Institution: Durham University

Unit of Assessment: 15 General Engineering

Title of case study: Interactive stress analysis of mechanical and aerospace components

1. Summary of the impact

This case study concerns economic impact accruing in the aerospace engineering industry in Europe from software developed to perform stress analysis. Durham research has led to a spinout company, Concept Analyst, Ltd., and the software resulting from the research (Concept Analyst) is currently licensed by the following companies: BAE Systems (Brough, Samlesbury, Warton, Prestwick sites), Agusta Westland, Assystem, Jesmond Engineering, Spirit Aerospace. Trials are currently in place at Airbus UK and Bombardier, Canada. An agreement has been signed with the fatigue consultancy Jesmond Engineering, Ltd. to market the software within the aerospace sector. Economic impact arises from time savings for designers using Concept Analyst as compared to conventional commercial tools.

2. Underpinning research

Context

Research into rapid, interactive stress analysis has been carried out by the research group led by Professor Jon Trevelyan since he joined Durham in 1996. The research centres on the use of the Boundary Element Method (BEM), which is a standard method of solving systems of partial differential equations that first appeared around the 1960s. The BEM offers significant benefits over the Finite Element Method (FEM) for certain classes of problem. In this research, we exploit two of those advantages, i.e. (i) the ease, speed and robustness of remeshing resulting from the reduction in dimensionality, and (ii) the accuracy of stress solutions, particularly around discontinuities such as crack tips.

Nature of the research

The novel research developments are:

- the integration of the analysis with a user-friendly graphical interface, automating much of the traditional effort associated with building models for analysis. This allowed engineers to analyse designs sketched in a similar fashion to using graphical tools like Powerpoint – key outputs ***KO1***, ***KO3*** (see section 3).
- The acceleration of the analysis by developing rapid integration schemes and a bespoke preconditioned linear equation solver for "re-analysis", i.e. a stress analysis of an object similar to one that has just been analysed, to the extent that real-time update of stress contours is achieved on an evolving geometry – key outputs ***KO2***, ***KO4***.
- The use of innovative methods in numerical fracture mechanics to provide accurate estimation of fracture and fatigue parameters – key output ***KO5***.

Period of the research and key researchers

The research has been an on-going project in Durham since 1996, when Prof. Trevelyan joined the university. He has remained the leader of the project throughout, and so his name is not listed in the following material. Key dates and associated projects are:

- **1998-2000**: EPSRC award GR/L73128 (1998-2000, £64k). With Dr. Peiji Wang (PDRA), implemented object oriented code in 2D and first 3D code, optimised quadrature schemes, and first interactive BEM re-analysis for conceptual design.
- **2000-2003**: With Miss Eva Cervera (PhD student) developed the first evolutionary structural optimisation scheme using BEM with spline-based control of geometry.
- **2001-2005**: With BAE Systems funding (two contracts, 2001-2005, 166k) Mr. Gareth Bird (RA) automated robustness checks, adaptivity and domain decomposition.
- **2003-2006**: EPSRC/BAE Systems Industrial CASE award (2003-2006, £72k). With Mr. Derek Scales (PhD student), developed fast integration schemes and a pre-conditioned iterative solver specifically for BEM re-analysis – key output ***KO4***.
- **2007-2010**: EPSRC award EP/E12310/1 (2007-2010, £80k). With Mr. Robert Simpson (PhD student), developed enriched fracture approximations for BEM – key output ***KO5***.

- **2009-2013**: EPSRC award EP/H000046/1 (2009-2013, £374k). With Dr. Shadi Mohamed (PDRA) and Mr. Tim Foster (PhD student), extension of our ideas to 3D.

3. References to the research

Key outputs

KO1. J. Trevelyan (1998), On the use of partial re-analysis in conceptual mechanical design, *Communications in Numerical Methods in Engineering*, **14**(11), 1047-1053. DOI: 10.1002/(SICI)1099-0887(199811)14:11<1047::AID-CNM208>3.0.CO;2-4

KO2. J. Trevelyan & P. Wang (2001), Interactive Re-Analysis in Mechanical Design Evolution. Part II: Rapid Evaluation of Boundary Element Integrals, *Computers & Structures*, **79**(9), 939-951. DOI: 10.1016/S0045-7949(00)00177-2

KO3. J. Trevelyan, P. Wang, S.K. Walker (2002), A scheme for engineer-driven mechanical design improvement, *Engineering Analysis with Boundary Elements*, **26**(5), 425-433. DOI: 10.1016/S0955-7997(02)00014-0

