain

$$\mathbf{Z}(\omega)\tilde{\boldsymbol{U}} = \tilde{\boldsymbol{F}}_{ex} - \tilde{\boldsymbol{\lambda}}$$

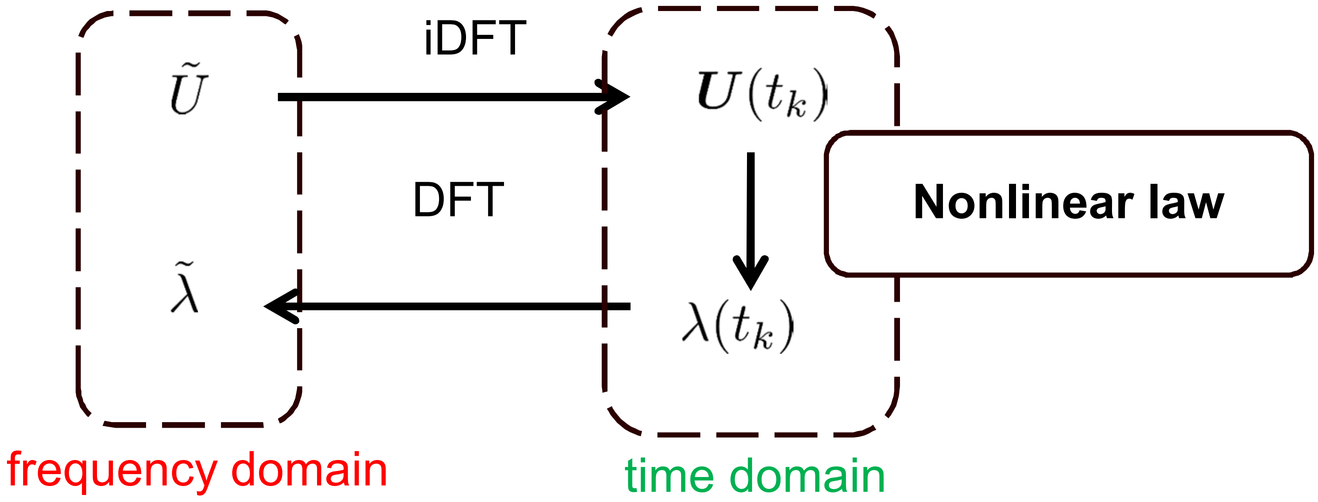
**Z** is the dynamic stiffness

$$\mathbf{Z} = \begin{bmatrix} \mathbf{K} & \cdots & \mathbf{0} & \mathbf{0} \\ \vdots & \ddots & \mathbf{0} & \mathbf{0} \\ \mathbf{0} & \mathbf{0} & \mathbf{K} - (N_h\omega)^2\mathbf{M} & N_h\omega\mathbf{C} \\ \mathbf{0} & \mathbf{0} & -N_h\omega\mathbf{C} & \mathbf{K} - (N_h\omega)^2\mathbf{M} \end{bmatrix}$$

- Nonlinear Forces
  - Forces cannot be explicitly handled in the frequency domain
  - The AFT procedure is applied to calculate the coefficient of Fourier's series of forces in time domain

# AFT procedure

**Scheme of AFT procedure**



# Contact Modelling

- Tangential stresses

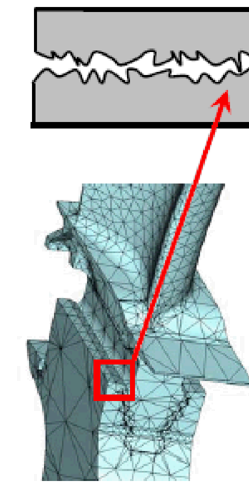
$$\sigma_t = \begin{cases} \sigma_t^0 + k_t\left(x(\tau) - x_0\right) & \text{for stick} \\ \pm\sigma_n(\tau) & \text{for slip} \\ 0 & \text{for separation} \end{cases}$$

