Institution: University of Nottingham

Unit of Assessment: UOA 10 – Mathematical Sciences

Title of case study: Enhancing vibro-acoustic modelling of built-up structures for industrial partners in the transport sector

1. Summary of the impact

Having itself developed **Dynamical Energy Analysis** (DEA), a numerical simulation tool that significantly enhances the modelling of noise and vibration (NV) in large-scale engineering structures in the mid- to high-frequency range, The University of Nottingham (UoN) has advanced the method to a practical numerical tool used in a commercial environment. By working with industrial partners, the team has influenced numerical simulation products developed by consultants to the transport sector and obtained investment in the new technology from vehicle manufacturers.

The method provides time and cost savings by making it possible to undertake NV modelling over the entire frequency range, and further contributes to the industry's objectives to reduce traffic noise and enhance passenger comfort.

2. Underpinning research

Research into traffic noise reduction is becoming increasingly important as highlighted in a recent joint report by the World Health Organisation and the European Commission (EC) - tinyurl.com/64mm7fm - as well as by the Directorate-General for Internal Policies of the European Parliament - tinyurl.com/pfatzcr - stating that "With regard to road traffic noise, the most effective control strategies involve noise control at source. This can only be achieved by stricter and more ambitious targets for reduction in permissible noise levels from motor vehicles" (page 9). In addition, manufacturers constantly seek to improve prototypes and to enhance passenger comfort by providing a noise-free driving experience. This leads to a growing demand for accurate tools covering the full audible frequency range.

Simulating the distribution of vibro-acoustic energy in complex built-up structures (e.g. vehicles) in the mid-to-high frequency regime is an extremely challenging task for standard numerical tools such as Finite Element Methods (FEM). A range of high-frequency techniques have been developed in the engineering community, the most successful being based on Statistical Energy Analysis (SEA) and SEA-FEM hybrid techniques. SEA has a limited range of applicability and does not describe accurately the mid-frequency range. The potential value of DEA is reflected in e.g. Jaguar Land Rover (JLR) commenting in this context that: "*Both of these codes* [FEM and SEA] *are suitable for their respective frequency ranges. FE is used when the modal count is low and the response is dominated by single resonance peaks. SEA is used whenever the modal count is high. Unfortunately between the two frequency ranges, there is an area, mid-frequency, where the conditions of each code cannot be satisfied, leaving a gap within the CAE* [computer aided engineering] *techniques which then leaves a reliance on physical testing*." [B1]

For cars, this range lies between 1-5 kHz, well within the audible range important for passenger comfort. Nevertheless, software packages based on SEA are offered commercially, with market leader ESI generating multi-million dollar revenues (tinyurl.com/pgb9ono).

A new method, *Dynamical Energy Analysis*, proposed by Dr Gregor Tanner (UoN, 1998 to date, Associate Professor and Reader) in 2009 [A1] and developed further with his research assistant Dr David Chappell at UoN, overcomes the limitations of SEA. Based on ideas of wave or quantum chaos, it approximates wave transport in terms of ray dynamics; the flow of ray trajectories is described in terms of linear phase space operators [A2]. These types of operators have been studied intensively in mathematical-research areas such as dynamical system theory and Frobenius-Perron or transfer-operator methods. By using operator techniques, DEA established for the first time an effective implementation of a ray-tracing algorithm in mechanical structures [A3, A4]. In particular, the implementation of DEA on FEM meshes (termed Discrete Flow Mapping – DFM, [A5]) opened up the method to curved shells and complex built-up structures and embeds the algorithm in a typical engineering simulation environment [A5]. The group also developed hybrid FEM-DEA methods using wave chaos results [A6].

An efficient numerical implementation of these ideas has been achieved with the help of funding from the EPSRC and an EC Industrial Partnership grant joint with inuTech GmbH, Germany, the Institute of Sound and Vibration Research (ISVR), UK, and industrial partners such as JLR, UK, and Germanischer Lloyd, Germany. The following main practical results have been established:

i. Improved bounds for the applicability of SEA [A1, A2, A4].
ii. Demonstrable improvements to SEA by including non-diffusive wave transport [A2, A3, A4].
iii. Hybrid DEA-FEM methods [A6].
iv. An implementation of DEA for multi-component structures (with Germanischer Lloyd) [A5].
v. An efficient DEA algorithm on triangulated meshes thus extending the method to complex, curved structures given in terms of FEM grids for JLR [A5].

