Introduction to the 2nd Workshop on Joints Modelling, 2009

Imperial College London

Background

Joints have long been a problem for the structural dynamicist and, increasingly, the joints are becoming the weakest link in many design analyses.

This has been recognised often and there have been many previous attempts to improve the situation. This workshop is the latest in one series of such efforts that can be traced back at least 10 years…

Previous Activities

SD2000: Forum for Future Directions in Structural Dynamics
1999, Sponsored by LANL

Workshop on Predictive Models for Joints and Interfaces
2000, Sponsored by SNL

Workshop on Modelling, Analysis and Measurement for Friction Constraints in Gas Turbine Components
2001, Sponsored USAF, AFRL, AFOSR

Workshop on Benchmarks in Contact Mechanics and Friction Damping ***2002, Sponsored by USAF, AFRL, AFOSR***

Workshop on Joint Mechanics
2006, Sponsored by NSF, SNL

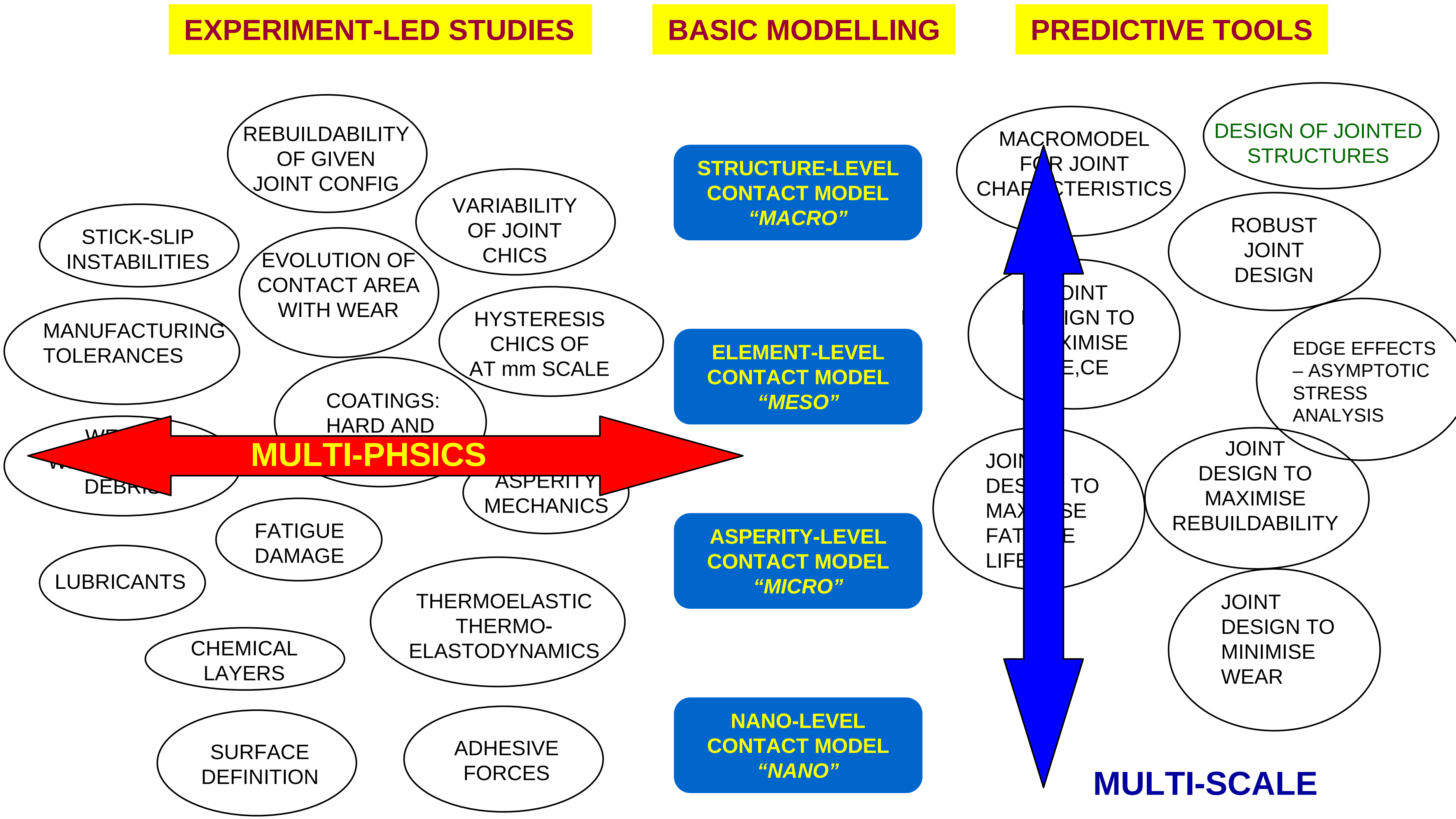
Previous Workshop

Brought together wide range of engineers from different groups, and covered a much broader range of disciplines than had been present in the earlier workshops. That meeting a Road Map as a central feature around which to structure discussions from the macro scale down to the nano scale. There, the objective was to construct a comprehensive map of all the features that might be important in the construction of a truly predictive model for friction contact phenomena.

Previous Workshop

We started with…..

RESEARCH ROADMAP FOR FRICTION CONTACT AND WEAR IN STRUCTURES



Friction CONTACT ROADMAP v 6.3

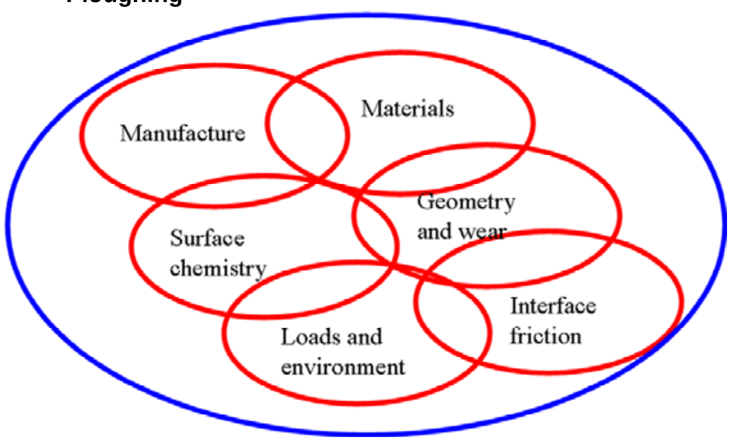
Previous Workshop

and ended up with…..

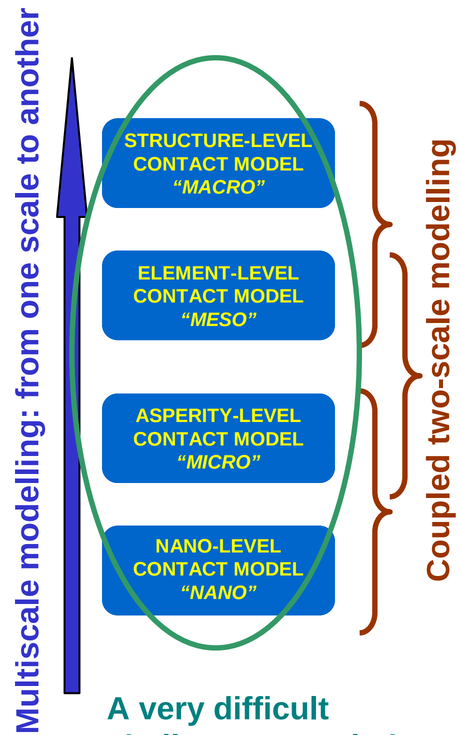
RESEARCH ROADMAP FOR FRICTION CONTACT AND WEAR IN STRUCTURES

PHYSICAL PHENOMENA

- Friction
- Materials properties
  - Elastic, plastic, visco, creep, microstructure, thermal exp
- Lubrication
- Fatigue, Fracture
- Wear
- Debris
- Thermal (heat gen?)
- Environment
- Contamination
- Surface Chemistry
- Ploughing
- Loads
- Load history
- Manufacturing
- Tolerance
- Residual stress
- Oxidation
- Corrosion
- Roughness
- Surface registration
- Adhesion (stick/slip?)
- Adhesives
- Dynamics



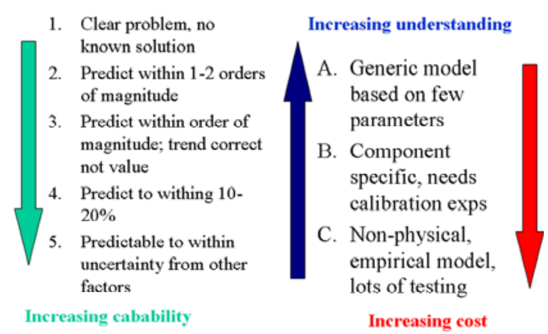
MODELS



A very difficult challenge: coupled multiscale modelling

PREDICTIVE TOOLS

- Vibration damping 3B
- Self-excitation
- Accuracy of positioning (in robots and manipulators)
- Stiffness 4B
- Hysteresis loop
- Fatigue life 2B
- Wear life 2C
- Impact strength 3C
- Temperature
  - Macro 4B
  - Micro 2C
- Heat transfer
  - Macro 4B
  - Micro 2C
- Electrical resistance ?
- Shock load transmission 3B
- Acoustic transmission ?
- Frictional limit (onset of slip) 3B
- Deformed shape (when slipped) 3B
- Surface roughness evolution
- Concept evaluation tool 1C



Previous Workshop

One of the specific outcomes from the previous workshop was the formulation of three 'mini challenges':

Challenge 1: Experimental Measurements of Joint Properties

Challenge 2: Interface Physics

Challenge 3: Multi-scale Modelling

These were intended to focus attention for future research, and we shall hear shortly what has happened in the 2+ years since Washington

This Workshop

We need to re-group and move ahead…..

GOAL, OBJECTIVE, TASKS

GOAL

To be able to optimise design of structures with joints and interfaces from structural dynamics and integrity considerations

OBJECTIVE

To be able to construct mathematical models of joints and interfaces from conventional input data

TASKS

(a) To review the specific requirements for modelling joints in critical engineering structures and to identify future trends in joint design which will become possible with better models

(b) To review recent developments and the current state of the art of joint modelling

(c) To explore ideas for future developments in modelling methods to provide the predictive capabilities required by (a)

Structure for this Workshop

Focus on 3 aspects of the subject:

A End User Needs, Requirements and Opportunities

B Current State of the Art in Joint Modelling

C New Ideas for Future Development of Joint Models

These correspond to -

A, Where do we want to be?

B, Where are we now?

C How might we get from B to A?

Session I: Monday morning

Introduction

0900 Welcome and Intro to the Workshop - ***(Ewins)***
0915 Introductions of all participants
1000 Objectives of the Workshop - ***(Ewins)***
1015 Outcomes from 1st Workshop (2006) ***(Nowell, Polycarpou)***

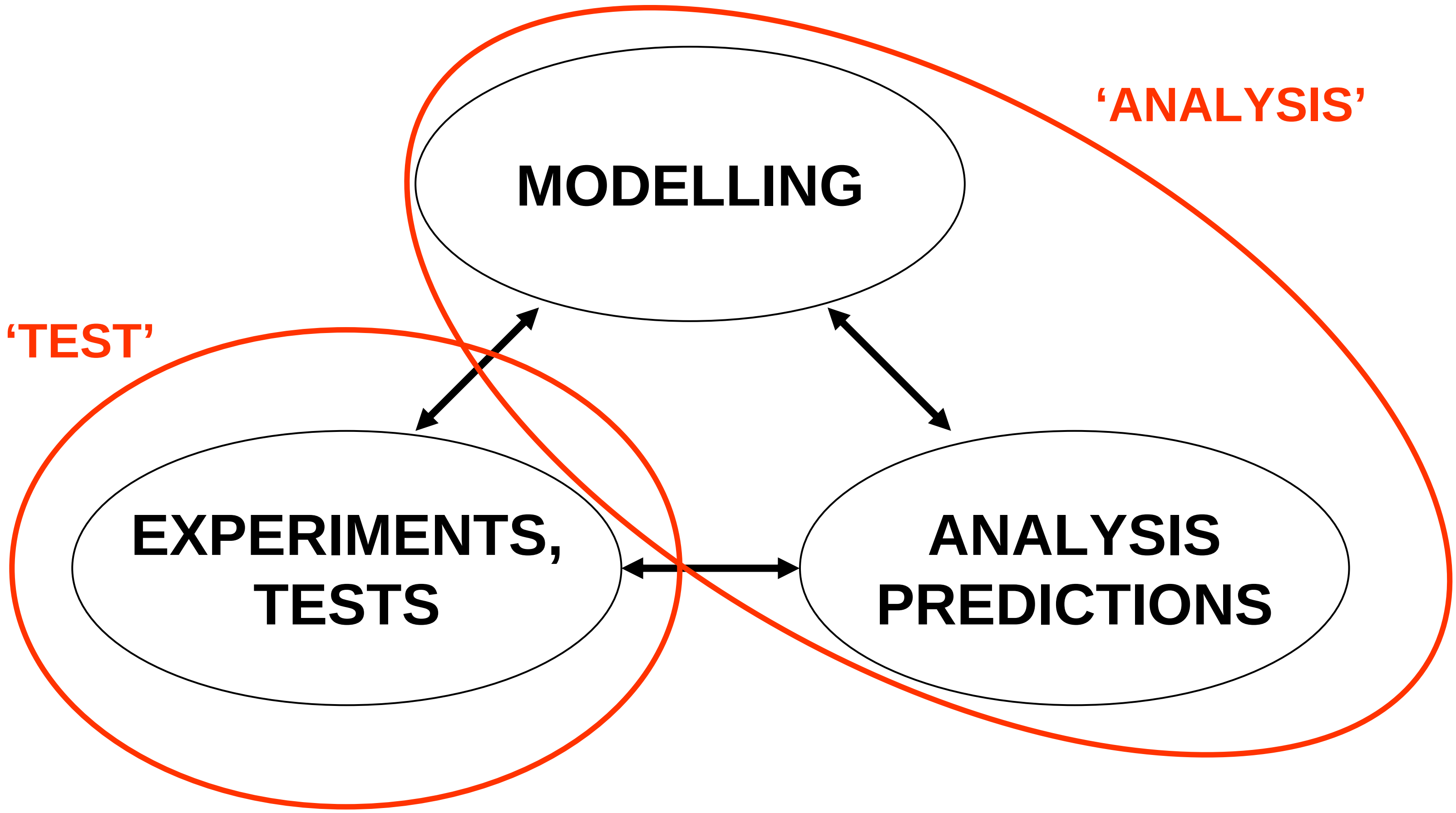
1045 Coffee

Stakeholder, Sponsor and End User Perspectives

1100 Overview of Previous Studies ***(Akay)***
1120 Industrial Perspectives from the Gas Turbine Industry (***Green/Schofield)***
1140 Sponsor Perspectives from Sandia and AWE ***(Segalman, Ind)***

1245 Lunch

THE STRUCTURAL DYNAMICIST'S TOOLKIT



Structure for this Workshop

The structure of the Workshop is built around 3 Breakout Sessions – one for each theme - with the participants split into 3 parallel groups all addressing the same issues.

