

Report on the seminar “Bridging the Gap between Theory and Experiment” on hybrid and inverse methods in experimental mechanics

Purpose of seminar

Engineers investigating the integrity of designs and components, and the dynamic/vibrational behaviour of structures, have a wide range of analytical, numerical and experimental techniques at their disposal. However, practical problems are not always sufficiently defined to analyse from first principles, and theoretical analyses generally require validation by comparison with experiments. Moreover, experiments generally involve inference of critical quantities (such as stress, natural frequency, damping etc.) from measurements of physical quantities (e.g. thermal emission, response to excitation etc.) rather than direct and unambiguous measurement.

In many cases the inference of these quantities from measured data takes the form of an inverse problem, in which the conventional direction of solving a problem (e.g. determining internal stresses from boundary conditions) is turned inside-out; effectively this involves fitting the input parameters of a conventional theoretical analysis to experimental data, a procedure which is both very powerful and subject to a number of practical and numerical pitfalls.

This seminar aimed to explore such hybrid experimental/numerical techniques so as to:

- Exploit theoretical or numerical models in the interpretation of experimental results
- Design our experiments to minimise the effects of experimental error and ill-conditioning
- Recover quantities such as contact stresses which are difficult or impossible to measure directly

Location and administrative details

This seminar was held on Wednesday 27 April 2005 in the well-appointed Lord Hives Suite at Rolls-Royce plc, Derby. It was organised by a subgroup of the SAVG Committee: Dr Arthur Jones (seminar chairman), Dr Janice Barton (SAVG chairman) and Paul Anuzis (host). It was co-sponsored by Rolls-Royce plc, IMechE Structural Technology and Materials Group, British Society for Strain Measurement (BSSM) and Engineering Integrity Society (EIS).

43 attendees were present, broken down as follows: 29 fee-paying delegates of whom 9 were postgraduate students and 12 were from industry, 11 speakers including the host, two SAVGC members and one invited guest. One further fee-paying postgraduate student was unable to attend and gave apologies.

A CD containing electronic documents (PDF format) of the presentations and some relevant supporting material was handed out to delegates.

Summary of technical content

For early arrivals, the seminar began with a self-guided tour of the Rolls-Royce technology exhibition. The formal proceedings began with welcome and introductions from the host and the SAVG chairman, followed by a talk by Dr Arthur Jones (University of Nottingham) on “An overview of the issues in hybrid

and inverse methods". This covered topics such as ill-conditioning, singular value decomposition, condition number, regularization and non-linear inverse problems, as well as some practical examples of inverse methods in experimental mechanics. The emphasis of the talk was on strategies for avoiding or mitigating the effects of ill-conditioning when applying inverse methods to experimental mechanics.

Some of the themes from the first talk were explored further in a joint presentation by **Dr Arthur Jones** and **Professor Adib Becker** (University of Nottingham) on the "**Reconstruction of contact boundary conditions from photoelastic data using an inverse boundary element method**". The boundary element (BE) method was introduced, and the issue raised that the combination of an inverse BE approach making use of results from phase-stepping photoelasticity involves a pair of nested inverse problems. The serious pitfalls of this situation were avoided by capturing the isoclinic (principal stress direction) data using a separate experiment from the isochromatic (principal stress difference) data, thus making the processing of the photoelastic results less numerically sensitive to error and improving the quality of the input data to the BE process. The whole system was illustrated with several examples including both synthetic and real experimental data.

Dr John Walker (University of Nottingham) presented a talk on "**Particle Characterisation using 'Dynamic Light Scattering'**". Particle characterisation finds application in a number of industries, such as pharmaceuticals, paint production, paper making, clays, insulation materials and lubricants. This talk examined the use of light scattering methods to measure the size and shape of particles in the micron and sub-micron range. The form of the data that is formed and the various inversion methods that can be applied to this problem were described and their effectiveness illustrated. This talk clearly illustrated both the manner in which careful analysis of experimental data, and *a priori* assumptions regarding the form of the results, can enable useful data to be extracted even from noisy and relatively featureless raw data; however the issues regarding ill-posed problems were also illustrated and discussed.