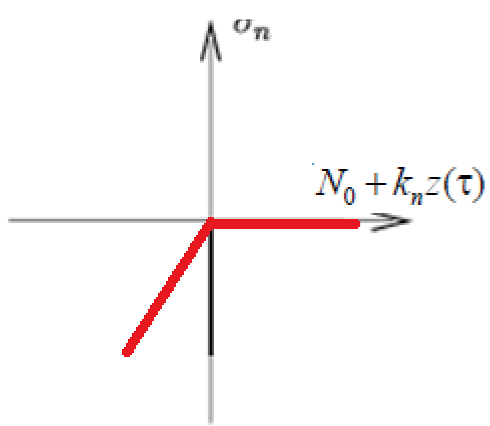
- Normal stresses

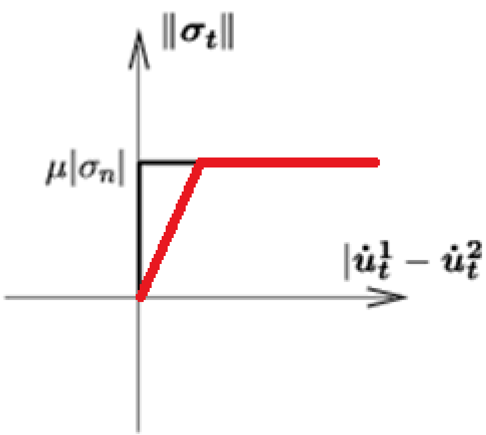
$$\sigma_n = \begin{cases} N_0 + k_n z(\tau) & \text{for contact} \\ 0 & \text{for separation} \end{cases}$$

$\boldsymbol{F_{NL}(U_0)}$

Contact of rough surface

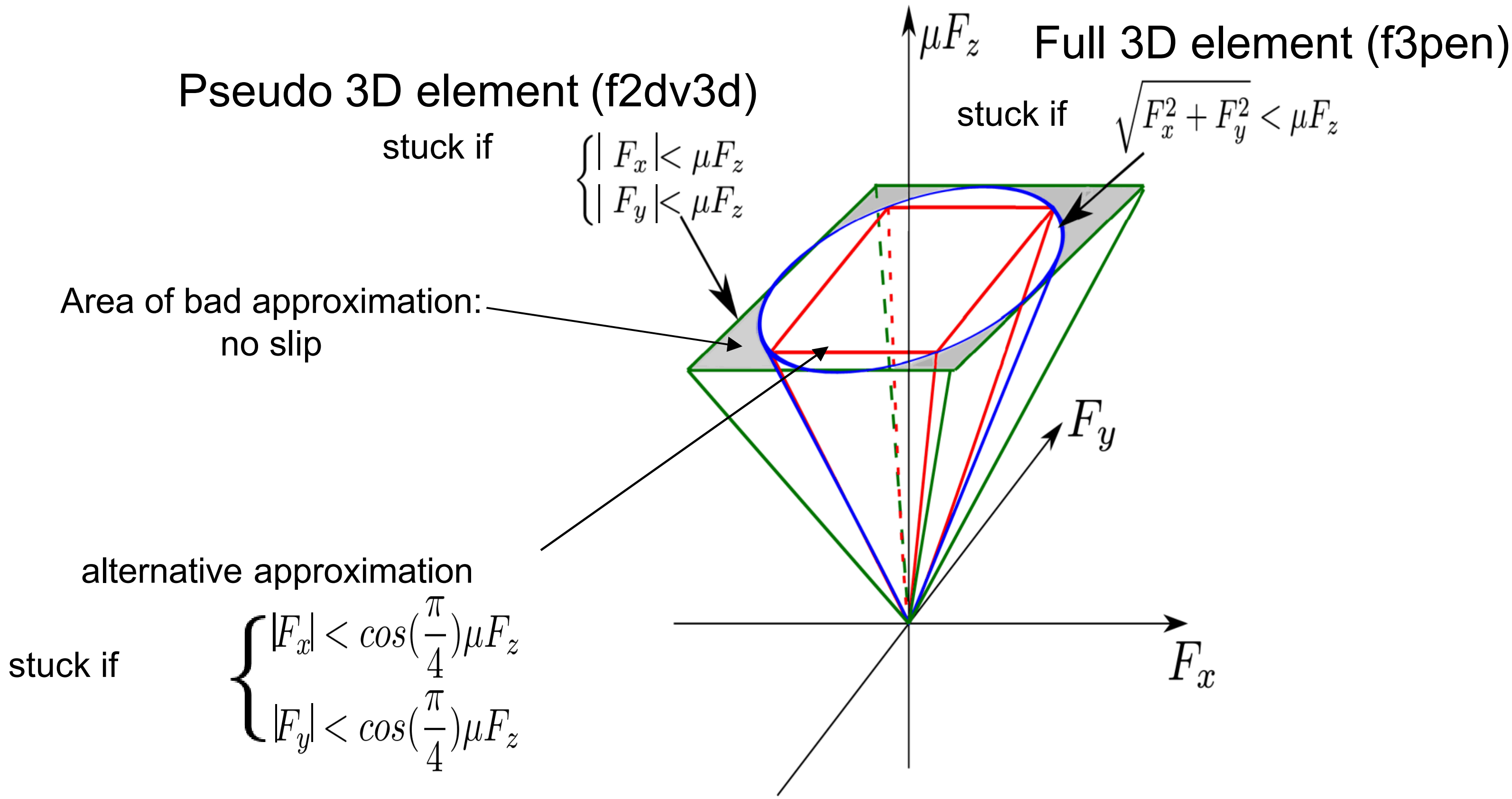




# 3D contact: friction cone

## Coulomb's friction cone



# Separation of problems

- Equation of motion

$$\boldsymbol{M\ddot{U} + C\dot{U} + F_{int}(U) = F_s + F_{ex}(t) - F_{NL}(U,\dot{U})}$$

