Effect of wear on the dynamics of structures with friction contacts

33° Cycle Annual PPT (2017-2020)

Lakshminarayana Reddy Tamatam

Supervisors: Prof. Stefano Zucca & Prof. Daniele Botto

POLITECNICO DI TORINO

EXPERTISE

Department of Mechanical & Aerospace Engineering, Politecnico di Torino, Italy

17-12-2020 — PoliTo

Outline

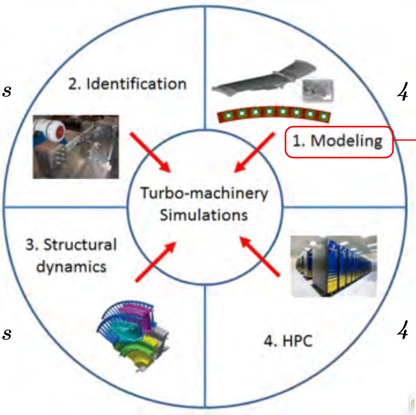
Outline

1. Motivation
2. Theory
3. Test cases
   - Cantilever Beam
   - Bladed Disk
4. New Test Rig
5. Conclusion
6. Appendix
   - Industrial Test Case
   - HPC

EXPERTISE - Horizon 2020 ETN

2 ESRs

4 ESRs



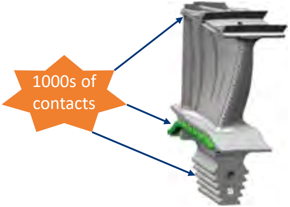
5 ESRs

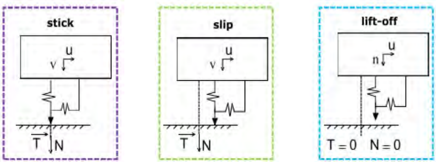
4 ESRs

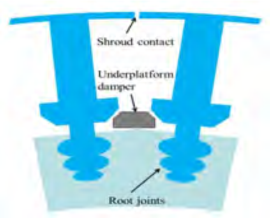
Advanced modelling of friction contacts

ESR3: Effect of wear on the dynamics of structures with friction contacts

The ultimate research objective of EXPERTISE is to develop advanced tools for the dynamics analysis of large-scale models of turbine components to pave the way towards the virtual testing of the entire machine. [Grant No. 721865]





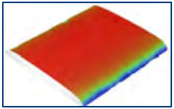


[1] Md Afzal Licentiate thesis. KTH 2015. https://pdfs.semanticscholar.org/a8c9/accd7a4e6de20cc0e7108f9afc14697fe564.pdf

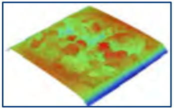
[2] Gastaldi, C. PhD Course: Models and methods for the dynamics of mechanical components with contact interfaces. Politecnico di Torino. 2016.

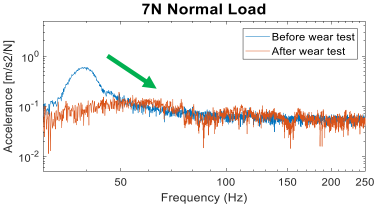
After sometime in operation

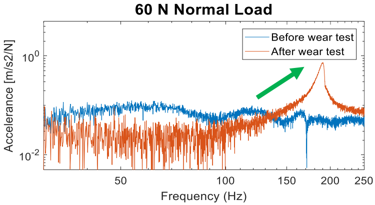
New surface



Worn surface



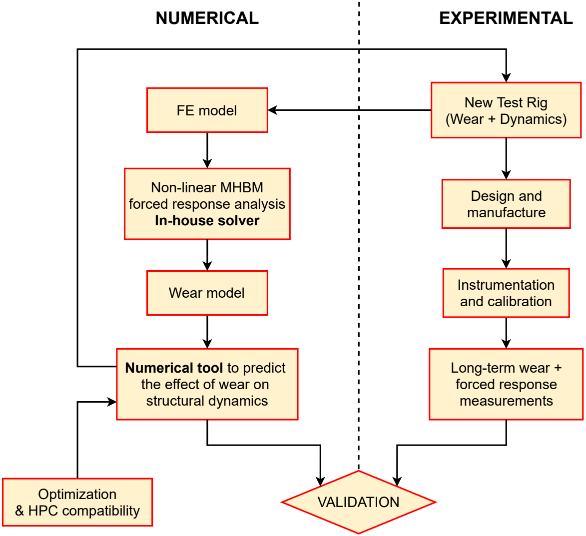




Objectives

- To develop and validate models to predict the effect of wear on the contact surfaces and their ability to dissipate energy by damping thereby affecting dynamics of structures with friction contacts
- The validated models to be embedded in non-linear solvers for forced response of turbine components

Expected Outcome



Outline

Formulation

Equation of motion: Time Domain

$$M\ddot{x}(t) + C\dot{x}(t) + Kx(t) = F(t) + F_{nl}(x, \dot{x}, t)$$

Frequency Domain

$$Q(t) = \Re\left(\sum_{h=0}^{H} \widehat{Q}^{(h)} e^{ih\omega t}\right) \mid \{x, F, F_{nl}\} \in Q$$

Harmonic Balance Method (HBM)

$$D^{(h)}\widehat{x}^{(h)} = \widehat{F}^{(h)} + \widehat{F_{nl}}^{(h)} \; with \; h = 0..H$$

$$\text{where} \quad D^{(h)} = \left((-h\omega)^2 M + ih\omega C + K\right)$$

Residual equation

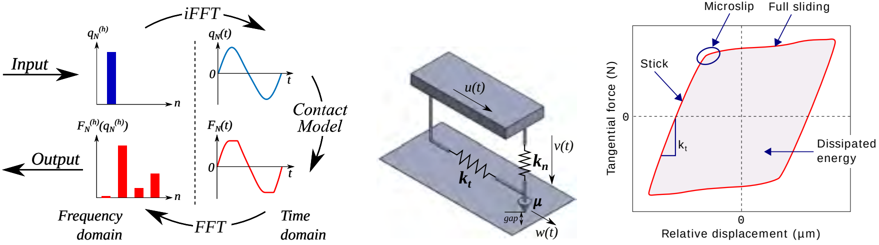
$$RES^{(h)} = D^{(h)}\widehat{x}^{(h)} - \widehat{F}^{(h)} - \widehat{F_{nl}}^{(h)}$$

Using coupled static/dynamic Harmonic Balance Method[1]

[1] Firrone, C.M, Zucca, S, Gola, M.M, "The effect of underplatform dampers on the forced response of bladed disks by a coupled static/dynamic harmonic balance method", *International Journal of Non-Linear Mechanics*, 46(2), pp. 363-375, 2011.

