Institution:
University of Cambridge

Unit of Assessment:
UoA15

Title of case study:
Vibration Modelling

1. Summary of the impact (indicative maximum 100 words)

A new hybrid analysis method, arising from research at the University of Cambridge Department of Engineering (DoEng), unites Statistical Energy Analysis (SEA) with Finite Element Analysis (FEA) to enable full-spectrum vibro-acoustic analysis of large and complex structures with modest computing resources for the first time. The method also allows for uncertainties in the manufacturing process. This research breakthrough has been exploited by ESI Group (ESI), which is a company that provides virtual prototyping solutions, in commercial software licensed to more than 600 companies across a wide range of industrial sectors to improve product design and performance with regard to vibrations and noise. Typical applications include the prediction and reduction of interior noise in automotive and aerospace structures, and the assessment of launch-induced vibration levels in satellite structures.

2. Underpinning research (indicative maximum 500 words)

In 1998, Robin Langley moved from his chair at the University of Southampton to become a Professor of Mechanical Engineering at the University of Cambridge Department of Engineering (DoEng). He had provided consulting services to Vibro-Acoustic Sciences Inc. (VASci), while at Southampton, to support the development and improvement of its Statistical Energy Analysis (SEA) software AutoSEA, culminating in the launch of AutoSEA2 in 1998. This software was designed to solve high-frequency vibro-acoustic problems.

On arrival at the DoEng, Langley focussed on a research question that had arisen from the VASci work: SEA is limited to high frequencies and the more conventional Finite Element Analysis (FEA) is limited to low frequencies, but is there a solution methodology for medium frequency vibrations that dominate many engineering applications? Langley collaborated with VASci to answer this question from 1998 onwards; continuing with ESI Group (ESI) from 2005 after it acquired VASci. Langley's work is theoretical in nature and consists of the mathematical analysis of engineering problems. Much of the research was undertaken in Langley's personal research time without grant funding. Some was funded by NASA SBIR grants (Small Business Initiative in Research), which were secured by VASci/ESI. The details are given below.

From 1998 to 2005, Langley and Philip Shorter of VASci/ESI collaborated on a method of coupling SEA and FEA within a single model: the difficulty is that SEA is based on energy flow, while FEA is based on equilibrium, and hence the methods are not readily compatible. Shorter proposed an initial idea for a solution to Langley, which was based on symmetry arguments. Langley used this starting point for rigorous mathematical analysis using a wave propagation model that led to the final form of the diffuse field reciprocity principle, which enabled SEA and FEA to be coupled. The work was published as a joint paper [1]. This work then led immediately to them creating the "Hybrid" analysis method [2], which could be employed across the full frequency range. This method used the diffuse field reciprocity principle to achieve efficient coupling of SEA and FEA. Overall, Langley and Shorter made approximately equal contributions to the work reported in both references [1] and [2] that underpin this case study.

The SEA approach allows for manufacturing uncertainties by implicitly employing a non-parametric uncertainty model. The results yielded by the method correspond to values that are averaged over the set of manufactured items, and, for around 30 years since the inception of the method, there was no robust method of predicting the variance of the response and confidence intervals. Langley devised an analytical solution to this problem at Cambridge for plate structures between 2000 and 2002 [3] and the work was then extended to general complex structures by Langley in collaboration with Vincent Cotoni of VASci/ESI in 2004 resulting in the SEA variance theory [4]. In this work the theory was developed completely by Langley, while computer implementation and numerical simulations were performed by Cotoni. Cotoni's contribution to the work was funded in part by a NASA SBIR grant (2002-2004), which included support from the US Air Force Research Laboratory for experimental validation studies.

Many aerospace structures have a repeating or “periodic” construction. Langley, Cotoni and Shorter recognised that this property could be incorporated into SEA and hybrid models to enable highly efficient vibro-acoustic computations to be performed. The solution utilised periodic structure theory and was published in 2008 [5] once the research results had been commercialised. Langley contributed the structural periodic structure theory and the wave dynamics that underpins the work, Cotoni contributed the acoustic radiation theory, and Shorter contributed to the practical implementation of the method.

Finally, Langley conducted research into rattle noise, which is the noise produced from impacting components. A theory of random impacts between components with uncertain properties was published in 2012 [6].

3. References to the research (indicative maximum of six references)

[1]* Shorter, P.J. and Langley, R.S. On the reciprocity relationship between direct field radiation and diffuse reverberant loading. Journal of the Acoustical Society of America, 117, 1, 85-95, DOI: 10.1121/1.1810271, 2005.

[2]* Shorter, P.J. and Langley, R.S. Vibro-acoustic analysis of complex systems. Journal of Sound and Vibration, 288, 3, 669-700, DOI: 10.1016/j.jsv.2005.07.010, 2005.

[3] Langley, R.S. and Brown, A.W.M. The ensemble statistics of the energy of a random system subjected to harmonic excitation. Journal of Sound and Vibration, 275, 3-5, 823-846, DOI: 10.1016/S0022-460X(03)00780-6, 2004.

[4]* Langley, R.S. and Cotoni, V. Response variance prediction in the statistical energy analysis of built-up systems. Journal of the Acoustical Society of America, 115, 2, 706-718, 2004, DOI: 10.1121/1.1642621.

[5] Cotoni, V., Langley, R.S. and Shorter, P.J. A statistical energy analysis subsystem formulation using finite element and periodic structure theory. Journal of Sound and Vibration, 318, 4-5, 1077-1108, DOI: 10.1016/j.jsv.2008.04.058, 2008.