- Dynamic problem around static equilibrium position $\boldsymbol{U_0}$

$$\boldsymbol{M\ddot{U}_d + C\dot{U}_d + K_T(U_0)U_d + K_T(U_0)U_0} \\ \boldsymbol{= F_s + F_{ex}(t) - F_{NL}(U_0) - \Delta F_{NL}(U_d,\dot{U}_d)}$$

- Separation of the static and dynamic problems

$$\boldsymbol{K_T(U_0)U_0 = F_s - F_{NL}(U_0)} \\ \boldsymbol{M\ddot{U}_d + C\dot{U}_d + K_T U_d = F_{ex}(t) - \Delta F_{NL}(U_d,\dot{U}_d)}$$

# Reduced Order Modelling

$$\mathbf{Z}(\omega)\tilde{\boldsymbol{U}} = \tilde{\boldsymbol{F}}_{ex} - \tilde{\boldsymbol{\lambda}}$$

- Frequency response function

$$\tilde{\boldsymbol{X}}_c = \underbrace{\mathbf{B}_c\mathbf{Z}^{-1}}_{\mathbf{H}(\omega)}\left(\tilde{\boldsymbol{F}}_{ex} - \tilde{\boldsymbol{\lambda}}\right)$$

- Modal synthesis

$$\mathbf{H}(\omega) = \mathbf{B}_c\mathbf{Z}^{-1} = \sum_{j=1}^{Nddl} \frac{\boldsymbol{\Phi}_j\boldsymbol{\Phi}_j^t}{(1+i\eta_j)\omega_j^2 - \omega^2}$$

- Truncated modal synthesis with static correction

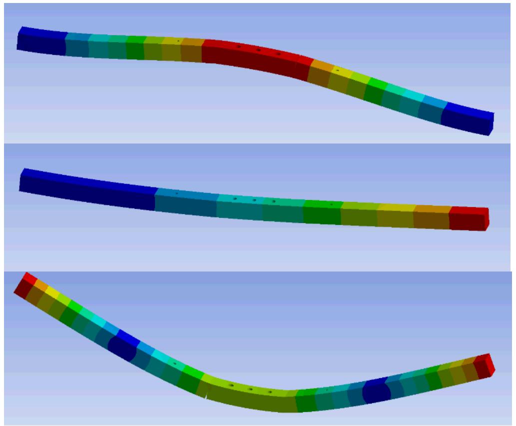
$$\mathbf{H}(\omega) \approx \sum_{j=1}^{Nr} \frac{\boldsymbol{\Phi}_j\boldsymbol{\Phi}_j^t}{\omega_j^2 - \omega^2} + \underbrace{\sum_{j=1}^{Nddl} \frac{\boldsymbol{\Phi}_j\boldsymbol{\Phi}_j^t}{\omega_j^2 - \omega_0^2}}_{(\mathbf{K}-\omega_0^2\mathbf{M})^{-1}} - \sum_{j=1}^{Nr} \frac{\boldsymbol{\Phi}_j\boldsymbol{\Phi}_j^t}{\omega_j^2 - \omega_0^2}$$