Alternating Frequency Time (AFT) Logic

- Friction contact non-linearity
- 2-D Jenkins element with variable normal load
- Contact states: Stick, Slip, Lift-off



(a) AFT Logic (b) Contact Model (c) Hysteresis Loop

Modelling wear

- **Using wear energy approach**[2]

$$v_w = \frac{Z}{A}\alpha E$$

where,

v_w	wear depth
Z	number of cycles
A	associated contact area of the node pair
α	wear energy coefficient
E	energy dissipated

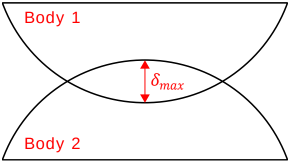
v_w is introduced to the 0^{th} order coefficient of the relative displacement in the normal direction

$$v(t) = \sum_{h=0}^{H} \widehat{v}^{(h)} e^{ih\omega t} \; - \; v_w^{(0)}$$

[2] M. Z. Huq and J. P. Celis, "Expressing wear rate in sliding contacts based on dissipated energy," *Wear*, 2002.

Modelling wear – contd.

- **Adaptive wear logic**



Nodal wear depth after 1 vibration cycle: Δh_{ij}

$$Z = floor\left(\frac{v_{w,max}}{max(\Delta h_{ij})}\right) \gg 1$$

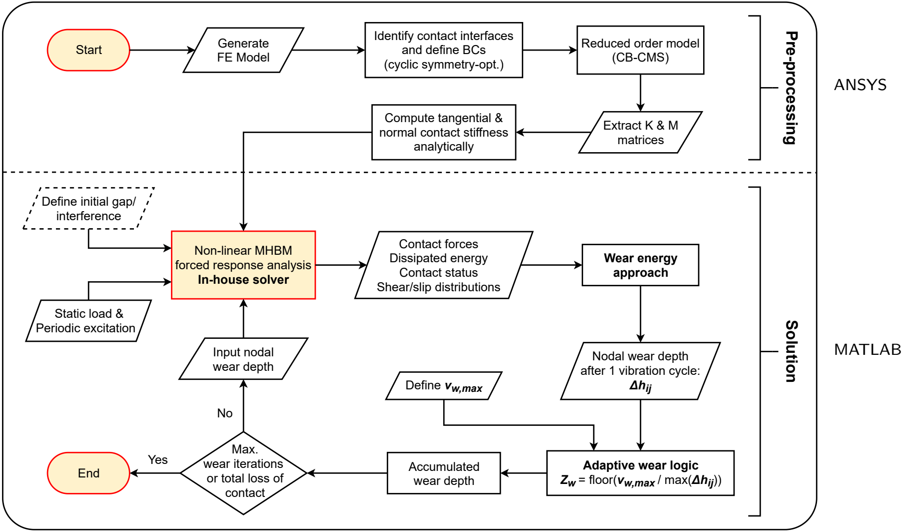
$v_{w,max}$ is a user defined parameter. It can be defined by:

- the maximum wear depth allowed for each wear iteration
- the percentage of the maximum static deflection (δ_{max}) for the given static loads acting at the contact
- the maximum tolerable error percentage in wear depth

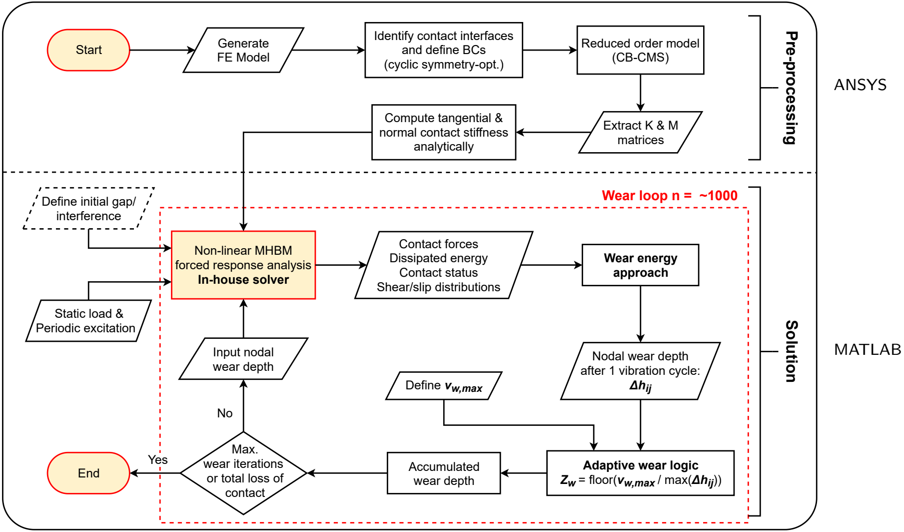
[3] J. Armand, L. Pesaresi, L. Salles, and C. W. Schwingshackl, "A Multiscale Approach for Nonlinear Dynamic Response Predictions with Fretting Wear," *J. Eng. Gas Turbines Power*, vol. 139, no. 2, pp. 1–7, 2017.

[4] Tamatam, L. R., Botto, D. and Zucca, S. (2019) 'Effect of wear on the dynamics of structures with contact interfaces by a coupled static/dynamic multi-harmonic balance method', in *First International Nonlinear Dynamics Conference. Book of abstracts*, pp. 129–130

Solution flowchart



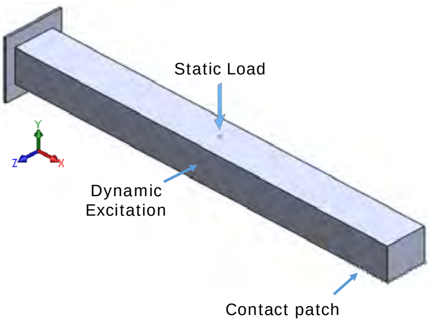
Solution flowchart

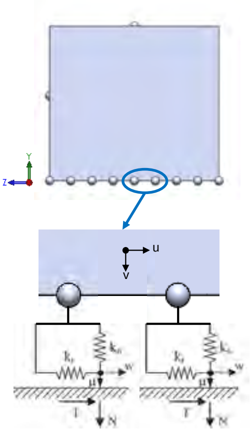


Outline

1. Motivation
2. Theory
3. Test cases
   - Cantilever Beam
   - Bladed Disk
4. New Test Rig
5. Conclusion
6. Appendix
   - Industrial Test Case
   - HPC