Professor Alistair McNab (University of Strathclyde) presented a talk on "**3D reconstruction of damage fields from ultrasonic data**". The mapping of defects from data obtained from ultrasonic testing presents a particular challenge, especially when possible defects are located within components of complex geometry. Issues explored included the detection of critical defects under worst-case conditions and the optimum way of scanning the component to detect these defects. The presentation and interpretation of the data were also discussed in detail. This paper considered software tools, which can be used to design the ultrasonic test, establish its capability and then to reconstruct and analyse 3D flaw images produced from the measured data.

Professor Mike Friswell (University of Bristol) made a presentation on "**Model Updating in Structural Dynamics: Parameterization and Regularization**". The talk concentrated on the practical application of regularisation techniques to various test structures including the GARTEUR benchmark example, an automotive body-in-white and several simpler structures. Key issues discussed included the need to choose carefully the parameters to be updated, the possibility of arriving at an updated solution which fits the results well but has no

physical meaning, and the need for engineering judgement rather than a blind acceptance of the results.

George Bibby (Rolls-Royce plc) presented a talk on “**Calculation of residual stresses from experiments**”, concentrating on the interpretation of results from X-ray diffraction (XRD) experiments. Historically the measurement of residual stress was done under the auspices of quality control and equivalence testing for manufacturing processes. More recent developments in material surface treatments and their application to aerospace products to enhance fatigue life have necessitated the need for residual stress data. This data is being used as a means of controlling the quality of the surface treatments and to provide design data for component lifing. This presentation examined the X-Ray Diffraction method as a means to measure residual stress in a consistent manner, with a particular emphasis on overcoming errors such as misalignment and missing data which can affect the accuracy of XRD.

Dr John Durodola and **Dr Luis Hector Hernandez-Gomez** (Oxford Brookes University) presented a short case study on “**Recovering elastic-plastic constitutive properties of metals from bending tests**”. The theoretical basis of the method and the inverse analysis techniques involved were outlined briefly, and some very encouraging results were presented, with the recovered stress-strain curves in many cases showing very good agreement with those obtained from uniaxial tests.

The final presentation was made jointly by **Dr Janice Barton** (University of Southampton) and **Professor Keith Worden** (University of Sheffield) on “**Obtaining crack tip parameters from thermoelastic stress analysis using curve fitting routines based on genetic algorithms**”. The technique of thermoelasticity, and some background on its origins and limitations, was presented, along with a discussion of the difficulty of extracting crack parameters and indeed of discovering the exact location of the crack tip on the thermographic images. This problem was overcome by fitting the parameters describing a cardioid curve to the cardioid features seen on practical thermoelastic results. In some cases excellent matching was achieved of the fitted cardioid to the experimental results; in other cases, agreement was less good, and was due in one case to the interference between the cardioids arising from the two ends of a slot-shaped crack. Techniques related to genetic algorithms (GAs) (notably Differential Evolution, a technique similar to GAs but for analogue parameters) were used in fitting the curves, and the presentation included a description of these techniques.

The final item in the programme was a panel discussion, which began with the seminar chairman’s question based on a delegate’s comment: “**How can the body of mathematical research on inverse problems and their solution be transferred to the world of experimental mechanics?**” No perfect solutions were proposed, but observations included the need for more technology transfer opportunities such as the present seminar, and a need to realise that numerical prediction techniques such as finite element analysis do not always tell the complete story. The comments were also made that hybrid and inverse methods are a very high-skill area, and that techniques which work in one situation are not always directly transferable to another. Areas for further work were suggested, including the identification of changing contact zones in

real contact problems and the need for more work on the tradeoff between fitting an oversimplified theoretical model cf. the ill-conditioning arising from fitting one with many less significant parameters.

Overall, there was a good and positive atmosphere and the standard of presentations by the speakers was high. The seminar chairman wishes to express his appreciation of the tremendous work by his co-chairmen and all those involved in organising and publicising the seminar.

I. A. Jones
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