with

$$Nr << Nddl$$

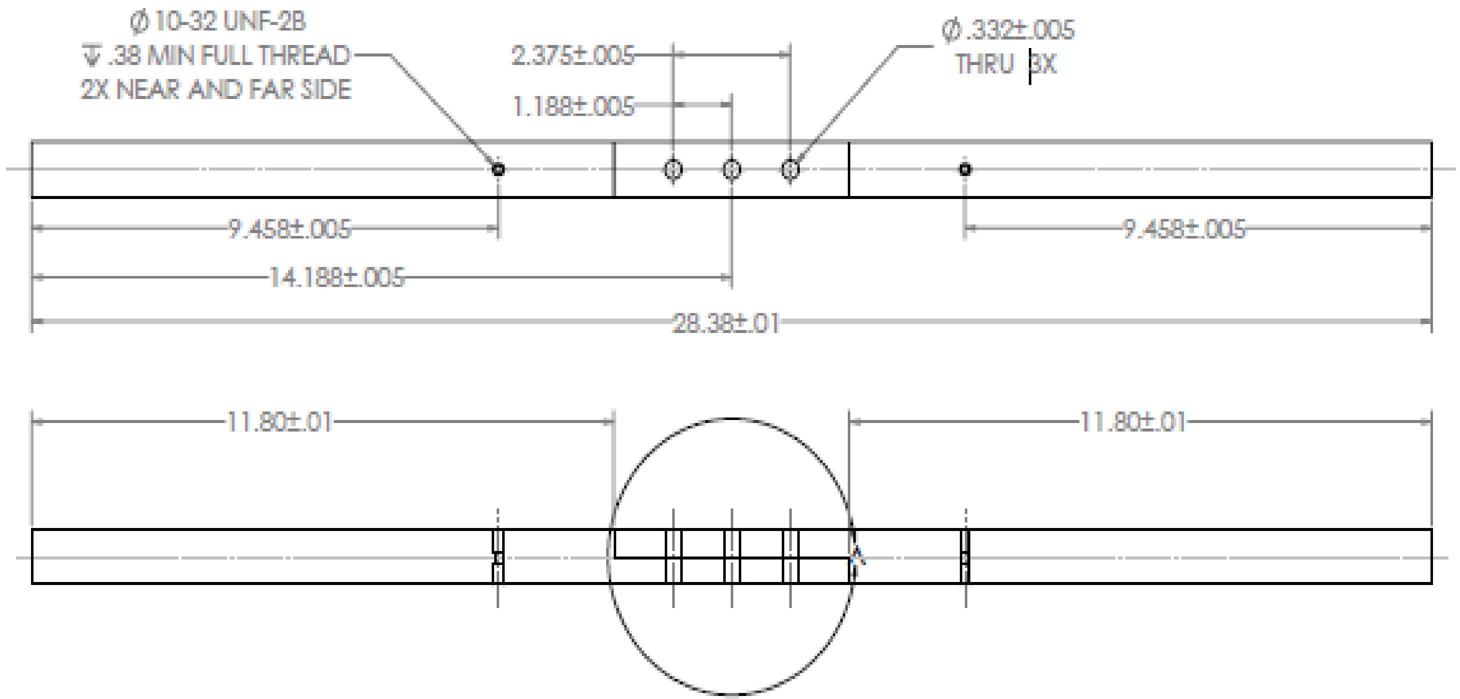
# Strategy of Round Robin

- Identification of benchmark model
- Set initial conditions, material properties and joint coefficients
- Boundary Conditions:
  - Fixed – Fixed
  - Fixed – Free
  - Free – Free

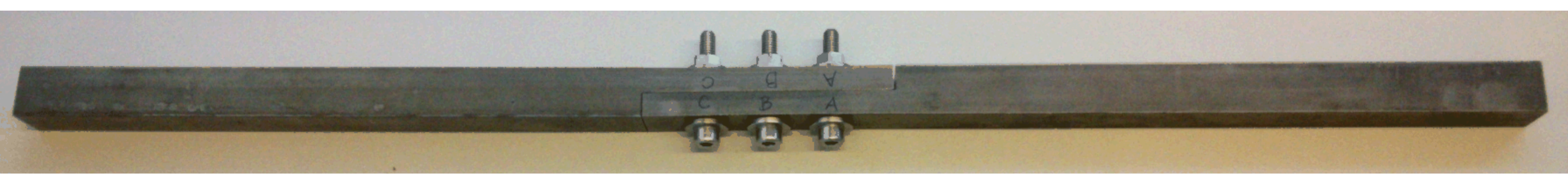


- Comparison to experimental data (Project 01)