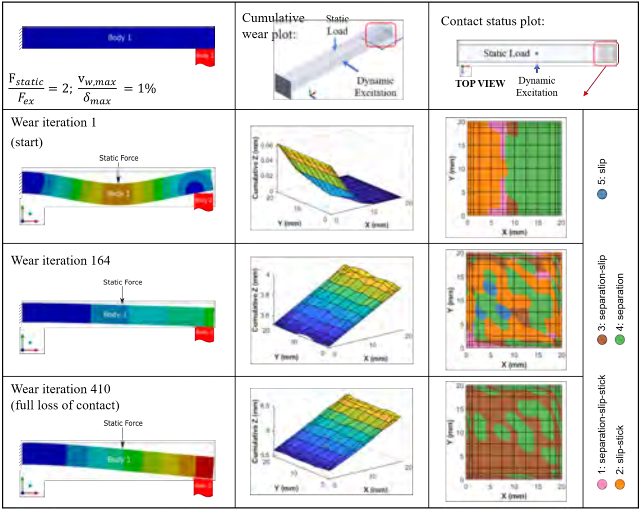
Test Case: Cantilever beam





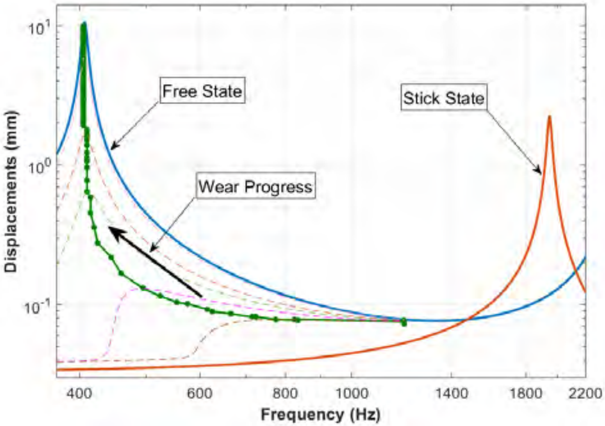
Effect of wear

- Cumulative wear depth and contact status at different wear iterations:

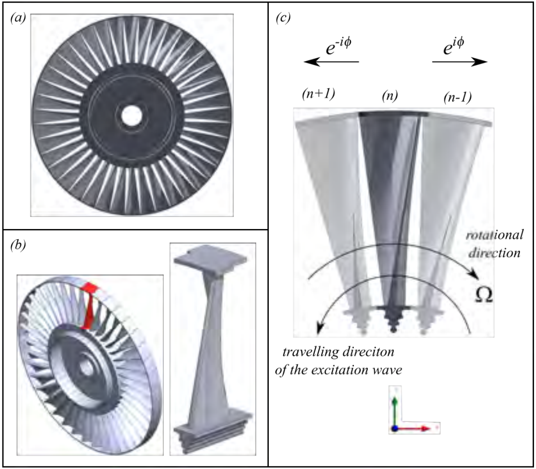


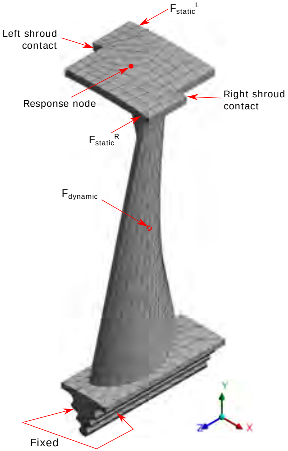
Effect of wear

- Response plot with backbone of non-linear forced response:



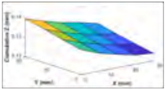
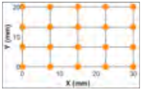
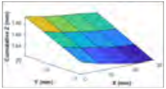
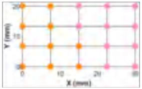
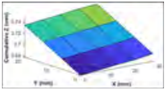
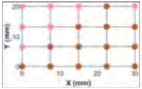
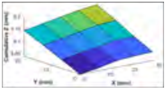
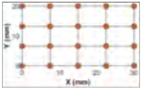
Shrouded bladed disk



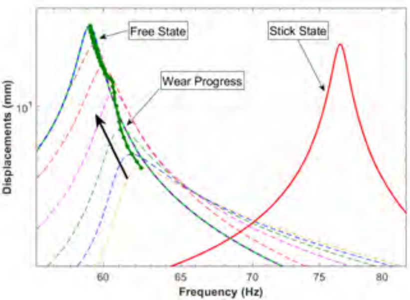


Effect of wear

Contact interface evolution

$\frac{F_{static}}{F_{ex}} = 12$ $\frac{v_{w,max}}{\delta_{max}} = 5\%$	Cumulative wear plot: 	Contact status plot: 1: slip-stick 2: separation-slip-stick 3: separation-slip
Wear iteration 1 (start)		
Wear iteration 12		
Wear iteration 27		
Wear iteration 62 (full loss of contact)		

Dynamic response



Outline

New Test Rig

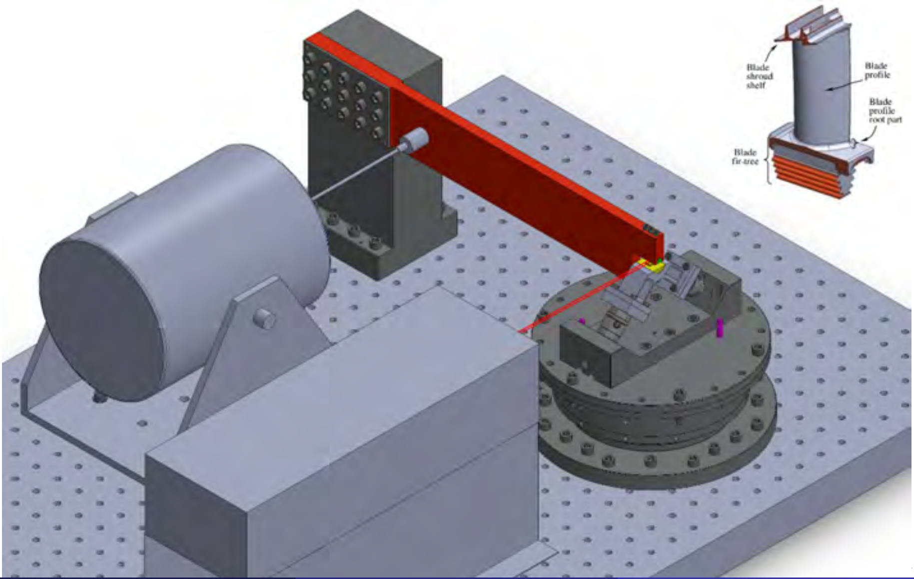
Goal:

- To design a new Test Rig to investigate the effect of wear at the friction contact on the long-term forced response of the structure

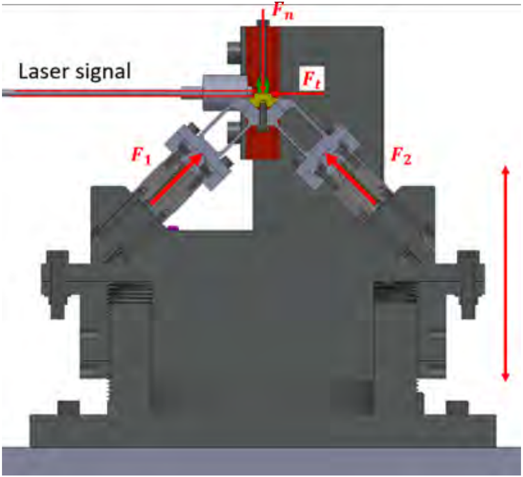
Requirements:

- Clean system FRFs to be able to quantify the effect of wear
- In-situ dynamic response measurement at various wear intervals
- Mechanism to apply static contact pre-load
- Ability to simulate varying contact pre-load with progressing wear
- Ability to study contact surface evolution

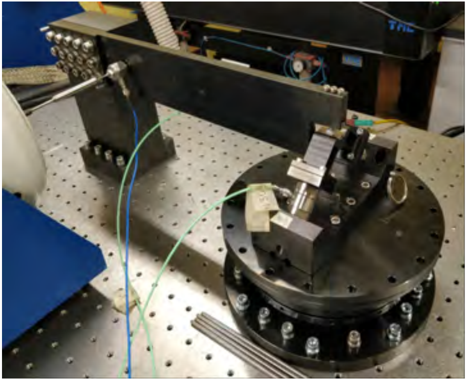
Iso view

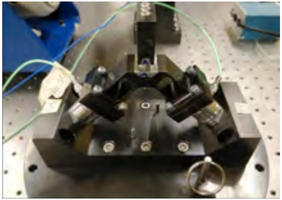

Blade shroud shelf
Blade profile
Blade profile root part
Blade fir-tree

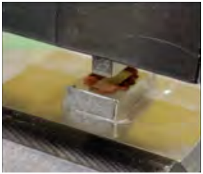
Contact loading mechanism - screw lift system



Test rig pictures

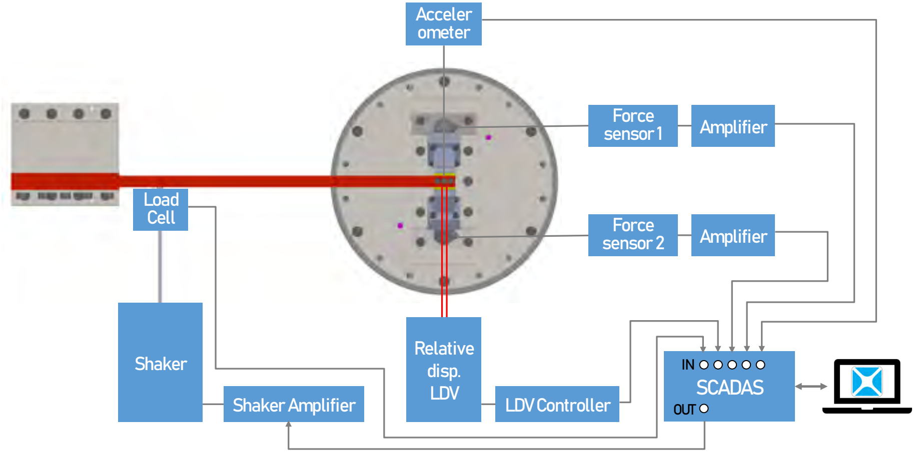






[5] L-separator adapted from: Botto, Daniele Umer, Muhammad. (2018). A novel test rig to investigate under-platform damper dynamics. Mechanical Systems and Signal Processing. 100. 344-359. 10.1016/j.ymssp.2017.07.046.

Instrumentation



Measured quantities

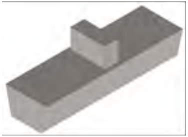
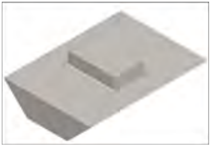
For wear:

- Relative displacement at the contact using Laser
- Tangential contact force $[F_t = F_1 \cdot cos(45^\circ) - F_2 \cdot cos(45^\circ)]$
- Normal contact force $[F_n = F_1 \cdot cos(45^\circ) + F_2 \cdot cos(45^\circ)]$
- Excitation force via Load Cell at the shaker-beam interface

For FRF:

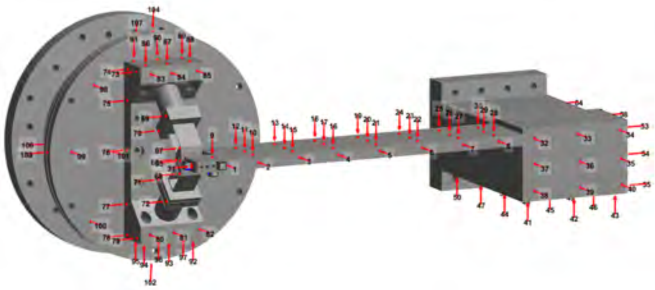
- Accelerometer

Consumables: Body 1 & Body 2

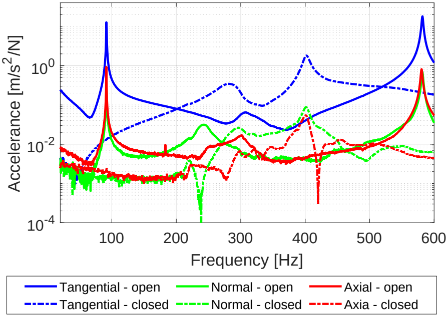

Roving Impact Hammer setup

- 107 impact points to visualize experimental mode shapes
- Performed on open and closed contact