3. References to the research

The three publications that best indicate the quality of the research are indicated *

[A1]* *Dynamical Energy Analysis – determining wave energy distributions in complex vibro-acoustical structures*, G. Tanner, Journal of Sound and Vibration 320, 1023 (2009).
DOI:10.1016/j.jsv.2008.08.032 (also listed in REF2)

[A2] *Solving the stationary Liouville equation via a boundary element method*, D. J. Chappell, and G. Tanner, Journal of Computational Physics, 234 487-498 (2013).
DOI: 10.1016/j.jcp.2012.10.002

[A3] *Boundary element dynamical energy analysis: A versatile method for solving two or three dimensional problems in the high frequency limit*, D. J. Chappell, G. Tanner, and S. Giani, Journal of Computational Physics 231, 6181-6191 (2012).
DOI: 10.1016/j.jcp.2012.05.028

[A4] *Dynamical energy analysis for built-up acoustic systems at high frequencies,* D. J. Chappell, S. Giani, and G. Tanner, Journal of the Acoustical Society of America 130, 1420 (2011).
DOI: 10.1121/1.3621041

[A5]* *Discrete flow mapping: transport of phase space densities on triangulated surfaces,* D. J. Chappell, G. Tanner, D. Löchel and N. Søndergaard, Proceedings of the Royal Society A 469, 20130153 (2013).
DOI: 10.1098/rspa.2013.0153 (also listed in REF2)

[A6]* *A hybrid approach for predicting the distribution of vibro-acoustic energy in complex built-up structures*, D. N. Maksimov, and G. Tanner, Journal of the Acoustical Society of America 130, 1337 (2011).
DOI: 10.1121/1.3621321 (also listed in REF2)

<u>Grants:</u>

- EPSRC Springboard Fellowship (EP/D064422/1) *Towards the mid-frequency regime - combining wave chaos methods and 'Statistical Energy Analysis'* (£81,708, Sep 2006 – Sep 2007).
- EPSRC grant (EP/F069189/1) *Vibrational energy distributions in large built-up structures - a wave chaos approach* together with Prof Brian Mace, ISVR, Southampton and inuTech GmbH; (Nottingham's share - £217,690, Jan 2009 – Dec 2011).
- EC Industrial and Academic Partnership & Pathways (IAPP) grant 230597 *Mid-frequency Energy Analysis* MIDEA; Coordinating partner: UoN; other main partners: inuTech GmbH, associate partners: ISVR (Southampton), Virtual Vehicle GmbH (Graz) and Bosch GmbH (€794,401 Jan 2009 – Dec 2012).

- EPSRC Knowledge Transfer Secondment Grant in collaboration with JLR: Competitive award from part of University KTS allocation EP/H500286/1 (£32,000, Jan – Aug 2012).
- Cash contribution by inuTech GmbH of £50,850 to support a 16-month sabbatical of Tanner, also supported by UoN, Sep 2012 – Dec 2013. Corroboration available from [B2].

4. Details of the impact

Traffic noise reduction is an important area for Computer Aided Engineering (CAE) both for minimising noise pollution and to meet high customer expectations. Providing quieter means of transportation leads to significant competitive advantages and enhances the reputation of a vehicle brand. The automotive industry alone spends over US$1bn p.a. on NV-related costs [B1] and virtual NV simulation and testing account for a steadily increasing slice of this outlay. However, due to a lack of reliable simulation tools, NV costs are still dominated by expensive measurements and prototype testing. NV simulation is thus an area of growing importance for vehicle manufacturers and CAE providers.

Since 2009, DEA has advanced from a mathematical concept to a practical numerical tool for engineers in the commercial NV sector. The UoN group developed the product alongside the main business partner, inuTech GmbH, a provider of numerical modelling solutions and expertise as well as software products. The strategy is based on transferring specialised research knowledge via inuTech into the wider modelling and simulation market, integrating it into the standard CAE environments used by key players in that market. From there it is introduced into the end user market of vehicle manufacturers and suppliers.

In order to achieve full impact in the commercial sector, it is vital to build up a solid reputation in engineering communities as well as within the academic sectors. The group therefore presents results regularly at mechanical engineering conferences (13 since 2009) and collaborates with key mechanical engineering groups in Southampton (ISVR), Cambridge, Leuven, Lyon, Graz and Munich. These efforts won the confidence of industrial partners and led to representatives of Bombardier, EADS, ViF and JLR speaking at the group's conference *InnoWave2012* at UoN: http://inutech.de/midea/events/InnoWave2012/.