# Beam Model

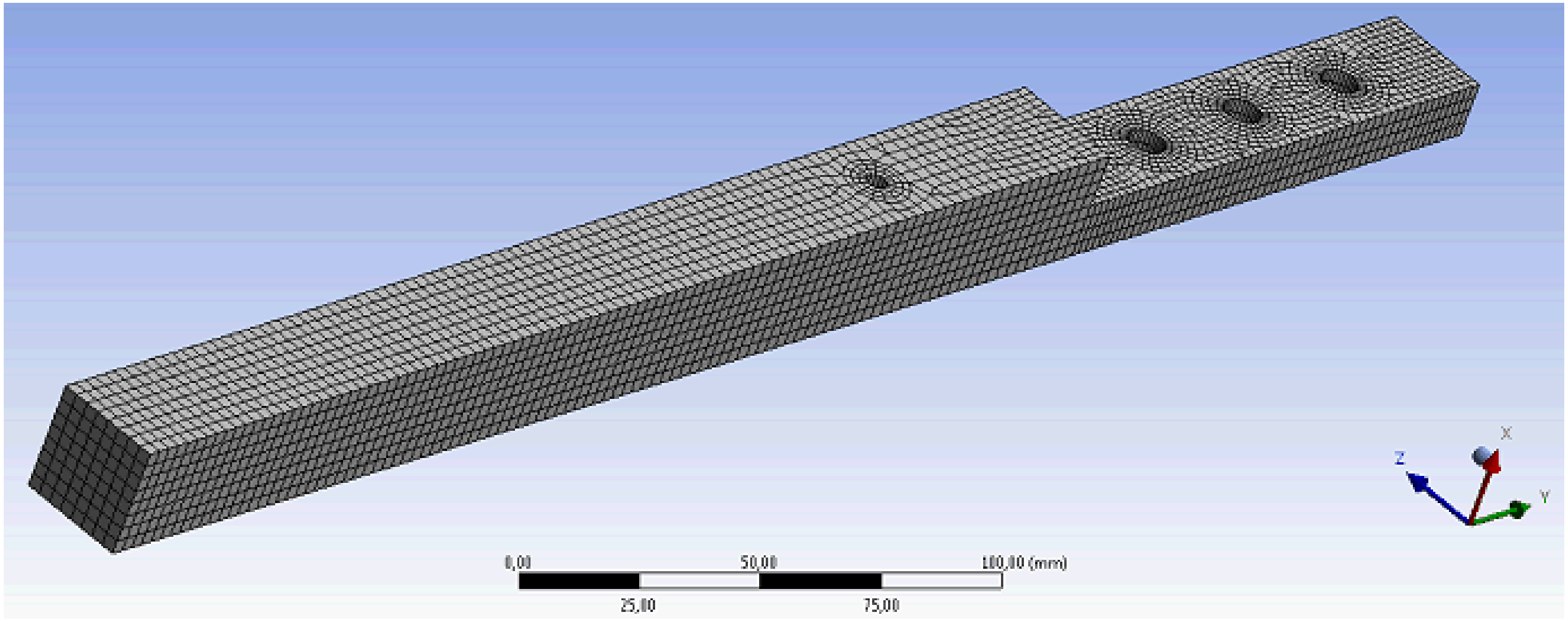


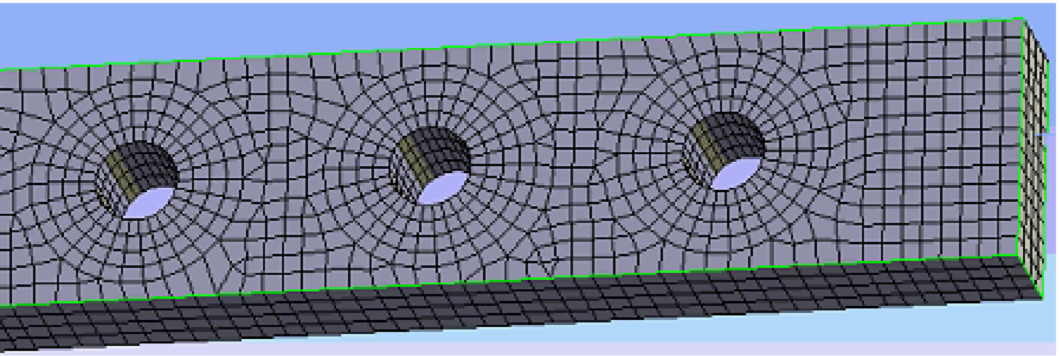
Ø 10-32 UNF-2B
↧ .38 MIN FULL THREAD
2X NEAR AND FAR SIDE
2.375±.005
1.188±.005
Ø .332±.005
THRU 3X
9.458±.005
14.188±.005
9.458±.005
28.38±.01
11.80±.01
11.80±.01

C
B
A

# Numerical Model



| | |
|---|---|
| Young's Modulus | 1.8248e11 N/m^2 |
| Poissons Ratio | 0.29 |
| Density | 7900 kg/m^3 |