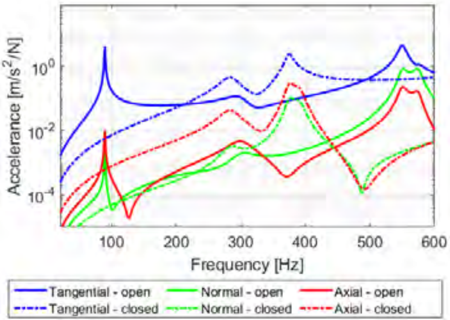


System FRFs

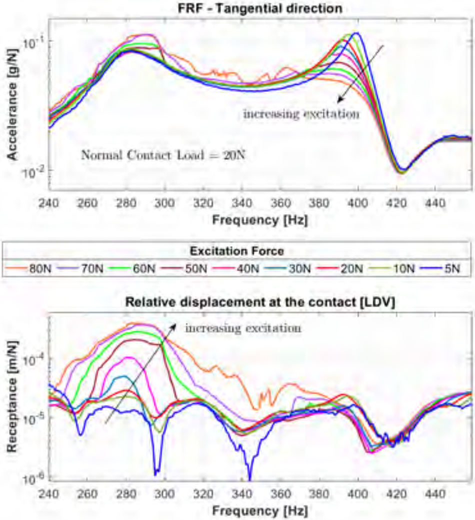
Experimental

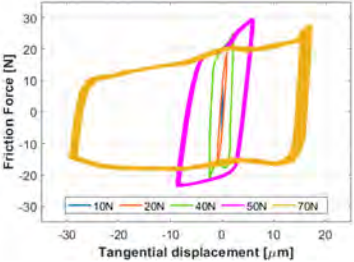


Numerical with tuned joints



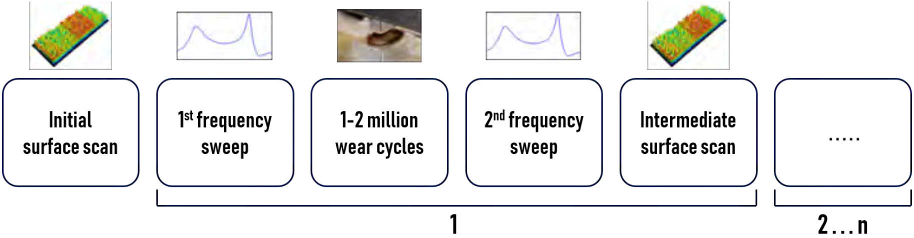
Effect of excitation on FRFs and resulting hysteresis loops





Test plan

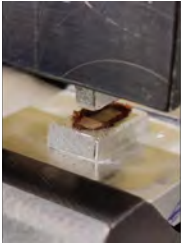
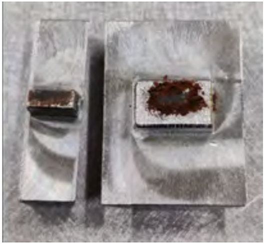
Forced response + wear:



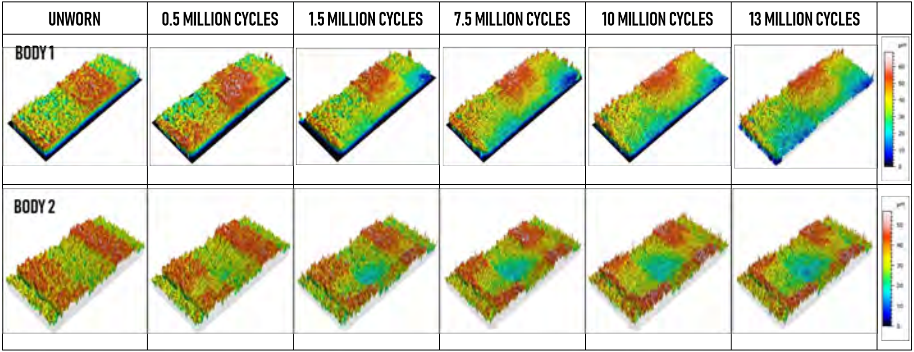
Worn specimens: Close-up

- Nominal contact area = 2*5 mm = 10 mm^2
- Static pre-load = 28 N
- Excitation force = 70 N @ 280 Hz
- 13 million fretting wear cycles