Each Session will be 'primed' by some short talks which are intended to stimulate ideas which can be debated in the ensuing small group discussions. The outcome of each Breakout Session needs to be an agreed and comprehensive statement of the issues covered by the title.

There will also be some other short talks, and posters, for the dissemination of recent work.

The Final Session will seek to reconcile the anticipated needs, current capabilities and future aspirations of the community with a view to identifying common or collaborative research activities, including benchmarking, all of which can strengthen individual bids for future funding.

Session II: Monday afternoon

Theme A: What does the eng. community need now/soon in terms of joint modeling, and what will it do when it has it?

1400 Short presentations
- Structural assemblies ***(Vakakis for Bergman)***
- Gas turbines ***(Petrov)***
- Model Uncertainty ***(Mignolet)***
- Issues on nonlinear system identification" ***(Vakakis)***

1500 Break

1515 Breakout into 3 groups (Chairs: ***Nowell; Schofield/Green; Starr)***

1615 Collection of group feedback and compilation of prioritized list
1715 Break
1830 Short Talks – 1
Johnson; Mottershead; Farris
1945- Dinner

Session III: Tuesday morning

Theme B: What can the community do today – analytical, computational, experimental?

0900 Review day 1 activities and confirm day 2 agenda
0915 Short presentations
- Analytical Issues ***(Hills)***
- Computational Issues ***(Laursen)***
- Experimental ***(Gola)***
- Experiments towards joint modeling ***(Gaul)***

1015 Break

1045 Breakout into 3 groups (Chairs: ***Gaul; Hills; Laursen***)
1145 Collection of group feedback and compilation of prioritized list

1245 Lunch

Session IV: Tuesday afternoon

Theme C: Ideas for new developments to take current capabilities closer to deliver the community's demands

1400 Short presentations

- Experiments and modeling at microscale ***(Polycarpou)***
- Experiments and modeling at mesoscale ***(Leming)***
- Experiments and modeling at macroscale ***(Mayes)***
- Multiscale modeling of interfaces ***(Masud)***

1500 Break

1515 Breakout into 3 groups (Chairs: ***Berger; Ciavarella; Farris***)

1615 Collection of group feedback and compilation of prioritized list

1715 Break

1830 Short Talks – 2

Ciavarella; Ding; Starr

1945- Dinner

Session V: Wednesday morning (details to be confirmed)

900 Review of Day 2; Plan for Day 3

915 Short Talks – 3
Quinn; Ma; Dini

1015 Break

1045 Develop Plan of Action

1230 Lunch and Departure

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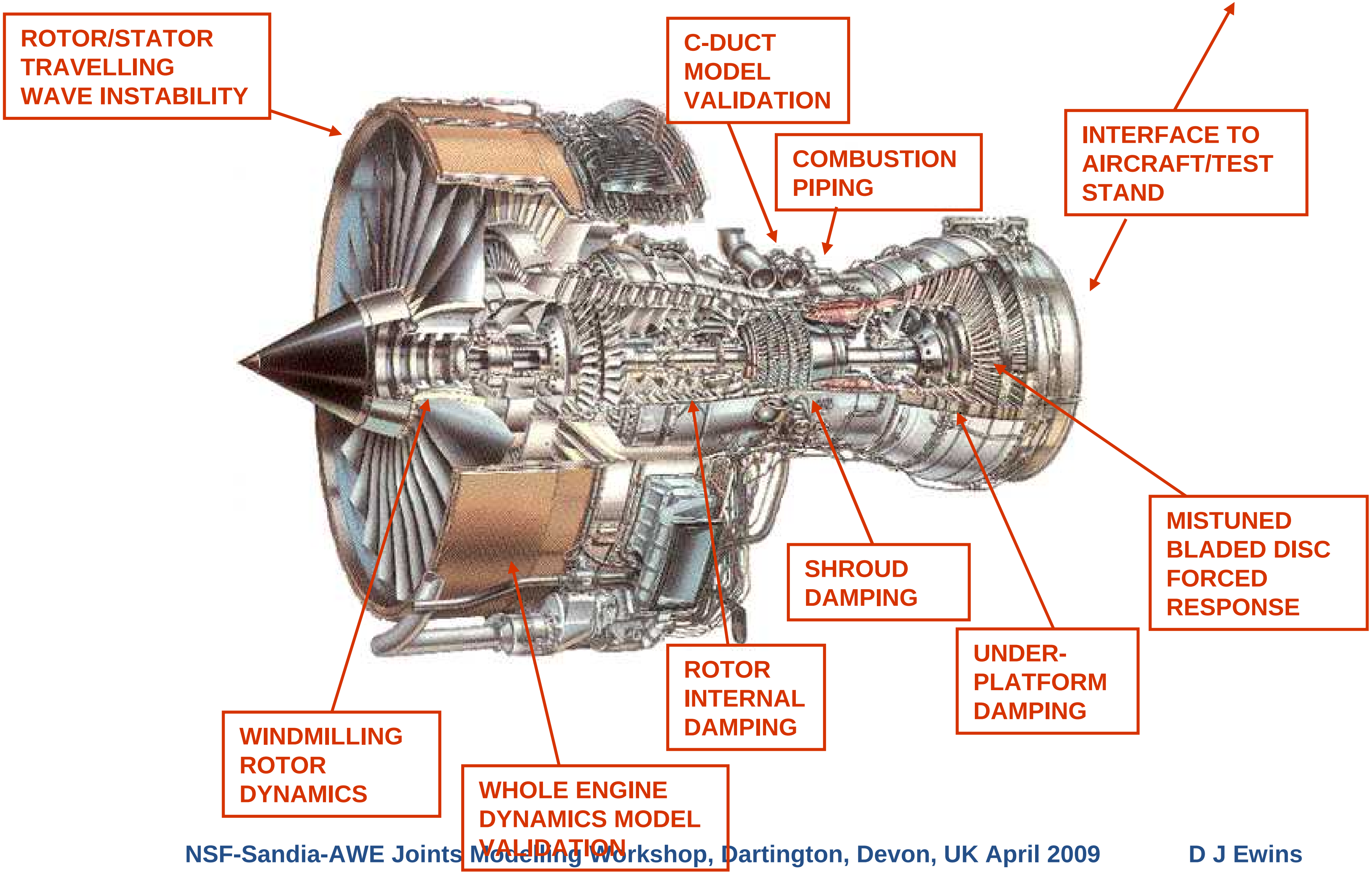
The Influence of Joints on the Dynamics of Gas Turbine Structures

David Ewins

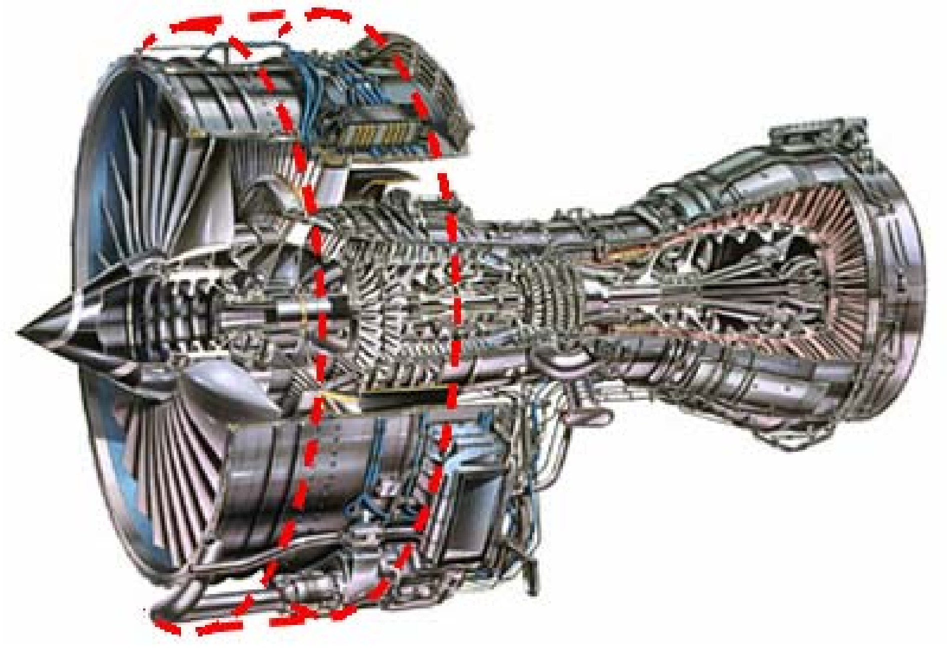
Imperial College London

TYPICAL VIBRATION PROBLEM AREAS IN JET ENGINES WHERE JOINTS & INTERFACES PLAY A SIGNIFICANT ROLE

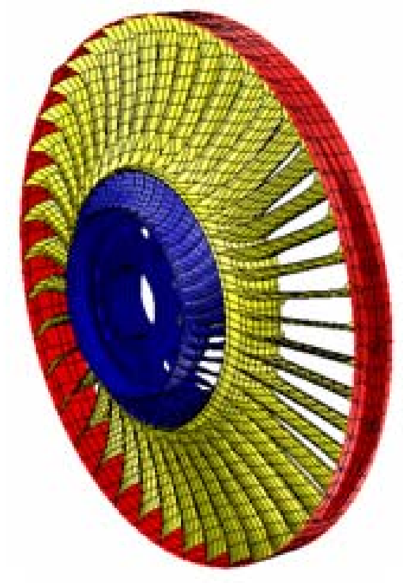


The Critical Influences of Joints on the Dynamics of Gas Turbine Structures

- 'Joints' exert a non-negligible effect on the stiffness (and thus natural frequencies) and damping of all structural assemblies
- Current structural dynamic modelling capabilities are very much less advanced in respect of joints and interfaces than for any of the components that they connect
- Such models as do exist are heavily dependent on the availability of associated experimental measurements, many of which are difficult and expensive to acquire
- Consequently, the optimal design of many critical structures in gas turbines is significantly restricted by the lack of reliable predictive models of joints



(a)



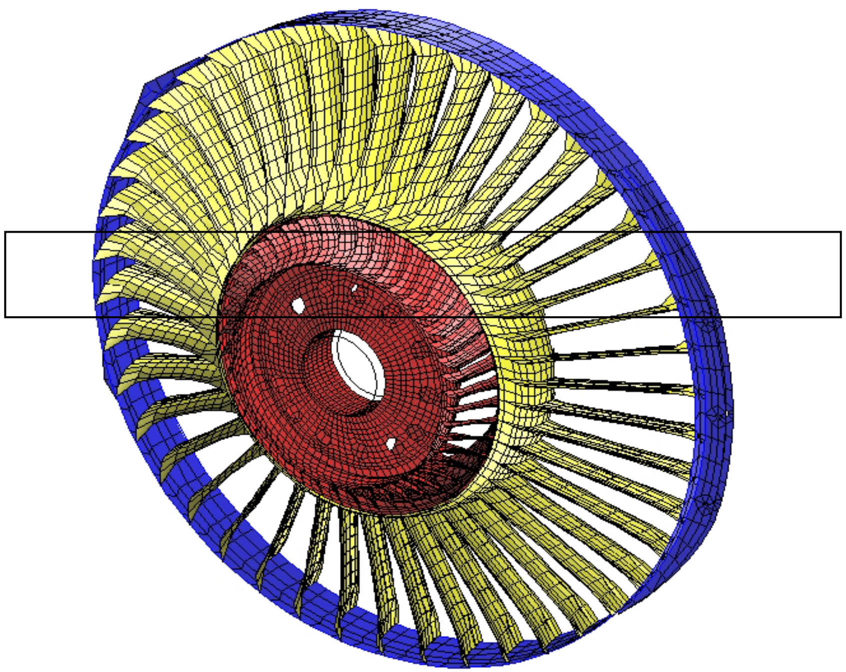
(b)

Figure 4.1. Front Structure. (a) Location in the aeroengine and (b) design model.