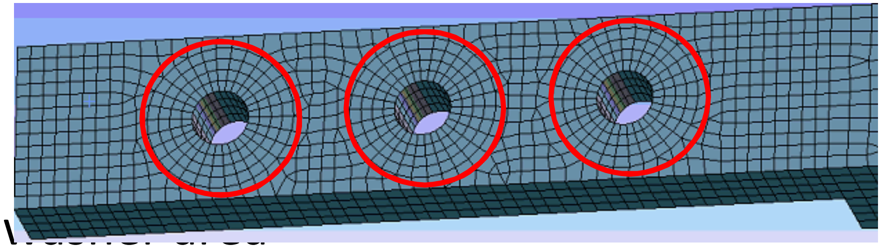
# First Steps

- Linear Modal Analysis and comparison of Substructures

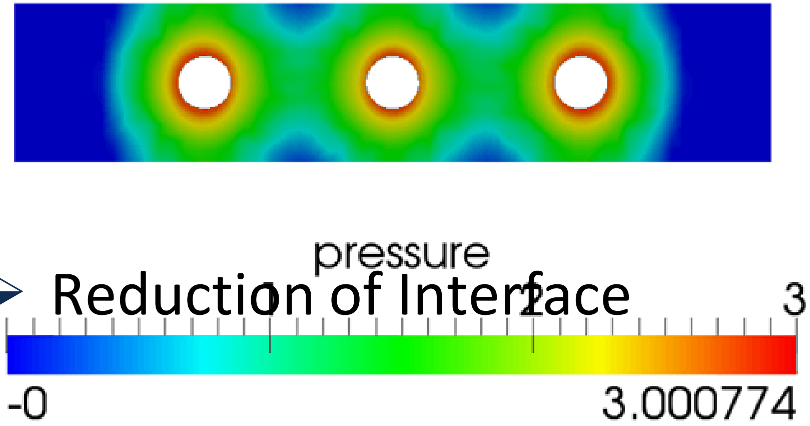
**Comparison of Eigen frequencies [Hz]**

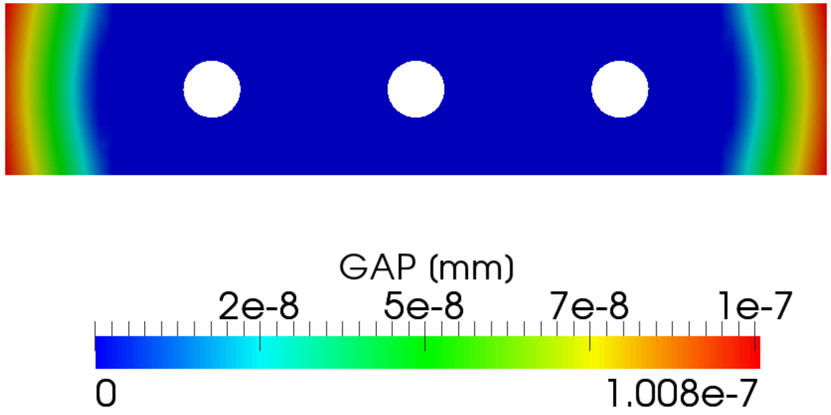
| Mode | Salinas | Code-Aster | Stuttgart-Matlab | ANSYS |
|---|---|---|---|---|
| 1 | 141.644 | 142.224 | 142.224 | 142.22 |
| 2 | 143.032 | 143.595 | 143.595 | 143.59 |
| 3 | 605.463 | 609.419 | 609.419 | 609.42 |
| 4 | 738.391 | 741.113 | 741.113 | 741.11 |
| 5 | 1386.73 | 1394.42 | 1394.419 | 1394.40 |
| 6 | 1839.11 | 1845.14 | 1845.143 | 1845.10 |
| 7 | 1990.88 | 1991.59 | 1991.586 | 1991.60 |
| 8 | 2913.91 | 2927.57 | 2927.574 | 2927.60 |
| 9 | 3332.32 | 3333.85 | 3333.851 | 3333.90 |
| 10 | 3557.36 | 3568.74 | 3568.738 | 3568.70 |

# First Steps



- Model of bolts:
  - Not modeled
  - Uniform pressure distribution on washer area
- Model of contact interface
  - Nonlinear contact static analyis