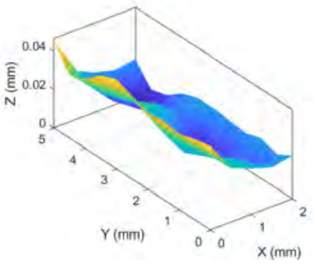



Specimen surface scans

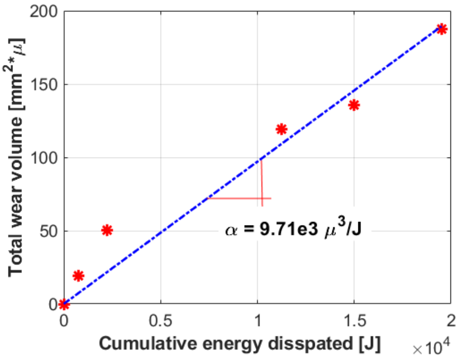


Wear volume vs. Energy dissipated

Cumulative wear profile

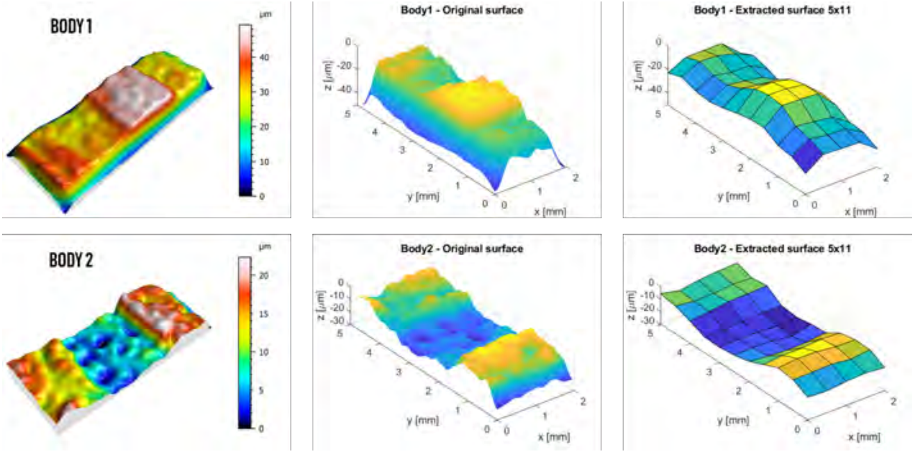


Wear energy co-efficient

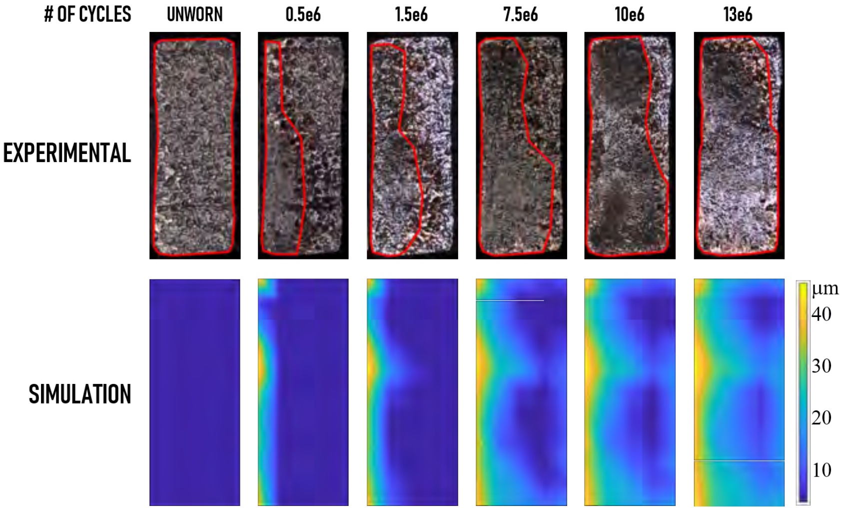


Extracting real surface profile for HBM Simulation

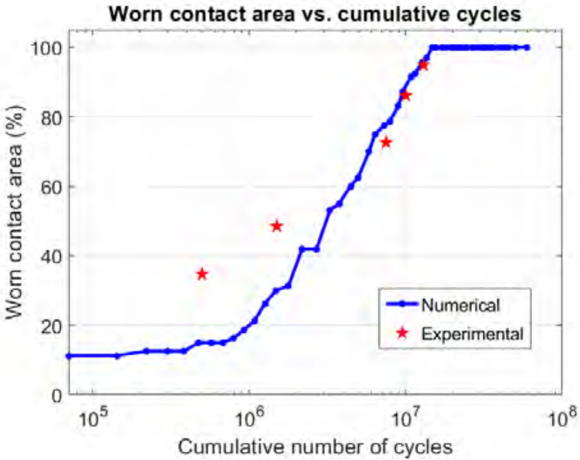
- Extract waviness and down-sample to match mesh grid (5x11 nodes)