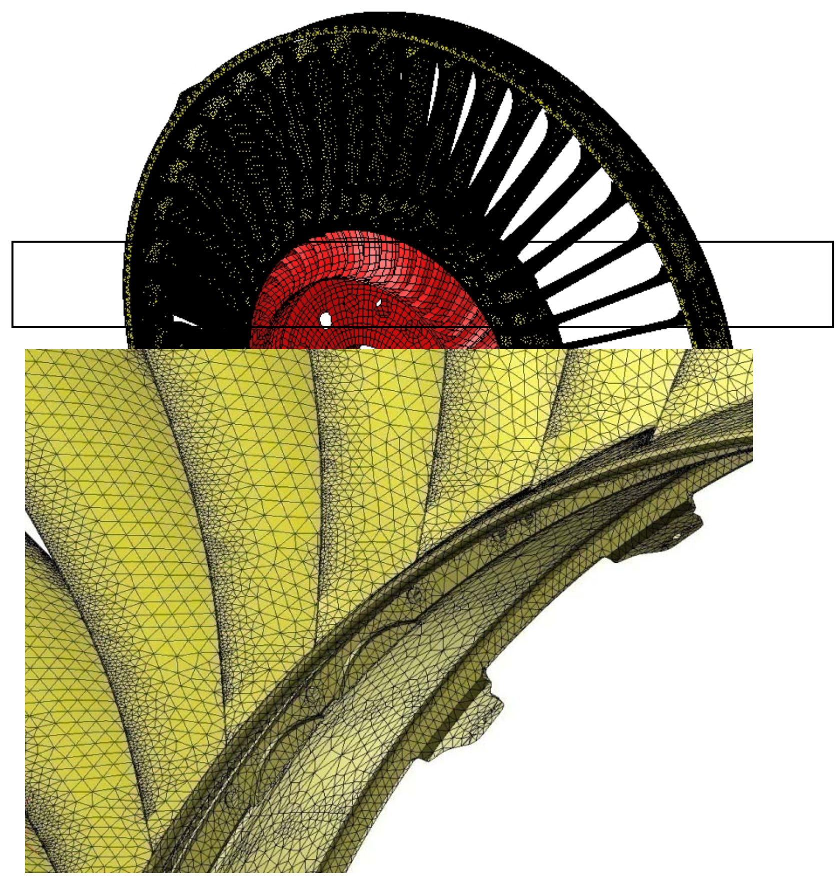
From: Garcia, J. 'Development of Valid Models for Structural Dynamic Analysis'; PhD Thesis, December 2008

Component Models

Design Model

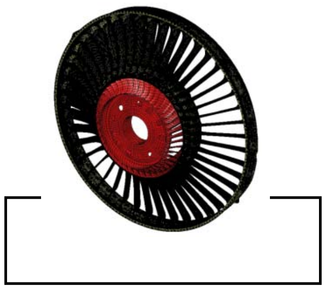


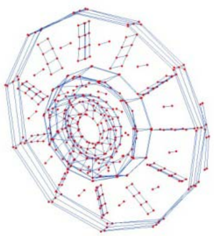
Supermodel

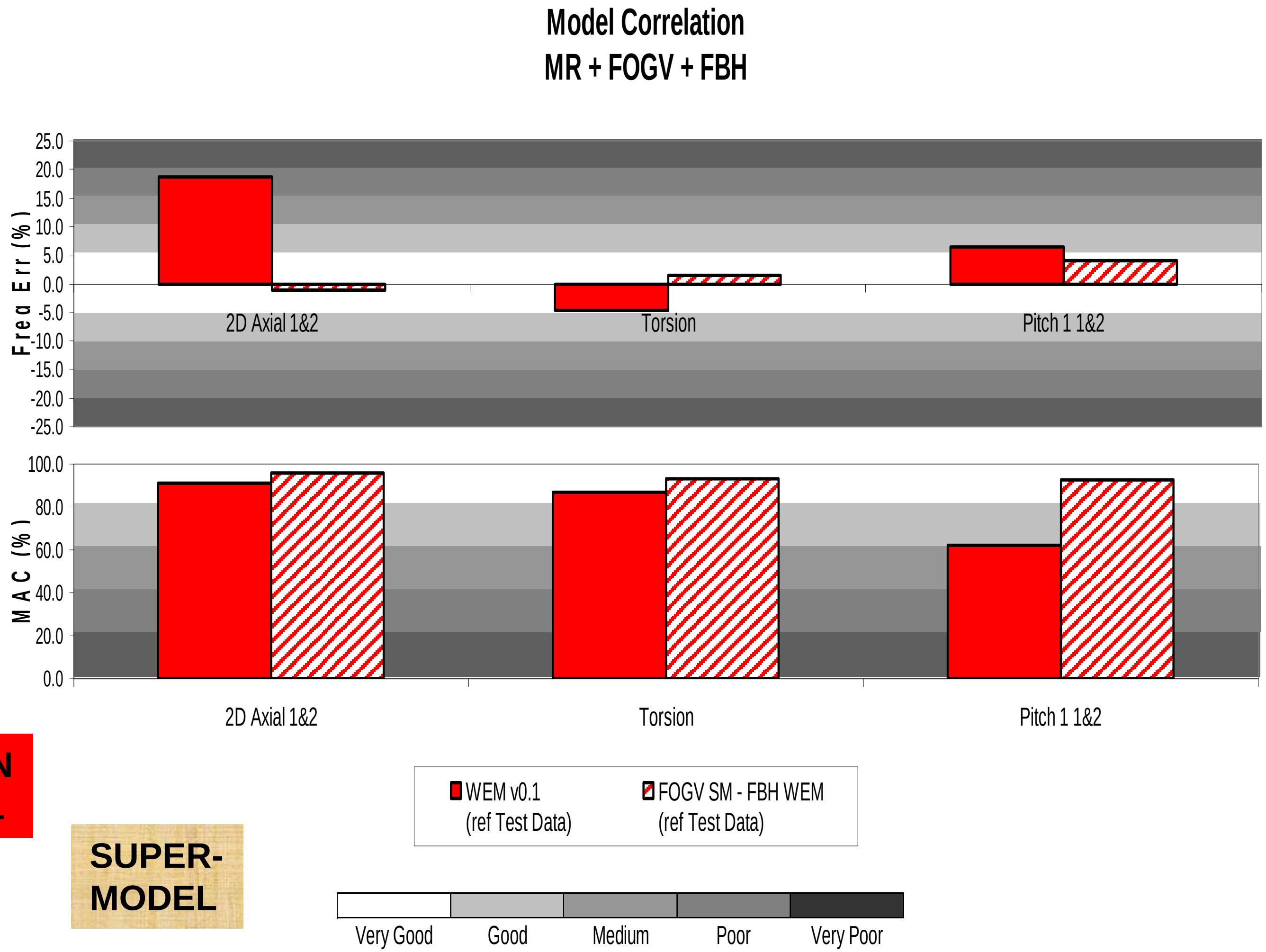


Courtesy: Rolls-Royce

Component Models





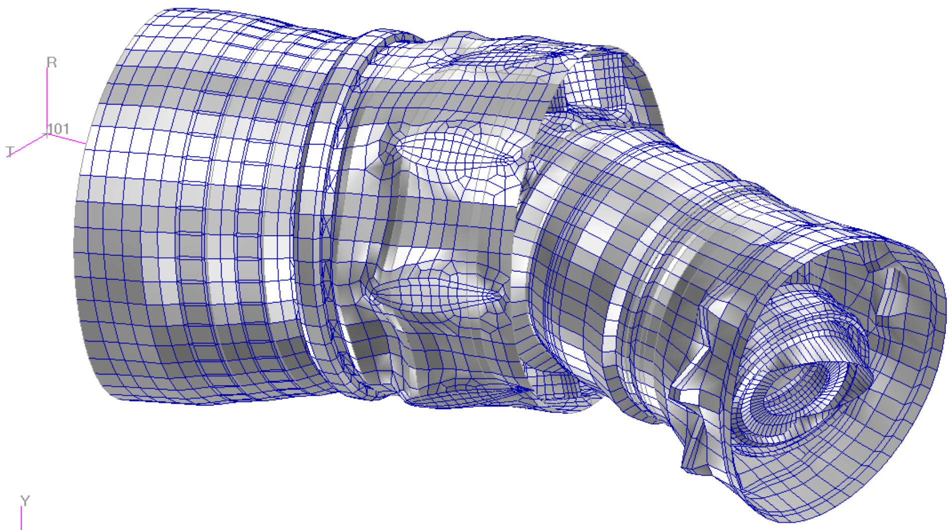


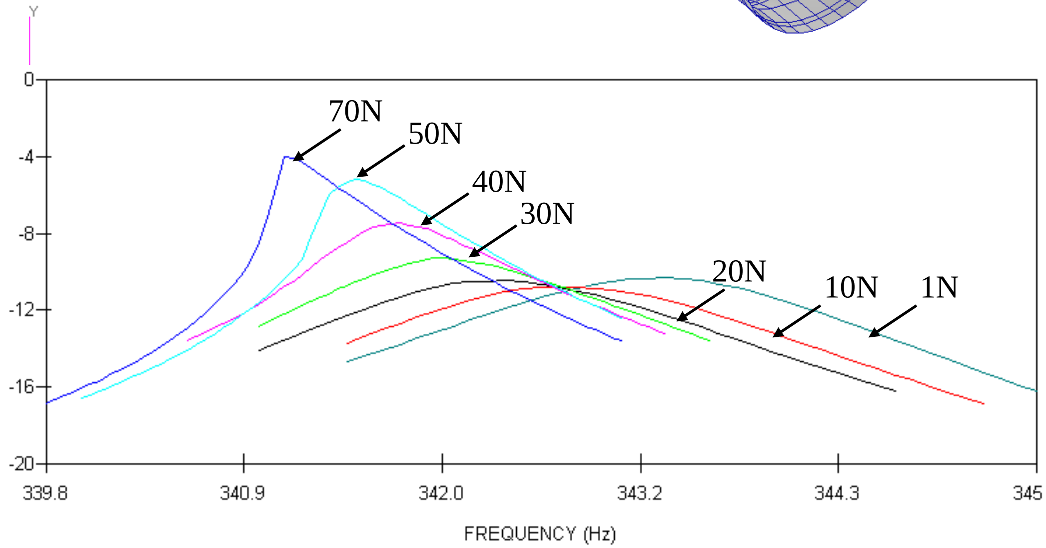
DESIGN MODEL

SUPER-MODEL

Courtesy: Rolls-Royce

Effect of Nonlinear Joint Dynamics on Dynamic Behaviour of Engine Structures





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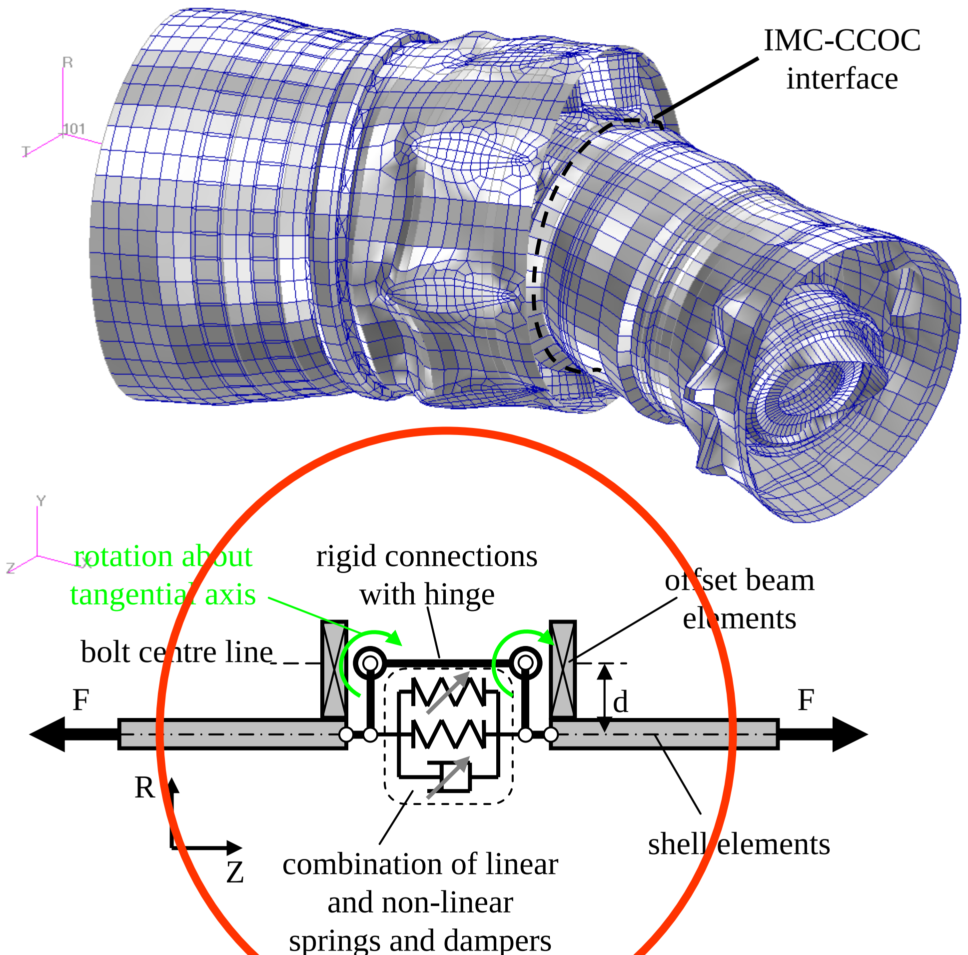
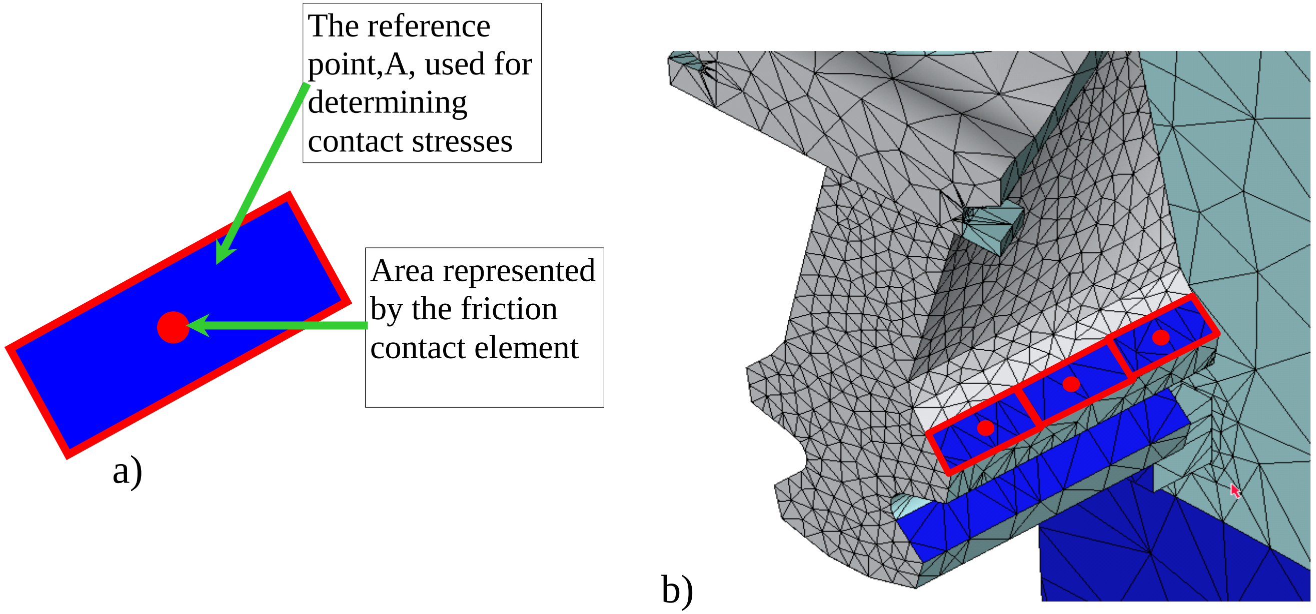
Incorporating Nonlinear Joint Behaviour into FE Models