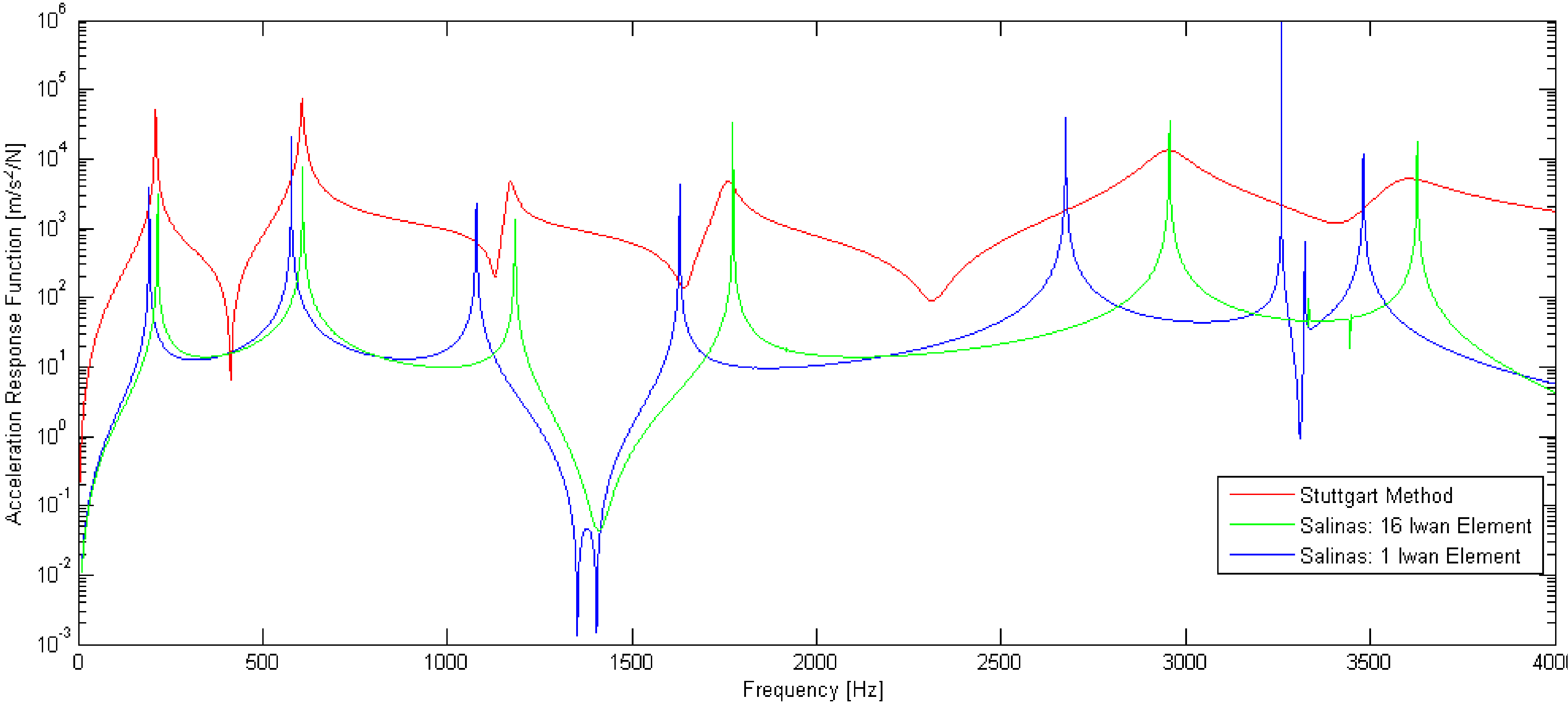



- Reduction of Interface

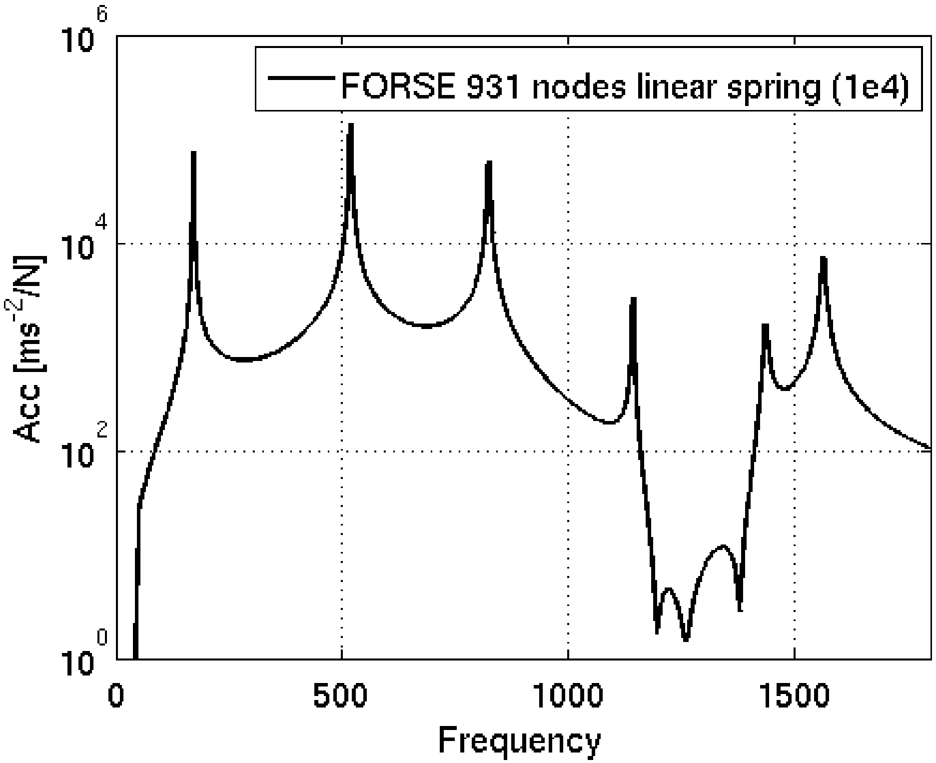
# Linear Results: Salinas

Defining multiple Iwan Tied Joints produces an FRF whose natural frequencies are more consistent with other results.