KO4. J. Trevelyan & D.J. Scales (2007), Techniques to accelerate BEM computation to provide virtual reality update of stress solutions, *Engineering Analysis with Boundary Elements*, **31**(11), 875-889. DOI: 10.1016/j.enganabound.2007.04.004

KO5. R. Simpson & J. Trevelyan (2011), A Partition of Unity enriched Dual Boundary Element for accurate computations in fracture mechanics, *Computer Methods in Applied Mechanics and Engineering*, **200**(1-4): 1-10. DOI: 10.1016/j.cma.2010.06.015

The invitation for Trevelyan to deliver a plenary keynote address entitled “Interactive stress analysis in an industrial context” at the TMCE 2012 Conference in Karlsruhe, Germany, May 2012, provides evidence of the international excellence of the research.

4. Details of the impact

History of impact generation:

Engineers from BAE Systems (Warton and Brough) were first exposed to the Durham research in interactive stress analysis in 1999. This was timely, since the company was actively seeking tools that would allow rapid and simple assessment of the stress concentrations that arise in aircraft structures. They undertook a six-month trial period (value £20k) of the Concept Analyst software in-house, and found that it offered a solution that was sufficiently intuitive that it could easily be used by their large number of stress engineers who were not regular finite element users. Usage of the system expanded, ultimately becoming part of the standard toolbox for about 100 structural engineers across multiple BAE sites (Warton, Brough, Samlesbury, Prestwick and Farnborough). Seven half-day training courses have been provided by Durham University staff at BAE sites, at each of which staff were present who worked at multiple sites (value £10.5k).

In 2001, the level of interaction with BAE Systems had developed to the extent that the Durham University spinout company Concept Analyst, Ltd. was formed with Prof. Trevelyan as Managing Director. While research projects are undertaken at Durham University, the spinout company handles software licensing, contracts and documentation, and also funds implementation of the algorithmic research outputs into the core Concept Analyst software that is made available commercially. The company has traded continuously to the present day.

The key contacts in BAE Systems became enthusiastically engaged in the project and funded further developments from 2001 to 2005.

Further links have been obtained with other industrial beneficiaries. Jesmond Engineering, a structural analysis consultancy in Brough, East Yorkshire, has become a regular user of the Concept Analyst software, undertaking fatigue analysis for a wide range of major aerospace companies in the UK and Europe. Since the signing of a reseller agreement in 2006, Jesmond Engineering has acted as an agent representing and reselling the Concept Analyst software throughout the UK and European aerospace sector. Through this arrangement the research outputs have been used in the REF period at Agusta Westland Helicopters (Italy), Assystem (UK)

and Pilatus Aircraft (Switzerland), and trials are in progress at Airbus (UK) and Bombardier (Canada). A training course was held at Agusta Westland in Milan (value £1.5k).

BAE Systems and Jesmond Engineering continue to be committed to involvement in Concept Analyst, providing letters of support for EPSRC grant proposals, acting as beta sites for new feature releases and participating in steering groups for new developments.

In an email dated 17th September 2013 (hereafter referred to as email 1), the F-35 DaDT Lead, Aft Fuse and Empennage, BAE Systems, Samlesbury, Lancashire, describes the impact these Durham research outputs have had within BAE Systems:

> *An accurate determination of fatigue life is of paramount importance to the design, manufacture and support of military aircraft … in order to provide efficiency and performance whilst maintaining structural integrity throughout their service life. Accurate determination of the stress concentration values associated with many unavoidable geometric features, such as fastener holes and changes in section and width of components, is a key element of this analysis. Concept Analyst has been employed for this purpose for over a decade now and the capability provided has expanded over this time to enhance the benefits that we see from this capability...*
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> *Throughout the lifecycle of the aircraft (initial design, through manufacture to in-service support) fatigue life calculations are required and these often need to be generated rapidly. Whilst there are various proven stress analysis tools available (both Finite Element and Boundary Element based) that are capable of the level of accuracy required, it is the speed and ease of use that set Concept Analyst apart and deliver key cost benefits*...
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> *The first F-35 aircraft was rolled out by Lockheed Martin at Fort Worth, Texas, at the end of 2008. Wikipedia reports a unit cost for Typhoon aircraft as approximately £65m and upwards of $150m, dependent on variant, for a single F-35. Whilst we do not manufacture and assemble all components of either of these aircraft, with such high values, it is easy to see how significant cost savings can be made through increased efficiency of analysis. Some individual parts are worth well in excess of $10,000. Production rate for the F-35 is currently of the order of 40 aircraft a year but this is set to increase to 1 aircraft per day. Concept Analyst allows completion of a fatigue analysis in a matter of minutes to hours whereas using other commercial FEM and BEM applications could take a day or two. In many instances, a delay to analytical results can, itself, cause increased costs through delayed production or lack of availability. The faster turn around that can now be provided also increases quality and customer relations providing longer term benefits to the company.*
>
> *During the period 2008 to present, increased benefits have been enjoyed as a result of improved capability of the application including areas such as: Increased model size capability; improvements to the interface, increases in speed resulting in true real time re-analysis and; part zoning.*
>
> *Concept Analyst has been, and will remain, a key analysis tool for airframe structures engineers within the company, continuing to yield cost benefits.*