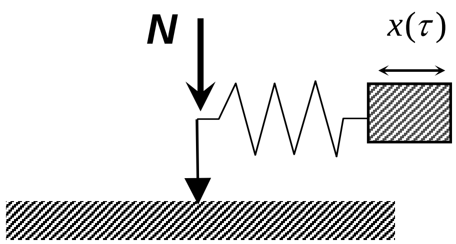
Modelling Approach for Bolted Flange Joints

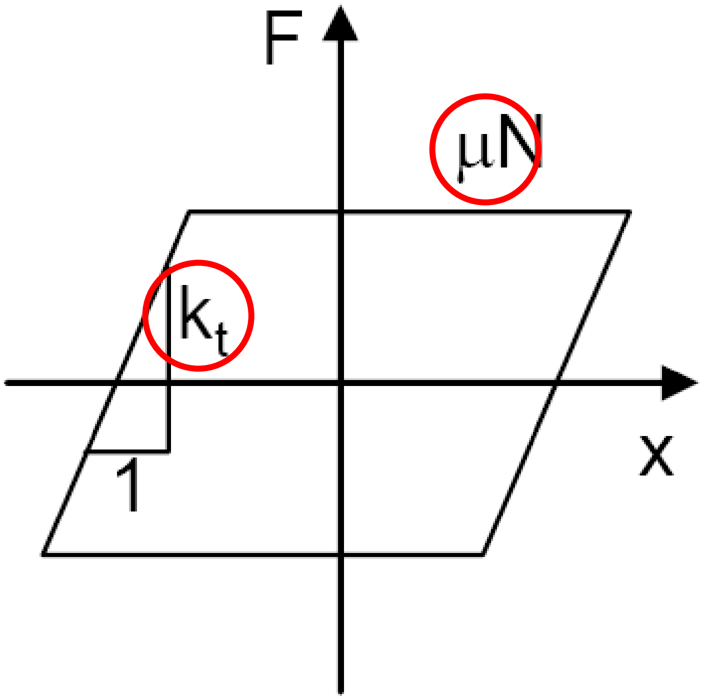
Courtesy: University of Kassel

Modelling of Interaction at Contact Surfaces: Area Contact Elements



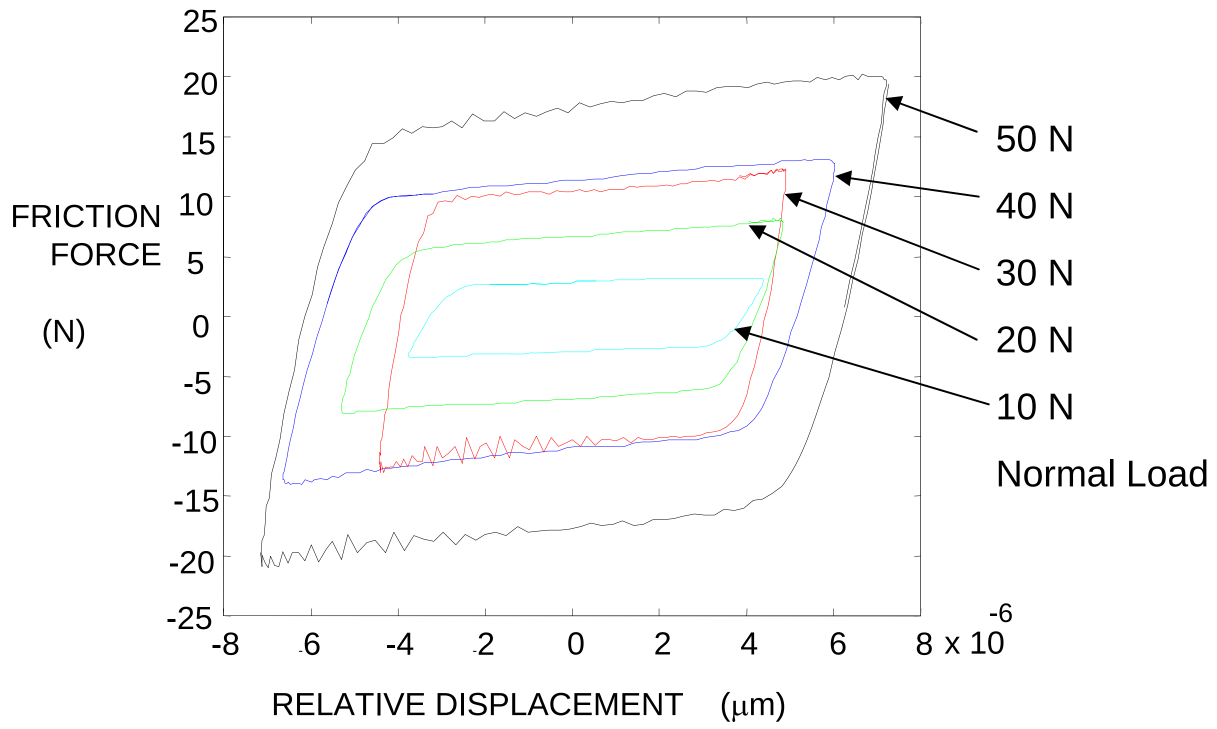
Friction Model Element Input Parameters





...and the role of experimental technologies therein?

A set of hysteresis loops, measured at different applied normal loads.



The Structural Dynamics & Integrity Needs for Much Better Modelling of the Joints in Gas Turbines – 1/2

- **Current methods to account for the effects of joints and interfaces on the dynamics and integrity of gas turbine structures are basic, expensive and ‘post’dictive, rather than predictive (sometimes referred to as ‘retropredictive’**
- **They do not provide a full understanding of the controlling physics and, as a result, a model constructed for one particular joint cannot readily be extrapolated to another joint**
- **Today’s joint models are much less advanced than those of the components which they connect**
- **The essential need for measured data inhibits attempts to use today’s models to design joints so that they exhibit specific properties**

…………

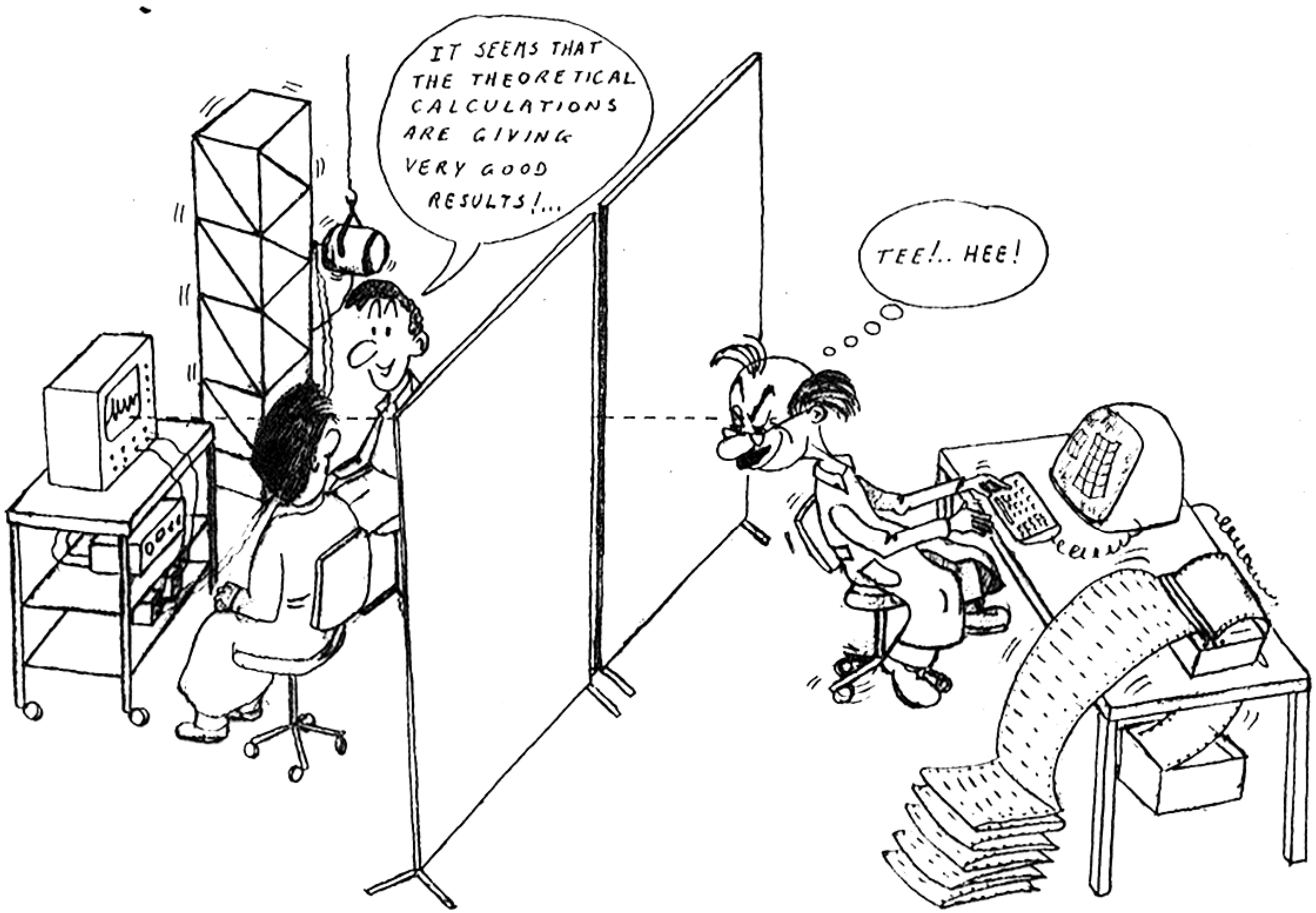
The Structural Dynamics & Integrity Needs for Much Better Modelling of the Joints in Gas Turbines – 2/2

…………

- **Truly predictive models for joints and interfaces are now urgently required:**

  (i) to restore a balance between the models of all the individual components in a complex structural assembly, and

  (ii) to pave the way to proactive design of joints to provide required properties (rather than simply representing characteristics that have been observed by measurement) and thereby to better optimise the design of these complex structures



RETRO - PREDICTION

Short Presentations

Ciavarella: **"Greenwood-Williamson roughness models with interaction" or Shakedown at frictional contacts" (B)**

Ding: **"Quantification of fretting damage via a contact-evolution based modelling approach" (B)**

Dini: **"New ideas and developments for improved modelling methods" (C)**

Farris: **"Recent Developments in Conformal Contacts" (B)**

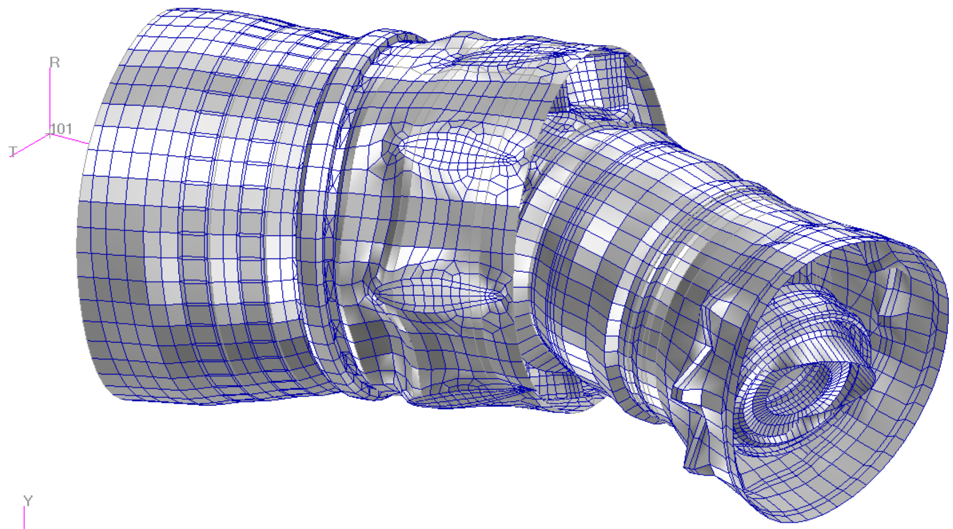
Ma: **"The dynamics of microscale plates submerged in fluid" (C)**

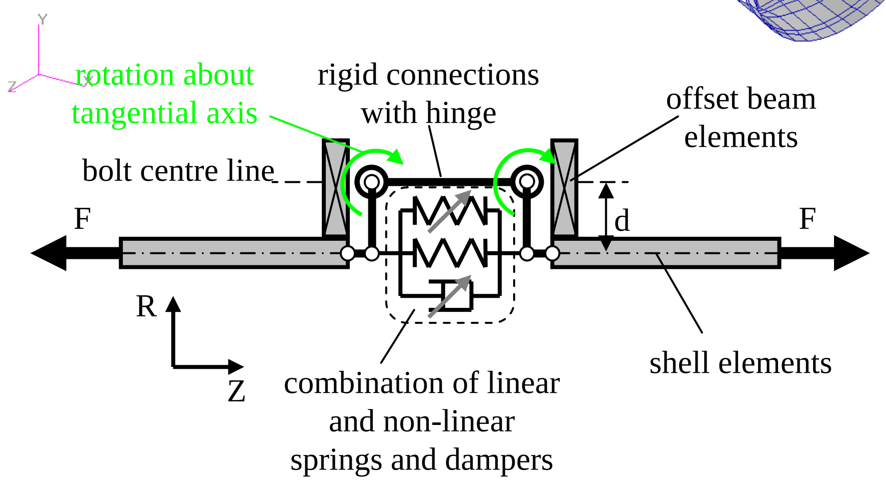
Mottershead: "Nonlinear bolted-joint identification by force-state mapping" (B)