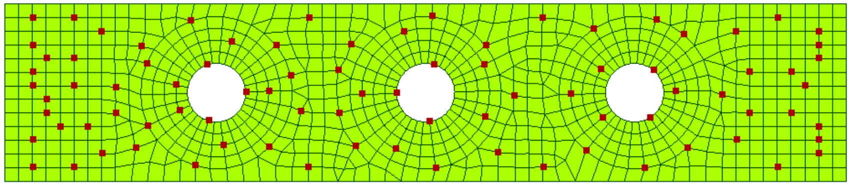
# Linear Results: FORSE

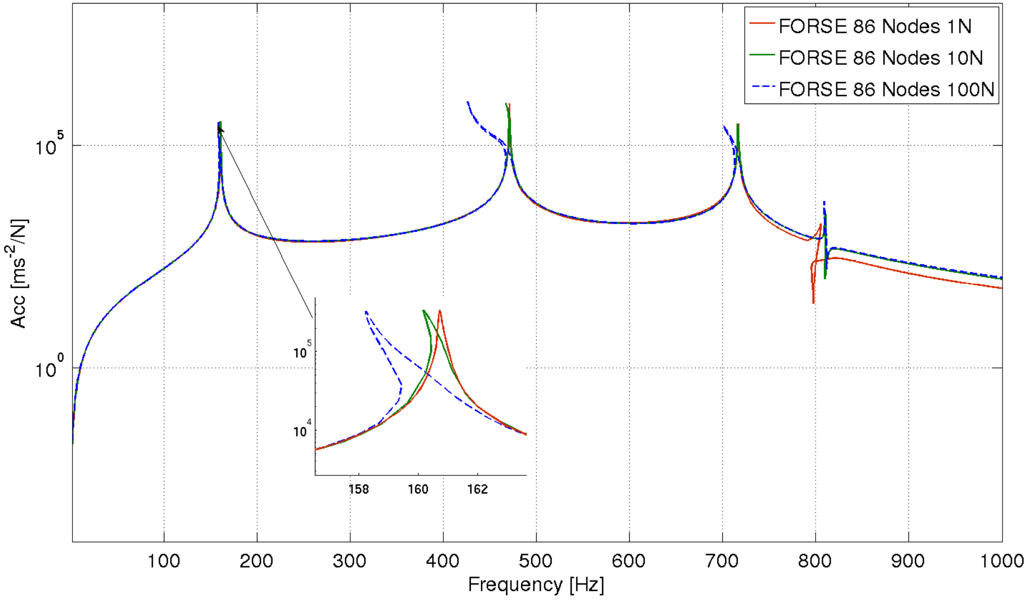
- 931 contact nodes
- Spring elements: 10000 N/mm



# Results FORSE

- 86 contact nodes
- Nodal Contact stiffness: 50000 N/mm
- Coefficient of friction:0.3
- Full 3D contact elements





# Conclusions

- Three methods tested
- No proper agreement betwen the different methods
- According to Imperial simulation not a lot of friction damping for this configuration (To verify)

Thank you for listening

# Questions?

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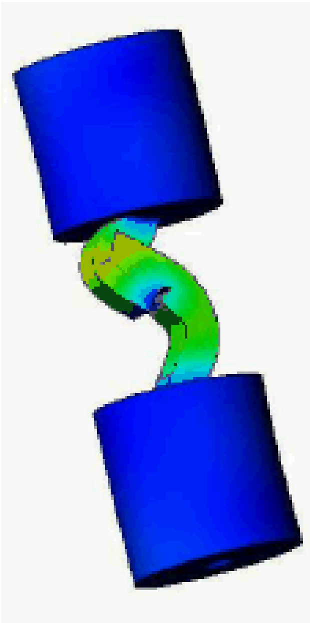

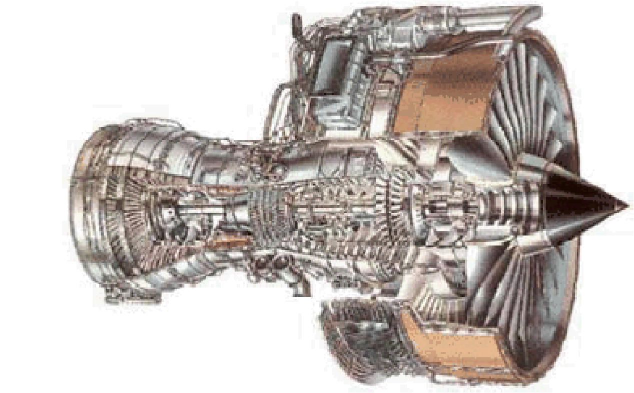

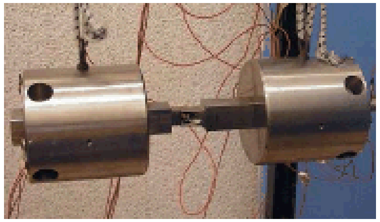

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