In a letter dated 20th May 2013 (hereafter referred to as Letter 1), the MD of Jesmond Engineering, East Yorkshire, lists the key impact-generating features as:

- *The level of interactivity in the system has meant that it is very easy and intuitive to use. It is perfectly possible for the many stress engineers to make effective use of the code without recourse to the comparatively very limited number of expert structural modelling analysts, and this has had positive impacts on productivity.*
- *The simplified and intuitive user interface has meant that occasional users can return to the software after an extended period without detriment to their productivity in using it.*
- *Engineers are able to evaluate stress concentration factors rapidly and with confidence to inform fatigue analysis.*
- *In benchmark tests the accuracy is of at least the same order as major commercial finite element tools. This is of crucial importance in fatigue analysis, since errors in stress solutions can be greatly magnified in calculations for life estimation.*

- *Increases in accuracy are also brought about by the fact that (unlike textbook solutions) the software can closely model the non-standard geometries typical of real aircraft structures.*

Aircraft on which the software has been used:
The Durham generated Concept Analyst software has been used to inform design, analysis and fatigue life estimation for aircraft structural components. In email 1, the F-35 DaDT Lead, BAE Systems, states that the:

> *Concept Analyst software is currently employed against design and production of the aft fuselage and empennage of the F-35 Lightning II (CTOL, STOVL and CV variants), Eurofighter Typhoon and Hawk aircraft. Concept Analyst is also employed to support older aircraft such as Tornado, Harrier. Concept Analyst has been employed during the production of some 150 or so F-35 aircraft aft fuselages, vertical tail pairs and horizontal tail pairs here at Samlesbury during the period 2008 to present.*

In Letter 1, the MD, Jesmond Engineering, states that the code has also been used on *"Airbus A350 (preliminary analysis)*" and lists some further categories of software usage:

> *Our customers at AgustaWestland have used the software during fatigue testing rig design to help avoid unexpected failures of rig parts which may cause unacceptable delays and expensive damage to the helicopter parts under test.*
> *We have found that Concept Analyst software is not only of use in the design stages of an aircraft, but throughout its lifecycle, including for maintenance, modifications and repairs. In my opinion the efficiency of its use can be considered to help bring safety and cost advantages to passengers and operators. The speed and ease of Concept Analyst has lent itself to use in production concessions, specifically undertaking rapid assessments to decide on the structural adequacy of parts (manufactured out of specification), each of which can cost hundreds to tens of thousands of pounds, and to verify whether a repair is acceptable.*

It is estimated that the total orders of Eurofighter Typhoon are over 500 aircraft. The value of each aircraft is estimated to be $100 to 150 million. Total Hawk orders number over 1000, with the value of each aircraft currently estimated to be $30 million.

The Airbus A350 is a family of long-range wide-body aircraft. As of 17th September 2013, a total of 682 orders have been placed (*http://www.airbus.com/presscentre/corporate-information/orders-deliveries/*) at list price $254 to 288 million (*http://www.airbus.com/presscentre/corporate-information/key-documents/?eID=dam_frontend_push&docID=14849*).

5. Sources to corroborate the impact (indicative maximum of 10 references)

(i) The web page of the spin-out company Concept Analyst, Ltd.: www.conceptanalyst.com

(ii) Individuals who may be contacted to corroborate this evidence are:

F-35 DaDT Lead, Aft Fuselage and Empennage, BAE Systems, Samlesbury, Lancashire: will be able to corroborate the details of the history of BAE Systems involvement with the research, of BAE Systems' funding of the research and of the impacts of the research on improving productivity and reducing wastage of parts.

Managing Director, Jesmond Engineering, Brough, East Yorkshire: will be able to corroborate the details of impacts of the research more widely in the UK & European aerospace sectors.