Quinn: **"Series-series Iwan models for two-sided interfaces" (C)**

Starr: **"Modeling Interfaces in a Structural Dynamics Analysis: Enriching our Joints Models and Capabilities" (A/B)**

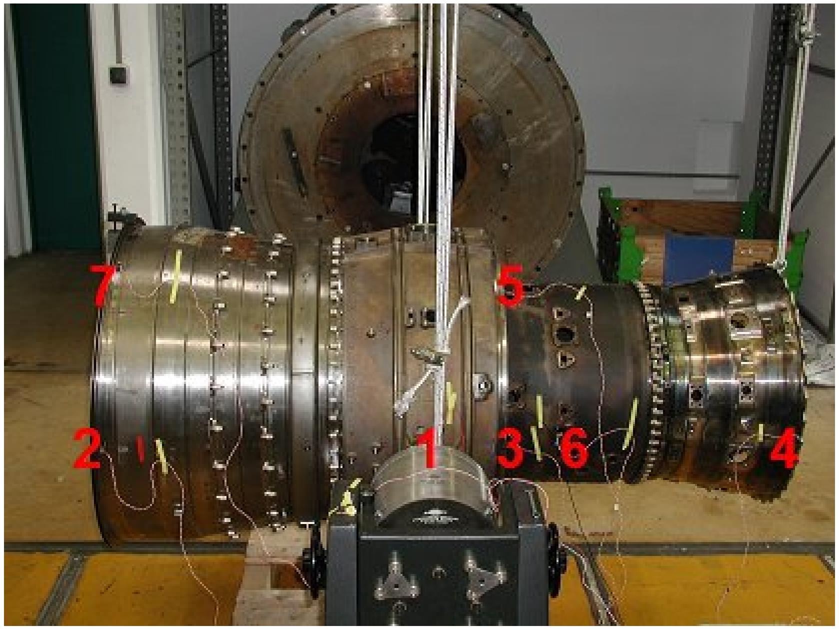
Incorporating Nonlinear Joint Dynamics Behaviour of the Structure into FE Models

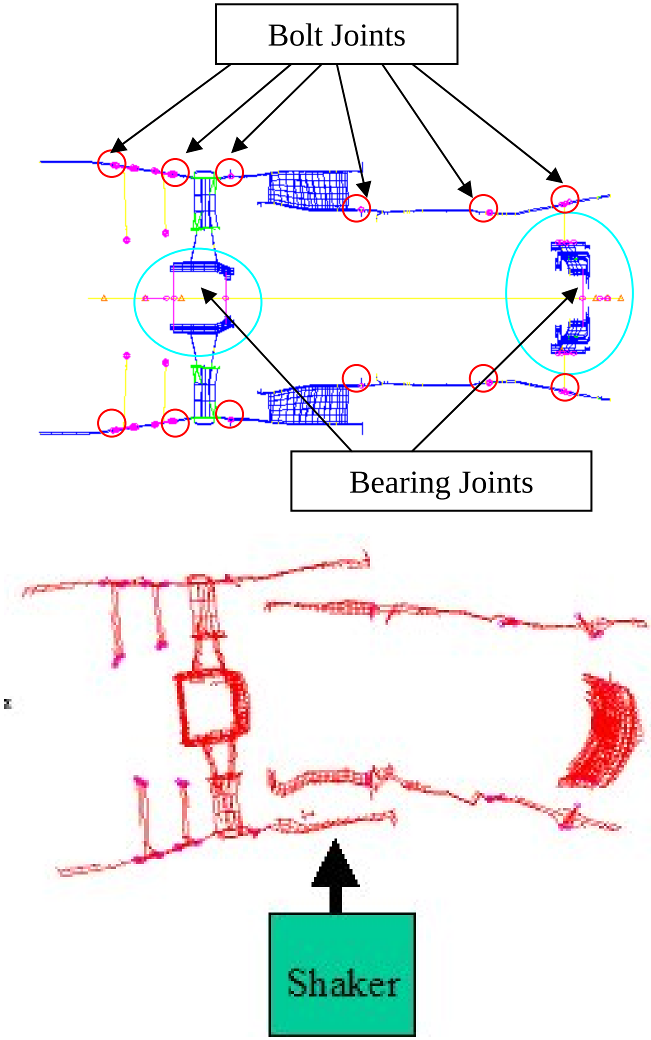




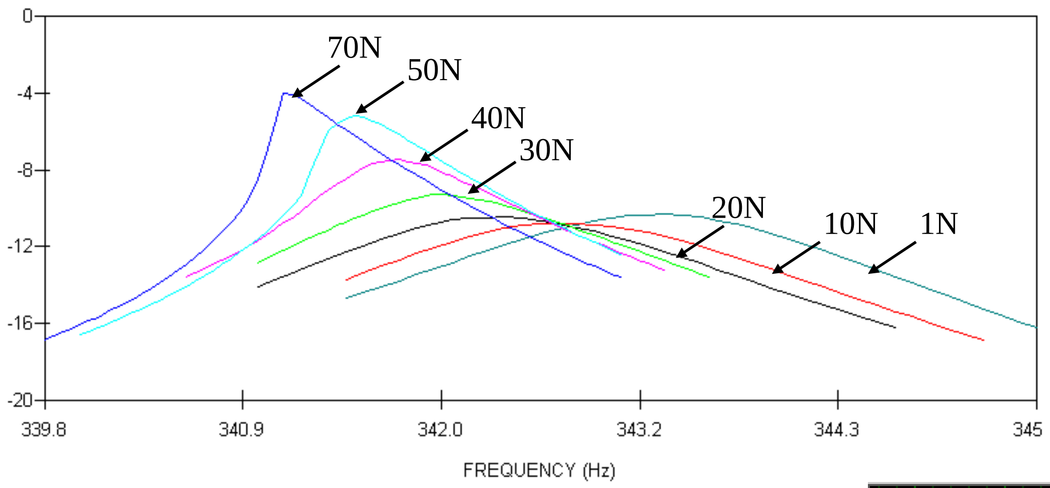
Modelling Approach for Bolted Flange Joints

Aero-engine Casing Test Configuration

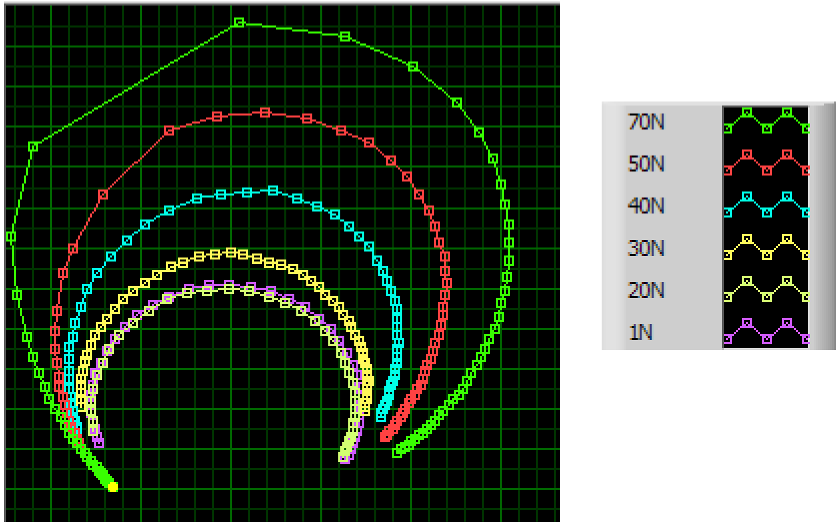


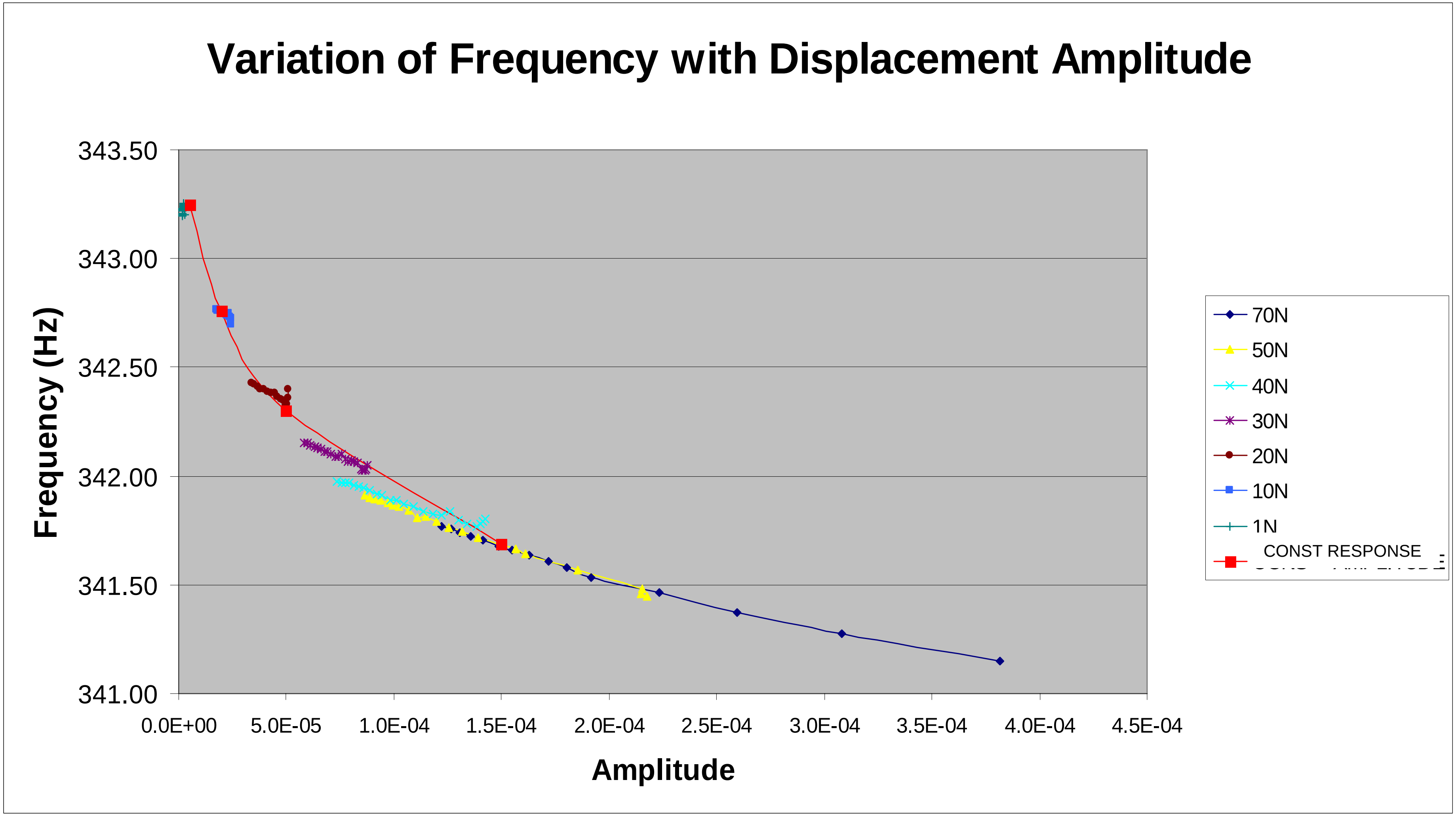


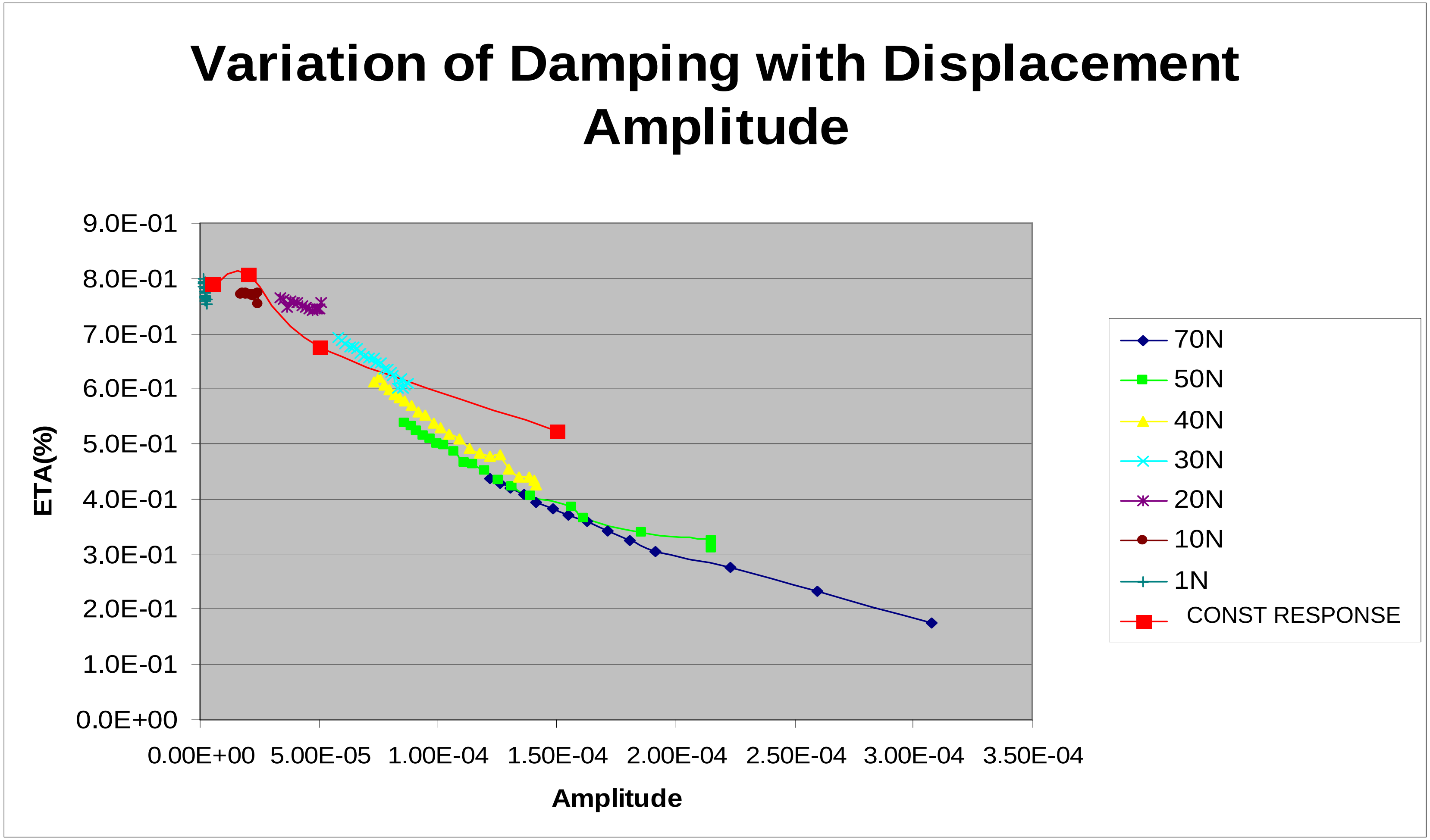
Test Data Obtained Using Force-Control Test