Contact interface evolution



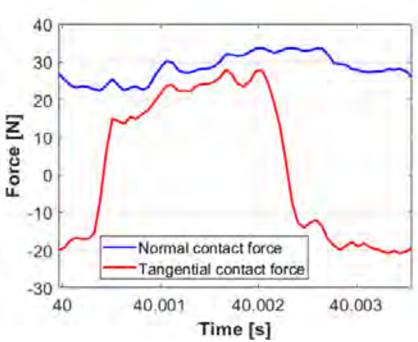
Establishing real contact area



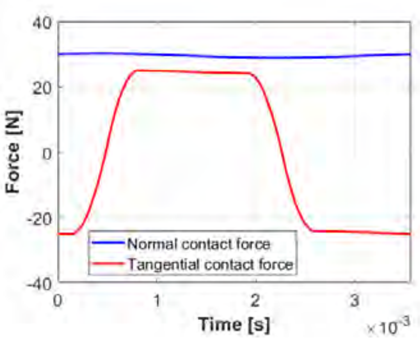
Contact forces

- Snapshot of contact forces in one vibration cycle

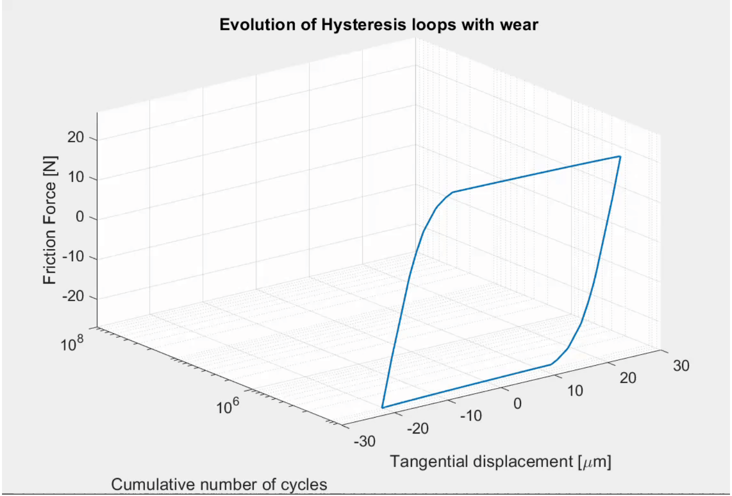
Experimental



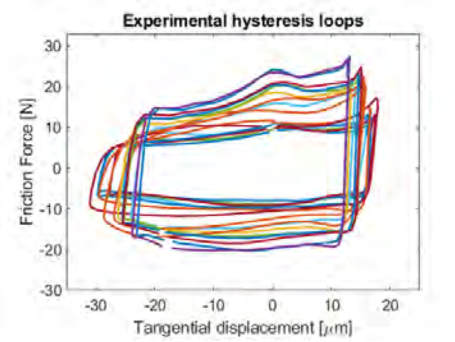
Numerical

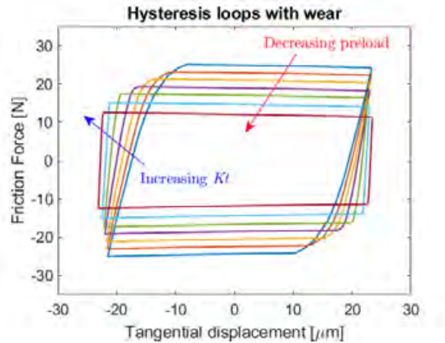


Evolution of Hysteresis loops

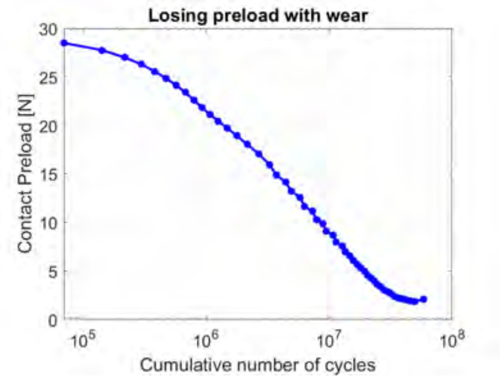


Experimental vs. Numerical Hysteresis loops





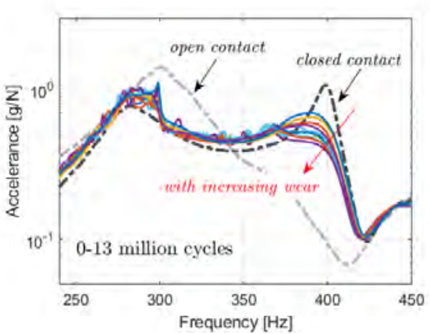
Effect of wear on static pre-load



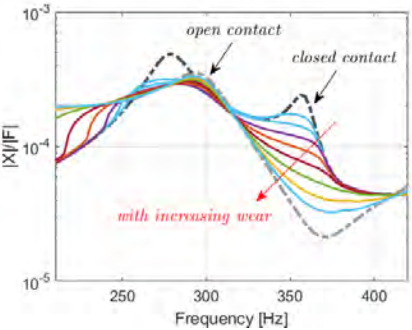
For the given geometry, material and loading conditions, 50 million cycles is not large enough life for a turbomachinery component.
An engine operating continuously at 3000 rpm excited at 1 engine order takes only 11.5 days to full lose the contact!

Effect of wear on the dynamic response

Experimental



Numerical



Test rig: Conclusions

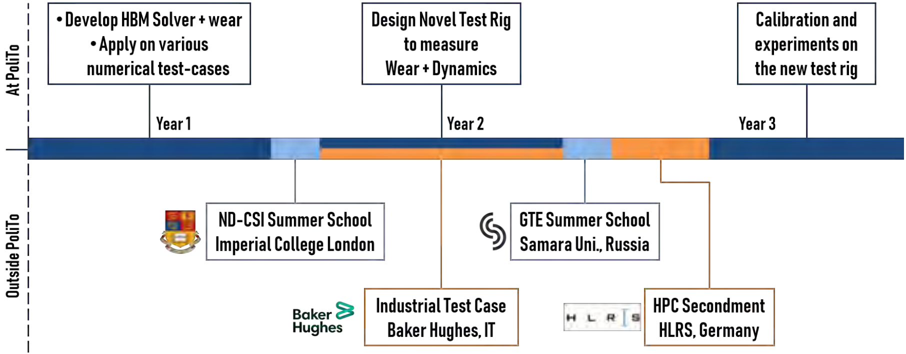
- Successful setup of the test rig, instrumentation, calibration and initial run
- Studied the evolution of contact interface due to wear and the effect on FRFs
- Extracted the contact parameters through hysteresis loops
- Studied the changing static pre-load phenomenon due to wear
- **First of its kind dedicated experimental test rig to study wear and the effect on dynamics with friction contact and changing pre-load**

Numerical simulation:

- Created an FE model of the test rig mimicking real boundary conditions
- Successful run of HBM and performed the effect of wear simulation
- Model needs fine tuning to match the natural frequencies accurately
- Simulated the effect of changing pre-load and the effect on wear evolution and FRFs

Outline

Summary


At PoliTo
• Develop HBM Solver + wear
• Apply on various numerical test-cases
Design Novel Test Rig to measure Wear + Dynamics
Calibration and experiments on the new test rig
Year 1
Year 2
Year 3
Outside PoliTo
ND-CSI Summer School
Imperial College London
GTE Summer School
Samara Uni., Russia
Baker Hughes
Industrial Test Case
Baker Hughes, IT
HLRS
HPC Secondment
HLRS, Germany

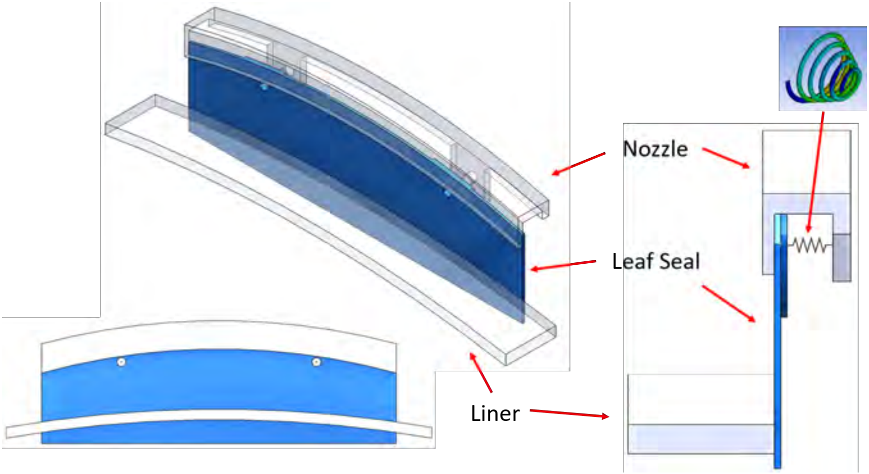
Acknowledgements

This project has received funding from the European Union's Horizon 2020 research and innovation programme under the Marie Sklodowska-Curie grant agreement No 721865.

