Introduction to the 2\textsuperscript{nd} Workshop on Joints Modelling, 2009
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

**EXPERIMENT-LED STUDIES**
- Rebuildability of given joint config
- Variability of joint chics
- Evolution of contact area with wear
- Hysteresis chics of at mm scale
- Coatings: hard and soft
- Asperity mechanics
- Fatigue damage
- Thermoelastic thermoelastic-treatment dynamics
- Chemical layers
- Surface definition
- Adhesive forces

**BASIC MODELLING**
- Structure-level contact model "MACRO"
- Element-level contact model "MESO"
- Asperity-level contact model "MICRO"
- Nano-level contact model "NANO"

**PREDICTIVE TOOLS**
- Macromodel for joint characteristics
- Joint design to maximise fatique life
- Joint design to minimise wear
- Joint design to maximise rebuildability
- Edge effects - asymptotic stress analysis
- Robust joint design
- Design of jointed structures

**MULTI-PHYSICS**
- Multi-scale

Friction CONTACT ROADMAP v 6.3
NSF-Sandia-AWE Joints Modelling Workshop, Dartington, Devon, UK April 2009 D J Ewins
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

MODELS

- Loads
- Load history
- Manufacturing
- Tolerance
- Residual stress
- Oxidation
- Corrosion
- Roughness
- Surface registration
- Adhesion (stick/slip?)
- Adhesives
- Dynamics

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
- Shock load transmission 3B
- Acoustic transmission 3B
- Frictional limit (onset of slip) 3B
- Deformed shape (when slipped) 3B
- Surface roughness evolution
- Concept evaluation tool 1C

Multiscale modelling: from one scale to another

A very difficult challenge: coupled multiscale modelling

1. Clear problem, no known solution
2. Predict within 1-2 orders of magnitude
3. Predict within order of magnitude, trend correct act value
4. Predict to within 10-50%
5. Predictable to within uncertainty from other factors

Increasing understanding

A. Generic model based on few parameters
B. Component specific, needs calibration exps
C. Non-physical, empirical model, lots of testing

Increasing cost

NSF-Sandia-AWE Joints Modelling Workshop, Dartington, Devon, UK April 2009

D J Ewins © D J EWINS 2006
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

MODELLING

EXPERIMENTS, TESTS

ANALYSIS

PREDICTIONS

‘TEST’

‘ANALYSIS’
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?

<table>
<thead>
<tr>
<th>Time</th>
<th>Activity</th>
</tr>
</thead>
<tbody>
<tr>
<td>0900</td>
<td>Review day 1 activities and confirm day 2 agenda</td>
</tr>
<tr>
<td>0915</td>
<td>Short presentations</td>
</tr>
<tr>
<td></td>
<td>- Analytical Issues (Hills)</td>
</tr>
<tr>
<td></td>
<td>- Computational Issues (Laursen)</td>
</tr>
<tr>
<td></td>
<td>- Experimental (Gola)</td>
</tr>
<tr>
<td></td>
<td>- Experiments towards joint modeling (Gaul)</td>
</tr>
<tr>
<td>1015</td>
<td>Break</td>
</tr>
<tr>
<td>1045</td>
<td>Breakout into 3 groups (Chairs: Gaul; Hills; Laursen)</td>
</tr>
<tr>
<td>1145</td>
<td>Collection of group feedback and compilation of prioritized list</td>
</tr>
<tr>
<td>1245</td>
<td>Lunch</td>
</tr>
</tbody>
</table>
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
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

- Rotor/Stator Travelling Wave Instability
- C-Duct Model Validation
- Combustion Piping
- Interface to Aircraft/Test Stand
- Windmilling Rotor Dynamics
- Rotor Internal Damping
- Whole Engine Dynamics Model Validation
- Shroud Damping
- Under-Platform Damping
- Mistuned Bladed Disc Forced Response

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

Component Models

Design Model

Supermodel

Courtesy: Rolls-Royce
Component Models

Model Correlation
MR + FOGV + FBH

Very Good  Good  Medium  Poor  Very Poor

Model Correlation
MR + FOGV + FBH

2D Axial 1&2  Torsion  Pitch 1&2

Fr Err (%)