The first-order FRFs in Nyquist format are used to select the frequency range and frequency interval of measurement for CLV test

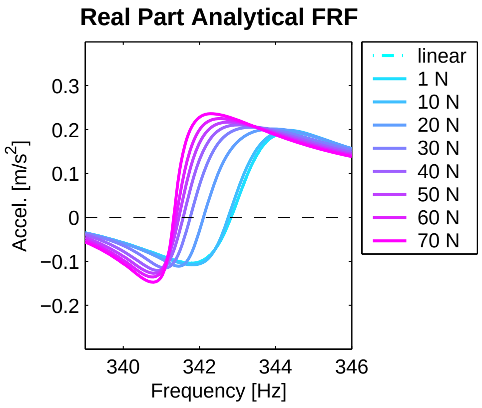



Variation of Frequency with Displacement Amplitude
343.50
343.00
342.50
342.00
341.50
341.00
Frequency (Hz)
0.0E+00
5.0E-05
1.0E-04
1.5E-04
2.0E-04
2.5E-04
3.0E-04
3.5E-04
4.0E-04
4.5E-04
Amplitude
70N
50N
40N
30N
20N
10N
1N
CONST RESPONSE

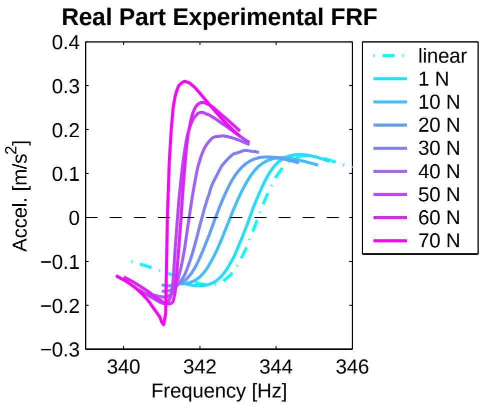

Variation of Damping with Displacement Amplitude
ETA(%)
9.0E-01
8.0E-01
7.0E-01
6.0E-01
5.0E-01
4.0E-01
3.0E-01
2.0E-01
1.0E-01
0.0E+00
0.00E+00
5.00E-05
1.00E-04
1.50E-04
2.00E-04
2.50E-04
3.00E-04
3.50E-04
Amplitude
70N
50N
40N
30N
20N
10N
1N
CONST RESPONSE

Comparison of Analytical and Experimental Non-linear FRF

ANALYSIS

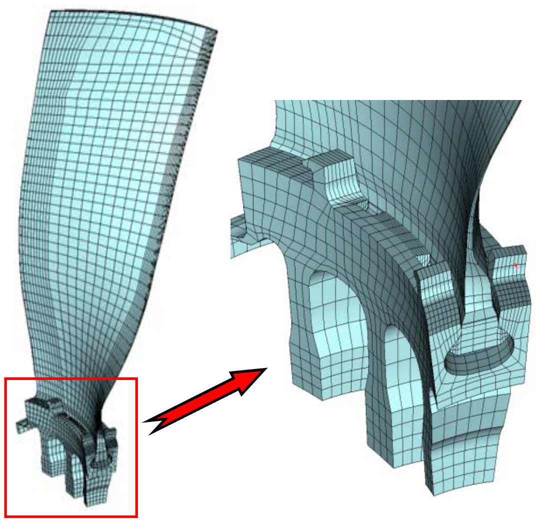


EXPERIMENT

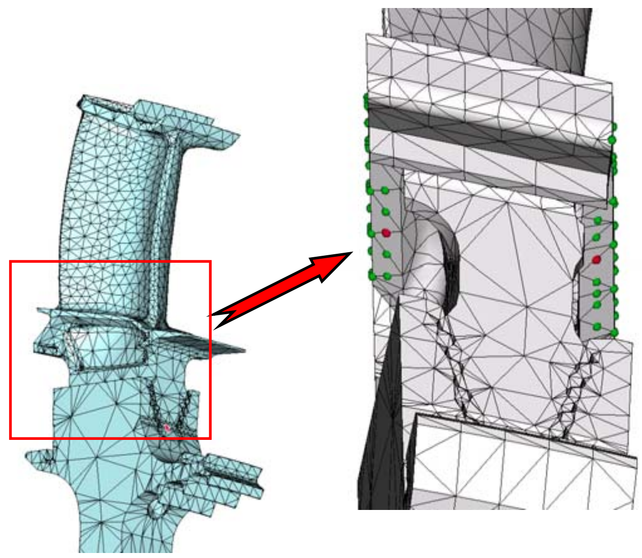


Examples of dynamic contact phenomena in bladed discs

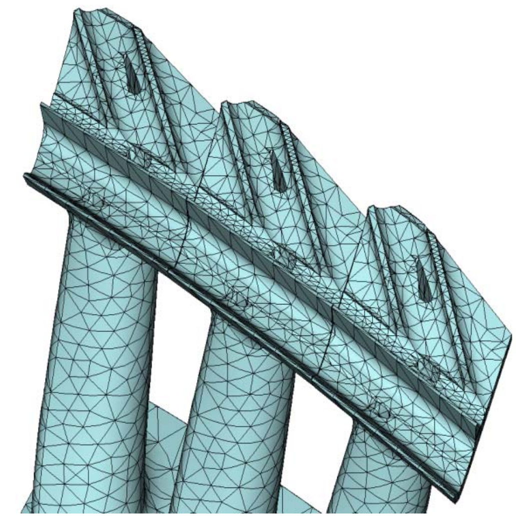
Root damping and variable contact

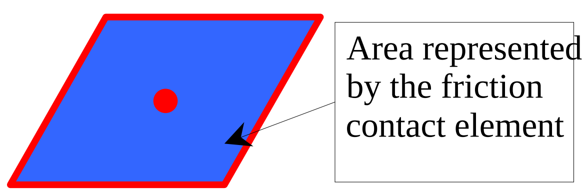


Underplatform dampers



Contact of shrouds

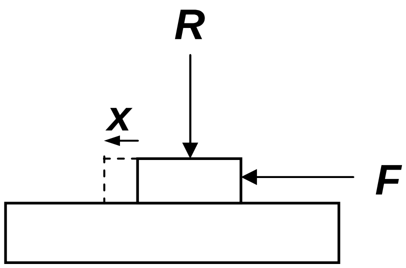


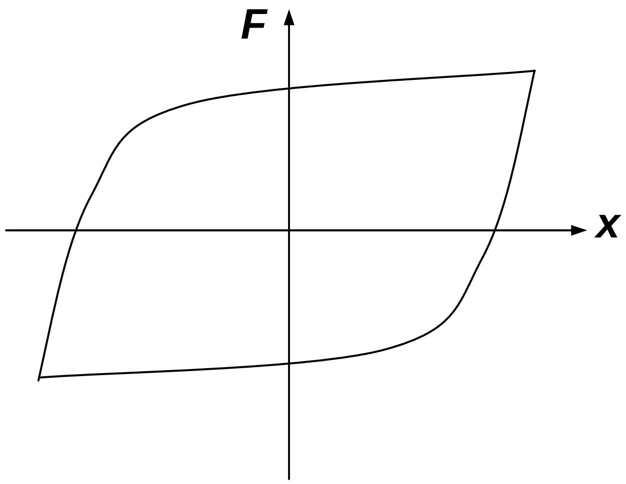


Characterization of Non-Linear Structural Elements

Non-linear, inertia-free structural components are generally characterized by a restoring force surface $F = f(x, \dot{x})$

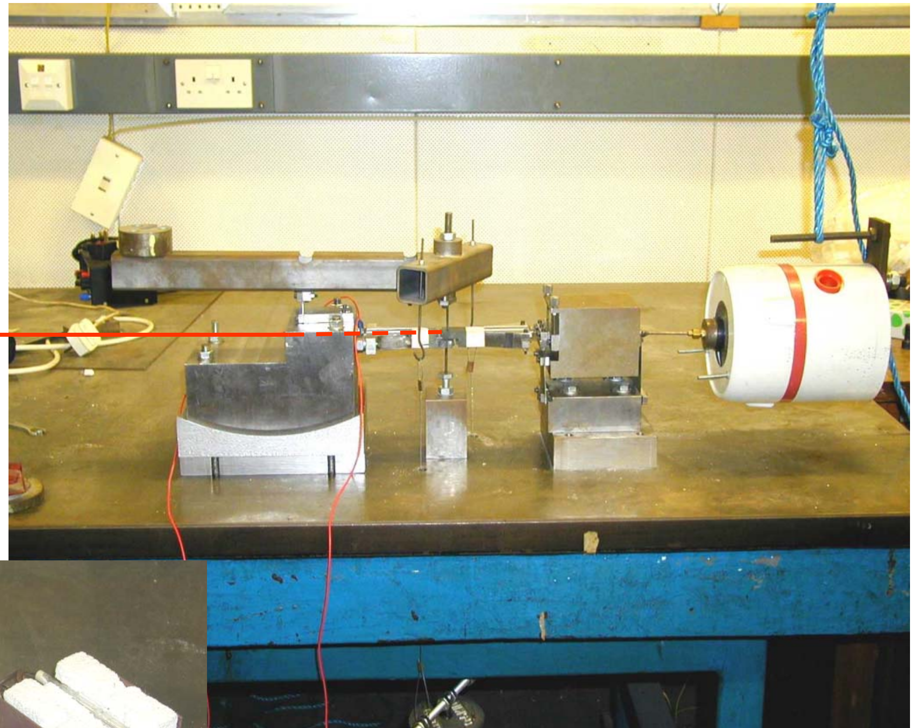
For a friction contact it is reasonable to assume that $F = f(x, sign(\dot{x}))$ and a Force/Relative Displacement hysteresis loop is used.



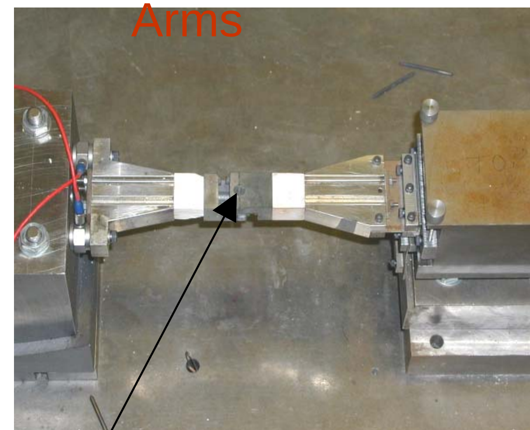


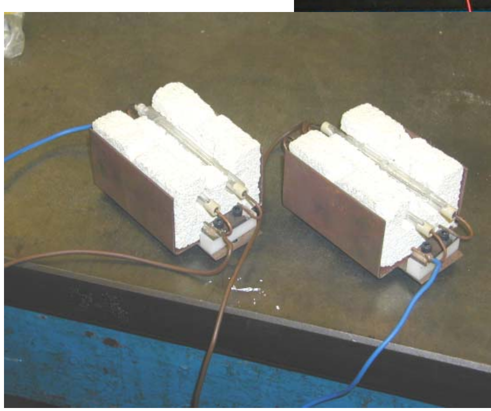
FRICTION HYSTERESIS LOOP TEST RIG.

Laser Doppler Vibrometer

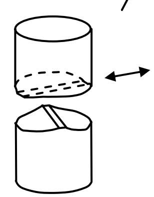


Support Arms



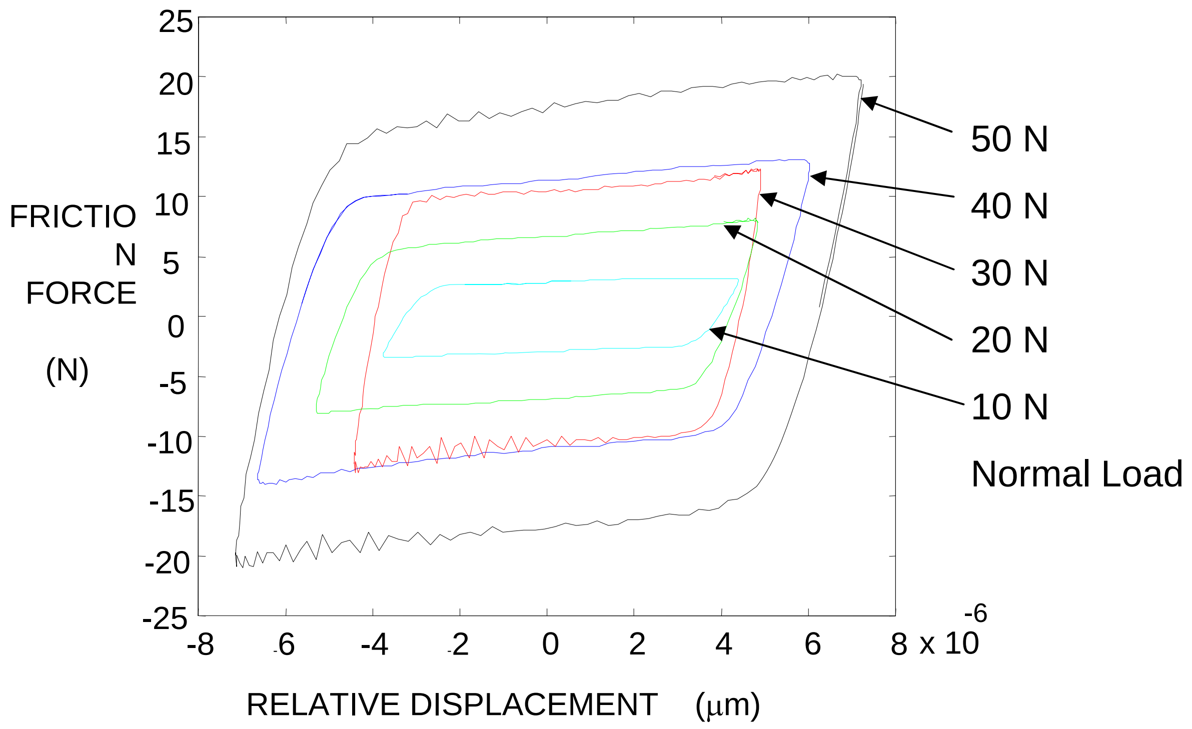


Heaters



Test Pieces

A set of hysteresis loops, measured at different applied normal loads.