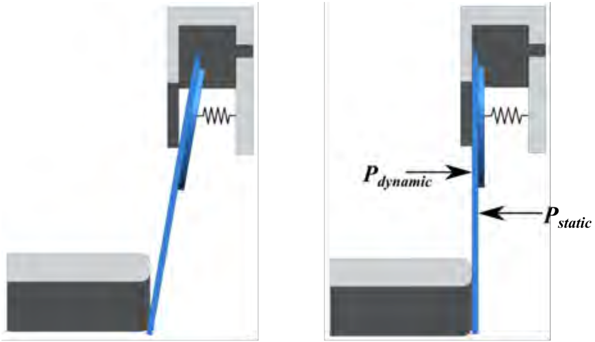
Outline

Gas Turbine Combustor Leaf Seal Overview

Industrial collaboration with Baker Hughes, Florence, Italy



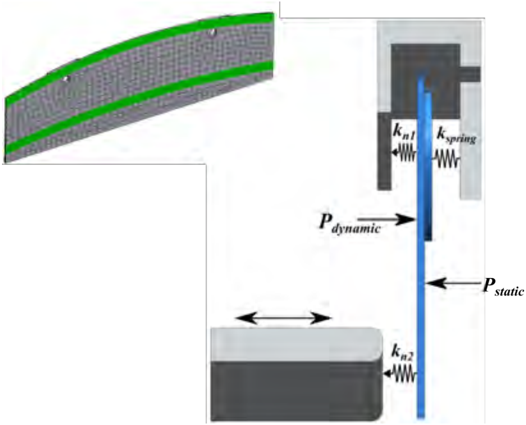
Kinematic & operating envelope

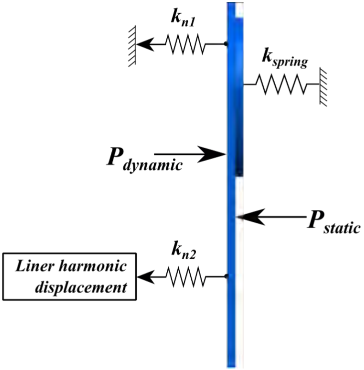


Outward position **Vertical position** **Inward position**

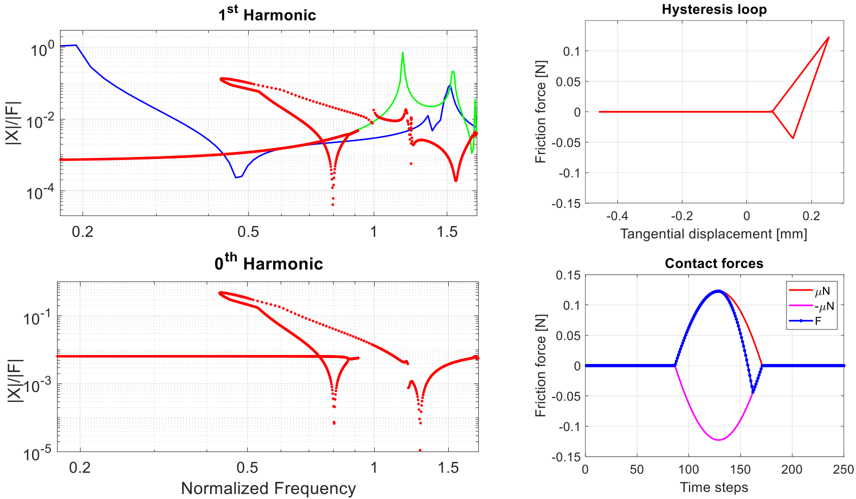
Schematic

- Schematic for dynamic analysis:

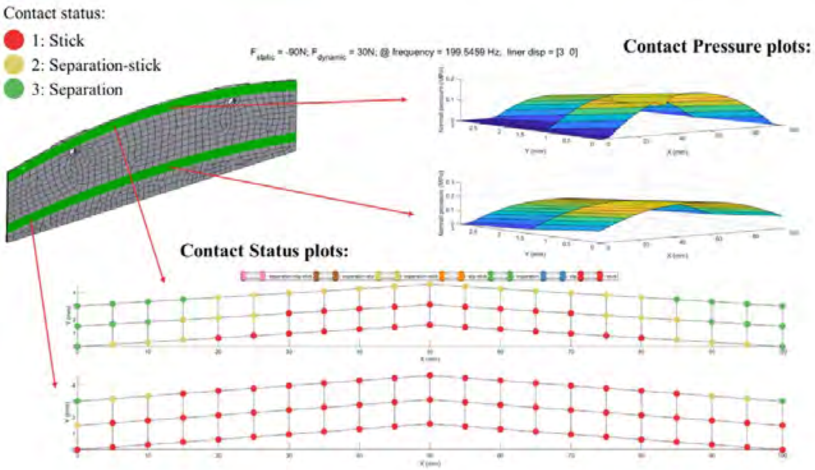




Dynamic results



Contact kinematics



HPC Secondment overview

Location: HLRS, Stuttgart, Germany

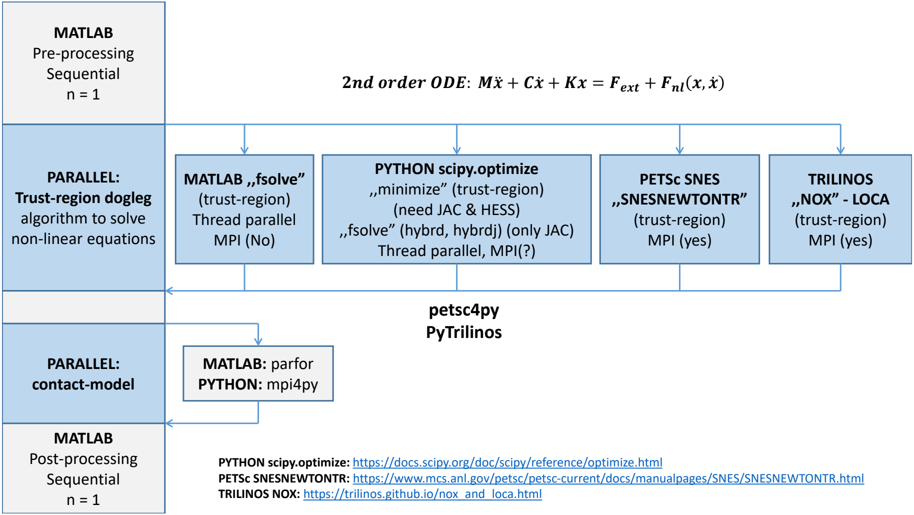
Goal:

- To study the feasibility of parallelization and HPC compatibility of the in-house developed HBM solver

Outcome:

- Learnt the basics of High Performance Computing to understand the hardware and software requirements
- Analyzed the bottlenecks relating to my code in terms of efficiency and MATLAB
- Parametric study on the size of non-linear problem, effect of harmonics and various input parameter space
- Achieved 80% reduction in run-time by re-writing parts of code and optimizing the instruction set compared to Supercomputer with personal computer
- High-level overview study of available external packages, programming languages and pros and cons of each routine specific to the non-linear dynamics domain

HPC – Bird's eye view



$$\textit{2nd order ODE}: \; M\ddot{x} + C\dot{x} + Kx = F_{ext} + F_{nl}(x, \dot{x})$$

PYTHON scipy.optimize: https://docs.scipy.org/doc/scipy/reference/optimize.html
PETSc SNESNEWTONTR: https://www.mcs.anl.gov/petsc/petsc-current/docs/manualpages/SNES/SNESNEWTONTR.html
TRILINOS NOX: https://trilinos.github.io/nox_and_loca.html