While the main impact so far (in terms of direct investment and change of business practice) is on the numerical simulation and software industry, the team at UoN has (alongside those industrial partners) made concerted efforts to advertise and collaborate with end users in the vehicle manufacturing industry: the impacts of DEA on both these industrial sectors are described below.

Numerical Simulation & Software Industry
(Impact: economic benefits, change in company practice and adoption of new technology)

A close collaboration between inuTech and UoN has developed over recent years boosted by various grants from EPSRC and the EU. inuTech has recently committed further to DEA: "*Due to positive feedback from customers, we decided in September 2012 to invest directly in the method with an emphasis on constructing a software package with user-friendly pre- and post-processing tools and adjusting the method to the needs of specific customers such as in the ship and aviation industry. inuTech's development efforts amount to in total approx. 160K € including the salaries of two members of staff as well as part funding your* [Tanner] *sabbatical*." [B2] This represents a substantial investment from the company into DEA of 10% of their annual revenue (2012 total revenues were €1.65 M; 21 employees).

Via contacts from inuTech, a business partnership with another numerical software company, CADFEM GmbH, Munich, started in Oct 2012. Investment by the company in DEA is already paying dividends: "*CADFEM has decided to support the commercialisation efforts of inuTech by actively promoting DEA to its own customers and contacts. Currently, CADFEM is leading the negotiations with a potential customer in the ship building industry in China via its partner company Peraglobal Inc. based in China*." [B3]

UoN is also a coordinating partner in a new grant (MHiVec, [B7]) together with the company CDH AG, Ingolstadt, who have leading expertise in vibro-acoustics in the car industry and whose research focus the team has influenced: "*CDH AG has also adapted its internal R&D policy in line with the collaboration with the MHIVec project and has extended its own research efforts in the mid-to-high frequency regime to reflect the wider objectives of the project*." [B4]

Vehicle Manufacturers
(Impact: economic benefits and competitive advantage, working towards reduction in vehicle noise and improved passenger comfort)

Following refinement of DEA tools in the past few years, inuTech is promoting the method widely to its userbase: "*New DEA tools developed over the past years make it possible to contemplate going into this market and consequently we sought and received additional funding through a new IAPP (Mid-to-High Frequency Modelling tool for Vehicle Noise and Vibration (MHiVec) starting in Sept 2013. inuTech is confident that DEA constitutes a true innovation in vibro-acoustic modelling and provides an additional lucrative market segment for the company*." [B2]

Since 2010, benchmarking projects with various partners from the sector have taken place to validate the method for real engineering structures. This is vital to convince the community of the advantages of the new methodology. The team has for example obtained benchmark problems and meshes from: Germanischer Lloyd (shipbuilding) [B5]; JLR (car manufacturer) [B6]; EADS/Airbus (aerospace) and Bombardier (train manufacturer).

The group has demonstrated that the method delivers cost and time savings and gives correct results. The method is now being assessed by end user industries for adoption in future design cycles.

JLR supported a knowledge transfer secondment, hosting Chappell for 8 months within the company and provided in-kind contributions worth £15,000. Based on the success of this project (culminating in the development of DFM introduced in [A5]), JLR joined the MHiVec consortium and has pledged to invest in the order of £65,000 over 4 years in terms of staff time, measurements and training of consortium members [B7]. The company comments that: "*We believe that DEA together with the DFM technology is a serious candidate for closing the mid-frequency gap*." [B6]

The combination of DEA with DFM is of great interest to industrial partners, and ensures the impact of the work will be further enhanced, e.g. Germanischer Lloyd: "*We see great potential in the new method, in particular in the extension of DEA to a mesh based approach using the DFM method as published recently in the Proceedings of the Royal Society* [A5]." [B5]

5. Sources to corroborate the impact

[B1] http://tinyurl.com/ntja6vz, retrieved 1 August 2013 [copy on file]

[B2] CEO, inuTech GmbH [letter on file]

[B3] CEO, CADFEM International GmbH [letter on file]

[B4] Managing Director, CDH AG [letter on file]

[B5] Vice President Information Management and Tools, Germanischer Lloyd SE [letter on file]

[B6] Technical Specialist Body Structure NVH CAE, Jaguar Land Rover Ltd [letter on file]

[B7] Grant – MHiVec (*Mid-High Frequency Modelling for Vehicle Noise and Vibrations*, with partners: Nottingham Trent University, ISVR, inuTech, CDH, JLR (Associate Partner); total value: €1,944,975; Sep 2013 – Aug 2017, http://cordis.europa.eu/projects/rcn/109993_en.html)