AN APPROACH TO THE TASK

Using the RoadMap as a guide,

(i) compile a list of all individual phenomena which need to be taken into account in modelling joint dynamics behaviour

(ii) Define the status of current modelling capability for each phenomenon

(iii) Develop the interdependencies between these various phenomena, and assess the status of their development

(iv) Chart possible scenarios for developing a uniform-level and consistent capability embracing all the critical phenomena, in graded stages – basic, design, advanced,…

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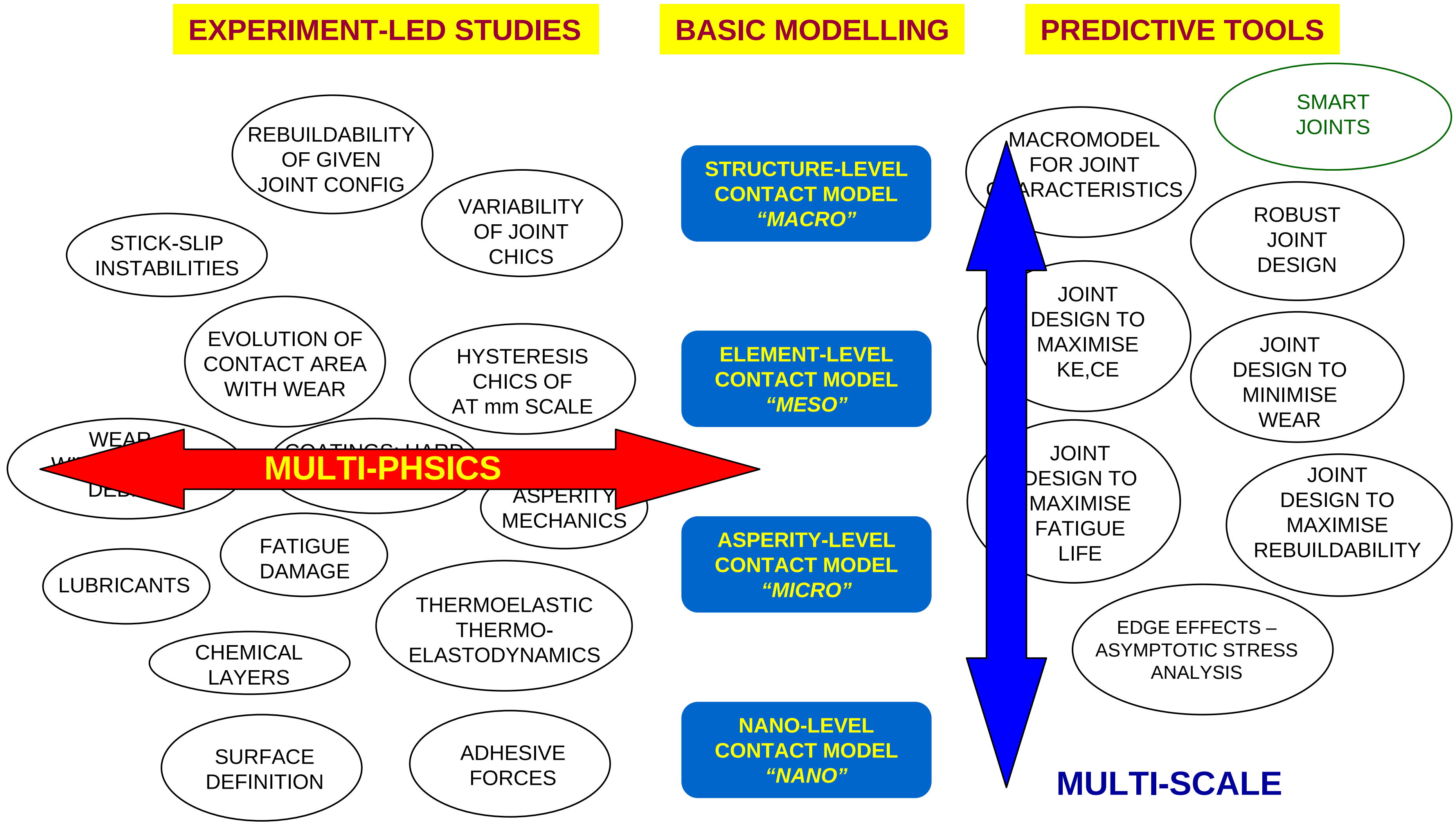
RESEARCH ROADMAP FOR FRICTION CONTACT AND WEAR IN STRUCTURES



Plan for Day 1 - Morning

0830-0900 Review and plan for the day's breakouts

0900-1015 1st Breakout session

1015-1030 Coffee

1030-1045 Brief review of progress

1045-1145 2nd Breakout session

1145-1315 Lunch

1315-1400 Group Session: report back from breakouts.

Plan for further session

1400-1500 Breakout 3

1500-1515 Coffee

1515-(1600) Report back from 3rd Breakout

(1600)- 1700 Funding Group to meet; Group to discuss results of the day’s sessions. Discuss outstanding actions. Agree plan for Day 3

Plan for Day 2 - Morning

Task: To define the territory of the Contact Mechanics Roadmap

0830-0900 Briefing, plan for day

0900-1000 Breakout session 1:

- **Review list of Topics on Roadmap**
- **Produce definitive and comprehensive list of Research Themes (necessary to cover all the phenomena that will/may be necessary to include in a universal contact/joints/interface mechanics models)**
- **Assess the current status of development of each theme (re the availability of the basis of a mathematical model of that phenomenon)**

1000-1015 COFFEE

1015-1130 Breakout session 2
Define the interdependencies of each of these themes, showing sequencies as appropriate

1130-1145 End of morning briefing

1145-1315 LUNCH

Plan for Day 2 - Afternoon

1315-1415 Group Discussion

Report back from Breakouts 1 and 2. To compile first version of New RoadMap

1415-1515 Breakout session 3

To chart possible routes through the map which emerges from 1 & 2

To indicate priorities, and perhaps develop ideas for phases of development

1515-1530 COFFEE

1530 – 1600 Group Discussion

To put together the three parts into the first draft of the overall RoadMap

1600 – 1700 Breakout session 4

Funding agencies group to consider the result and to develop comments, questions, suggestions for additinal information. What do the agencies look for from a workshop like this?

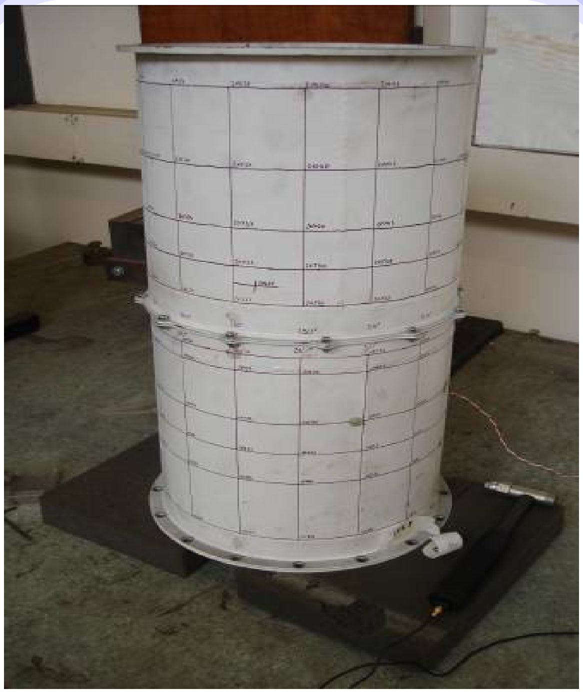
Rest of group . Discuss scale interface issues; to discuss the whole plan, and to compile a list of known research groups active in each of the research theme areas Also, to discuss procedures for day 3

1700-1715 Group Discussion (main group rejoined by Funding Agencies group)

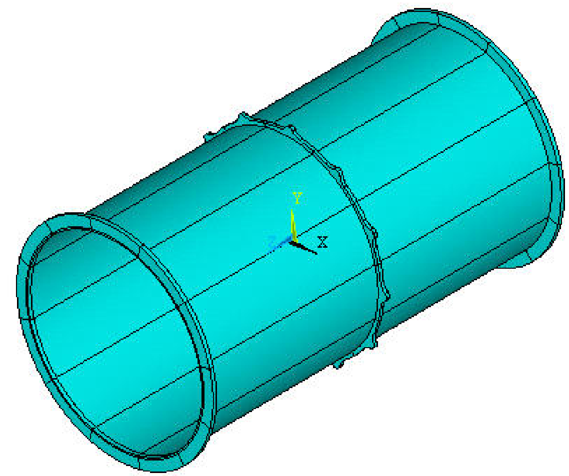
Summarise Day 2 & Agree plan for day 3

CTS Component I

CTS assy



Experimental modal analysis



Analytical modal analysis

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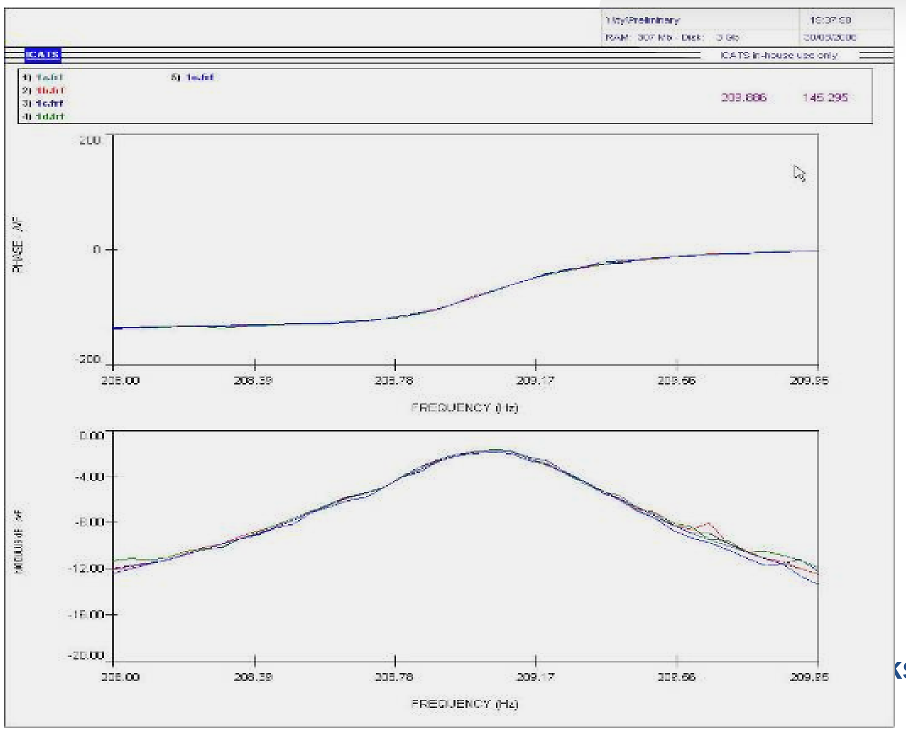
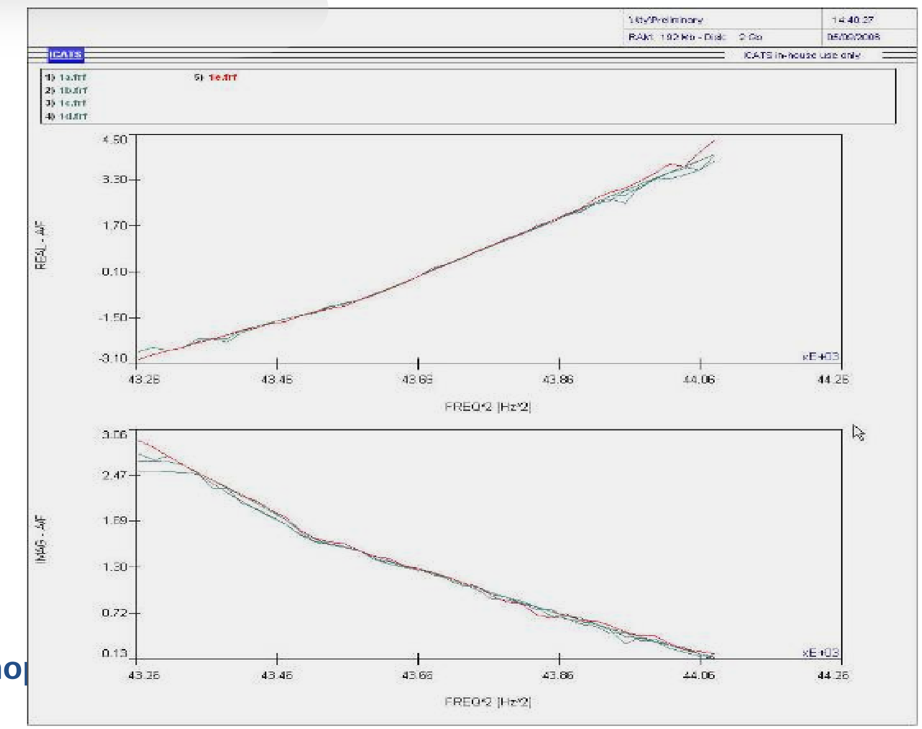
Repeatability