0.0  20.0  40.0  60.0  80.0  100.0

WEM v0.1 (ref Test Data)
FOGV SM - FBH WEM (ref Test Data)

DESIGN MODEL
SUPER-MODEL

Very Good  Good  Medium  Poor  Very Poor

Courtesy: Rolls-Royce
Effect of Nonlinear Joint Dynamics on Dynamic Behaviour of Engine Structures
Incorporating Nonlinear Joint Behaviour into FE Models

Modelling Approach for Bolted Flange Joints

Combination of linear and non-linear springs and dampers

Rigid connections with hinge

Offset beam elements

Shell elements

Rotation about tangential axis

Bolt centre line

IMC-CCOC interface

Courtesy: University of Kassel
Modelling of Interaction at Contact Surfaces: Area Contact Elements

The reference point, A, used for determining contact stresses

Area represented by the friction contact element
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
• 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
"IT SEEMS THAT THE THEORETICAL CALCULATIONS ARE GIVING VERY GOOD RESULTS!..."

"TEE!... HEH!"

---

RETRO - PREDICTION

NSF-Sandia-AWE Joints Modelling Workshop, Dartington, Devon, UK April 2009  D J Ewins
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
NSF-Sandia-AWE Joints Modelling Workshop, Dartington, Devon, UK April 2009  D J Ewins
Aero-engine Casing Test Configuration

Bolt Joints

Bearing Joints

Shaker
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

Amplitude

Frequency (Hz)

Amplitude

Frequency (Hz)
Variation of Damping with Displacement Amplitude

Amplitude

ETA(%)
Comparison of Analytical and Experimental Non-linear FRF

**ANALYSIS**

Real Part Analytical FRF

**EXPERIMENT**

Real Part Experimental FRF
Examples of dynamic contact phenomena in bladed discs

- Root damping and variable contact
- Underplatform dampers
- Contact of shrouds

Area represented by the friction contact element
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

\[ F = f(x, \text{sign}(\dot{x})) \]

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,…
RESEARCH ROADMAP FOR FRICTION CONTACT AND WEAR IN STRUCTURES

**EXPERIMENT-LED STUDIES**
- Rebuildability of given joint config
- Stick-slip instabilities
- Evolution of contact area with wear
- Wear - with/without debris
- Chemical layers
- Surface definition

**BASIC MODELLING**
- Macromodel for joint characteristics
- Variability of joint Chics
- Hysteresis Chics of at mm scale
- Asperity mechanics
- Adhesive forces
- Thermoelastic thermo-elastodynamics

**PREDICTIVE TOOLS**
- Structure-level contact model “Macro”
- Element-level contact model “Meso”
- Asperity-level contact model “Micro”
- Nano-level contact model “Nano”
- Joint design to maximise Ke,ce
- Joint design to maximise fatigue life
- Joint design to maximise rebuildability

**MULTI-SCALE**
- Smart joints
- Robust joint design
- Joint design to minimise wear
- Edge effects – asymptotic stress analysis

---

Friction CONTACT ROADMAP V 5.1
© D J EWINS 2006
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 sequences 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 additional 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

Experimental modal analysis

Analytical modal analysis

NSF-Sandia-AWE Joints Modelling Workshop, Dartington, Devon, UK April 2009

D J Ewins
Repeatability

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

5 runs
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)

### Natural frequency variation with torque level

- % change from 7Nm - mode 1
- % change from 7Nm - mode 3
- % change from 7Nm - mode 5
- % change from 7Nm - mode 7
- % change from 7Nm - mode 9

### Resonance frequency Hz

- % change from 7Nm - mode 1
- % change from 7Nm - mode 3
- % change from 7Nm - mode 5
- % change from 7Nm - mode 7
- % change from 7Nm - mode 9

### Torque (Nm)

- 0
- 1
- 2
- 3
- 4
- 5
- 6
- 7
- 8

### 5 runs

- Significant deviation
- Change in parameters
- Tightening tension is key to control parameter variability
Influence of Tightening Bolt Torque

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

5 runs
- Very little deviation
- Very good repeatability
- No change in 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
Influence of Interface Conditions

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

5 different conditions
- Significant deviation
- Strong influence on the damping
- Significant influence on the parameters
Two Areas of Particular Interest & Concern:
Whole-engine Casings & Bladed Assemblies