5 runs

- **Very little deviation**
- **Very good repeatability**
- **No change in parameters**





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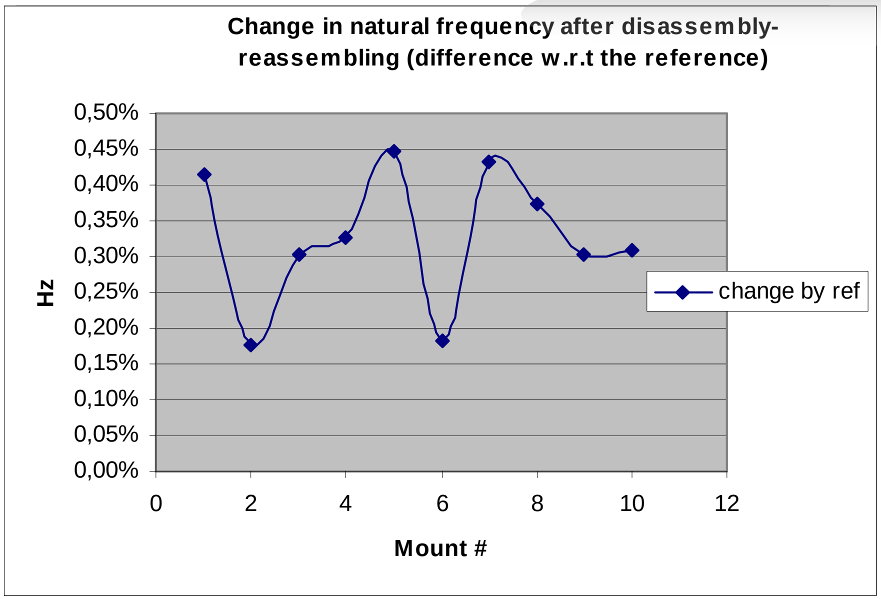
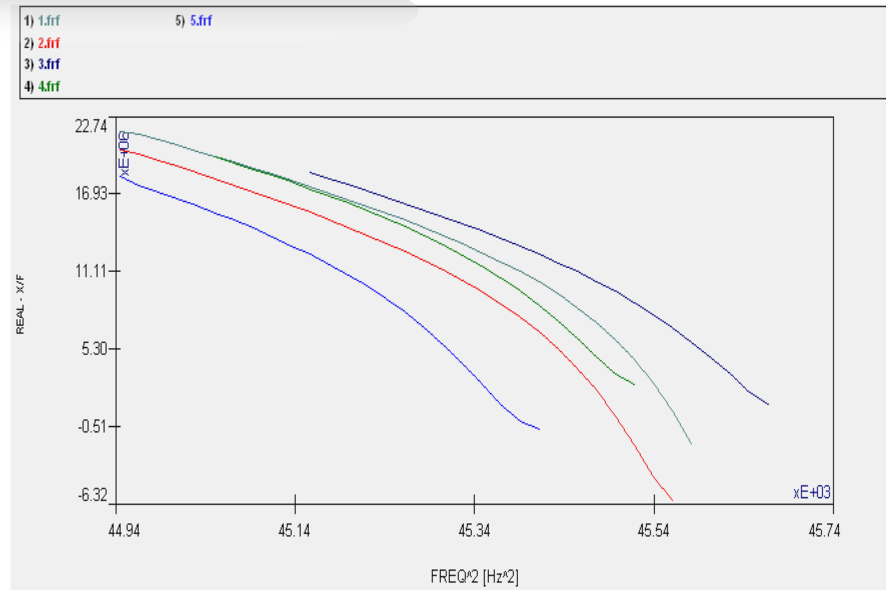
Assembling – Disassembling the structure

5 runs
Significant deviation
• Important change in parameters





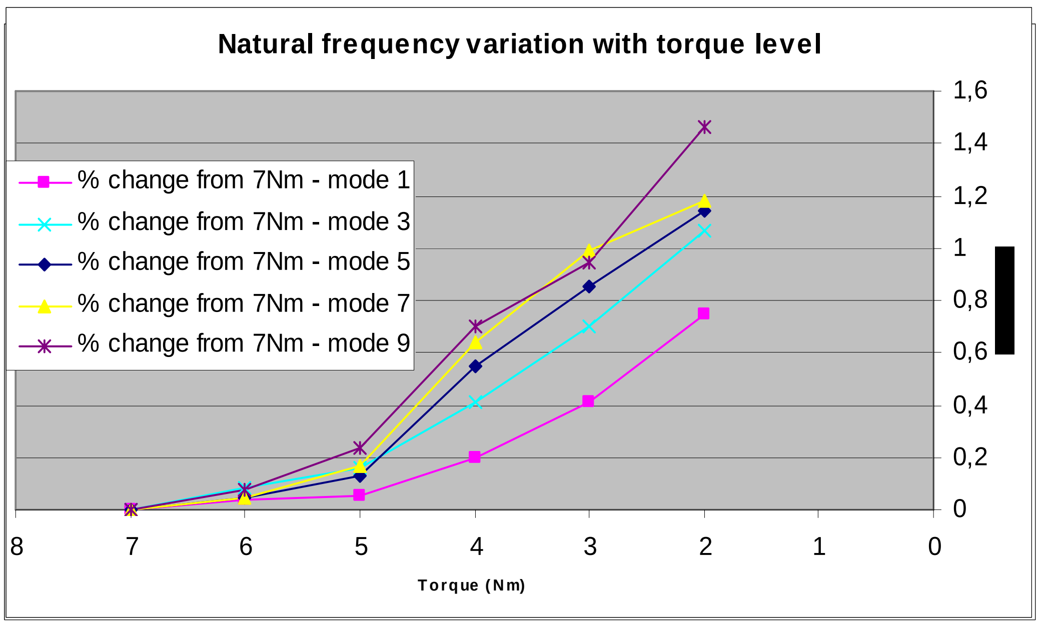
- **No global parameter changing** : Tightening Torque constant, same relative positions
- **Consequence:** change in the joint parameters

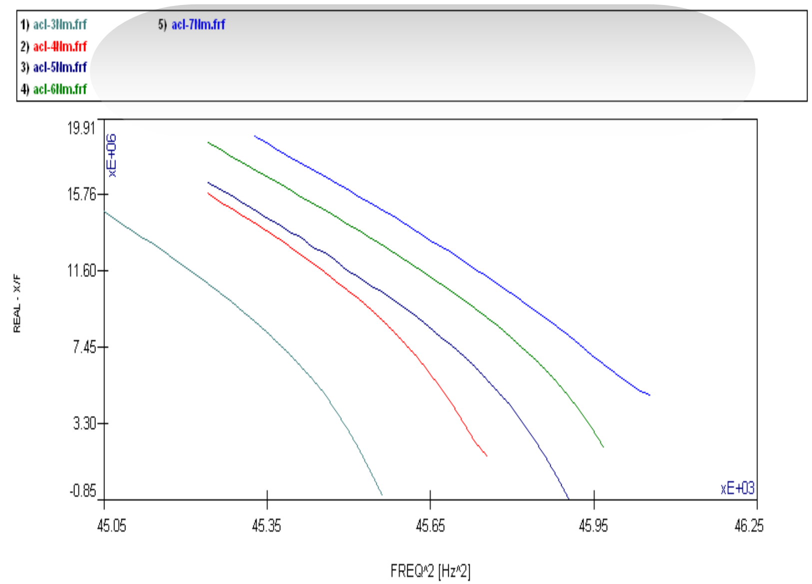
Influence of Tightening Bolt Torque

- **Shift** of the natural frequencies toward **lower frequencies**
- **Lower amplitudes** with lower tightening torque (more energy dissipated in friction)

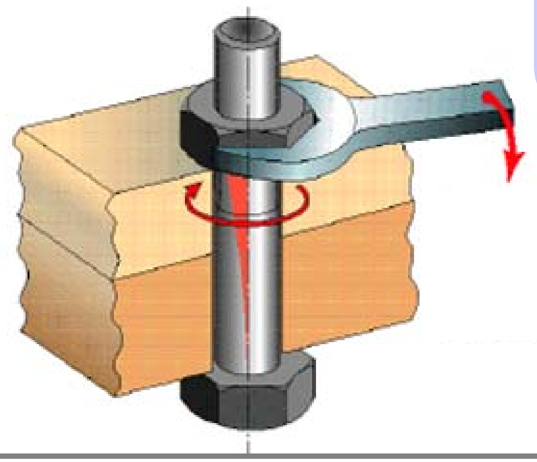
5 runs

- **Significant deviation**
- **Change in parameters**
- **Tightening tension is key to control parameter variability**





Influence of Tightening Bolt Torque



5 runs

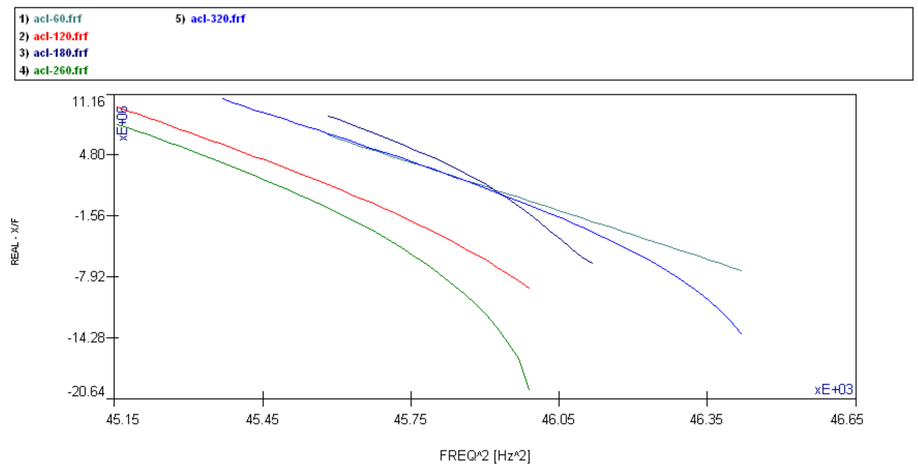
- Very little deviation
- Very good repeatability
- No change in parameters

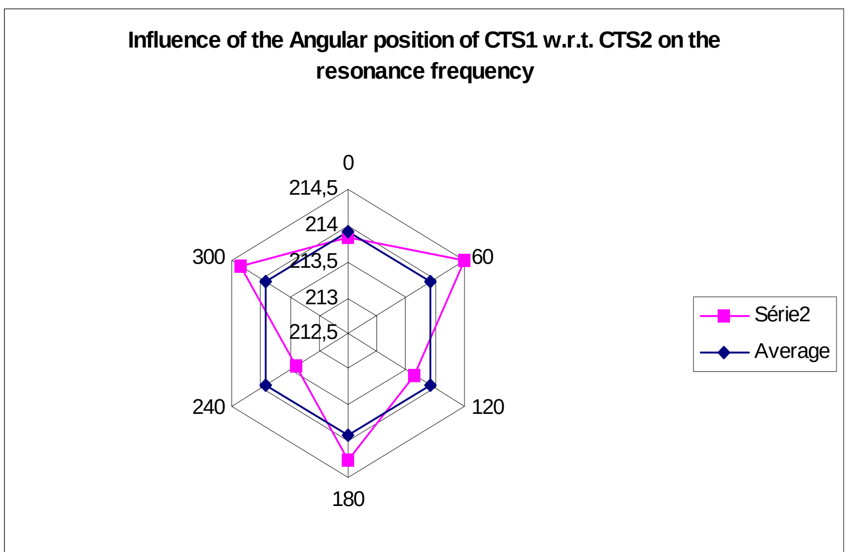
- **But the control in the tightening isn't really possible** : 20% change
- **Consequence:** no actual control of the joint parameters

Influence of the Angular Position

5 runs

- **Very little deviation**
- **Very good repeatability**
- **No change in parameters**





- **No global parameter changing** : Tightening Torque constant, relative positions changing
- **Consequence:** change in the joint parameters

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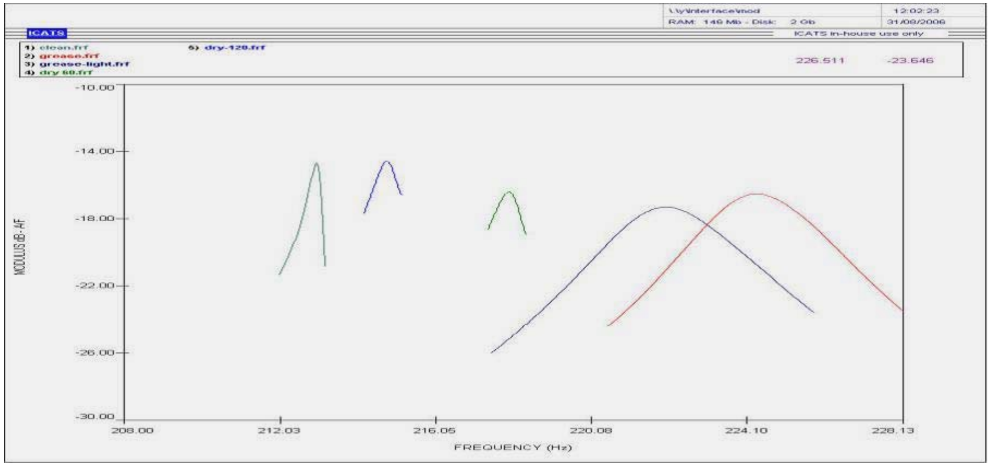
Influence of Interface Conditions



5 different conditions

- **Significant deviation**
- **Strong influence on the damping**
- **Significant influence on the parameters**

- **Nature of the interface changing** : Tightening Torque constant, relative position changing
- **Consequence:** change in damping

Two Areas of Particular Interest & Concern: Whole-engine Casings & Bladed Assemblies