[6] Langley, R.S. The analysis of impact forces in randomly vibrating elastic systems. Journal of Sound and Vibration, 331, 16, 3738-3750, DOI: 10.1016/j.jsv.2012.03.020, 2012.

*These outputs best reflect the quality of the underpinning research.

Langley’s work described above was largely responsible for him being elected a Fellow of the Acoustical Society of America (2000) and a Fellow of the International Institute for Vibration and Acoustics (2005). He was promoted in 2008 to become the Head of the Division of Mechanics, Materials and Design at DoEng with reference to these academic credentials. Langley gave the opening plenary talk at ICSV11 (2004 St Petersburg) on the hybrid method, and also gave a major keynote address on the method at Inter-noise 2005 (Rio de Janeiro).

4. Details of the impact (indicative maximum 750 words)

The research that yielded the hybrid analysis method underpinned the development of VASci/ESI’s vibro-acoustic analysis software, VA One, and provided the code with unique full frequency capabilities. The Langley-Cotoni SEA variance theory enabled VA One to predict variance of responses and confidence intervals. VA One was launched in 2005. Its impact continued and increased in the period from 2008 to 2013. [7]

The subsequent research that integrated periodic structure theory provided the solution that was commercially released as the VA One Periodic Structure Module in 2007. Its impact continued and increased in the period from 2008 to 2013. In addition, a further module released in 2010 concerning rattle noise was based on Langley’s work. [7]

ESI will not reveal sales data, but stated in 2013 that over 600 companies are currently employing VA One including large corporations such as Boeing, Ford, General Motors, Airbus, EADS and the US Navy as well as supply companies. ESI also stated that the periodic structure module has been used extensively by Boeing [8], Bombardier [9] and other ESI clients [10].

VA One answers a need, across a range of industrial sectors, to predict the vibro-acoustic performance of products at the design stage. For example, in the design of an automotive structure it must be ensured that the interior noise level meets customer requirements, and for commercial reasons this must be achieved at minimum cost of soundproofing or other noise control treatments.

The problem of predicting the vibro-acoustic response of a complex system faces two major difficulties: (i) a wide frequency range is of interest, and at high frequencies conventional methods of analysis such as the Finite Element Analysis method (FEA) can require millions of degrees of freedom and large computational resources, and (ii) the system response can be very sensitive to manufacturing uncertainties, and the "as-built" performance can differ significantly from the perfect design. [7, 10]

VA One overcomes these difficulties by: (i) employing SEA to model modally dense regions of the structure, thus leading to a dramatic reduction in the required number of degrees of freedom, (ii) employing FEA in regions of the structure which do not meet the conditions needed for the application of SEA, (iii) using the hybrid methodology to fully couple SEA and FEA in a single model, and (iv) allowing for manufacturing variability though non-parametric SEA statistics. The software allows a fast assessment of vibro-acoustic performance to be made, and this in turn allows iterative design studies to optimise the commercial and technical success of a product. [7, 10]

Many VA One customers have provided statements that are presented on the ESI website giving evidence of high impact including:

"There are a large number of problems in the aerospace industry that are amenable to vibro-acoustics analysis. These include aircraft interior noise, specification of launch vehicle and satellite vibration environments, and detailed stress analysis of lightweight reflectors under high intensity acoustic loading, among others. Because of the wide range of frequencies involved, no one method can solve all of these problems. VA One is the only tool that includes solvers that can perform analysis and design studies for low-, mid-, and high frequency problems. This allows for fast and effective vibro-acoustic analysis and design of aerospace structures, significantly reducing cost and schedule impacts compared to build and test approaches", Dr. Paul Blelloch, Director, Aerospace Analysis, ATA Engineering Inc. [11]

"One of the advantages of VA One for automotive applications is the ability to quickly start with the evaluation of simple yet useful conceptual models and progress through the evaluation of increasingly more sophisticated models as the design evolves. VA One can provide critical design assessments well before prototype vehicles are available such that proper noise control measures can be efficiently incorporated into the design; rather than inefficiently added as bandaids late in the program", Lear Corporation. [11]

"Even with JM's extensive testing capabilities, the next generation of acoustical solutions require sophisticated modeling techniques. ESI's vibro-acoustics software compliments our experimental facility proving the ideal tool for a broad spectrum of projects ranging from building construction to aerospace acoustics", Johns Mansville. [11]

"Boeing Integrated Defense has been a long term and successful AutoSEA2 user, and now has the capability of implementing all of the common vibro-acoustics analysis techniques, which are integrated into a single software package. The combined tools provide an efficient analysis environment when performing analysis to support Space Shuttle and International Space Station requirements. VA One is a standard software tool for Boeing Integrated Defense vibroacoustic analysis, and it is used to support a variety of other business activities", Ed O'Keefe, Associate Technical Fellow, Boeing Integrated Defense. [11]

"Hybrid FE-SEA analysis is a real leap forward when it comes to acoustical modeling technologies and is likely to set the standard for industrial computational acoustics of large structures for the future. The innovative integration of FE and SEA methods within one model allows the user to solve problems that cannot be addressed by applying SEA or FE methods separately", Ulf Orrenius, Senior Specialist : Acoustics and Vibration, Bombardier Transportation. [11]

"VA One is intuitive and straightforward to use. I was able to complete a detailed, coupled Boundary Element analysis the first time that I used the code", Jeffrey Larko, Aerospace Engineer Structural Dynamics, NASA Glenn Research Center. [11]

"The ability to simulate noise levels helped the engineers involved in the project consider the impact of their decisions on noise early in the design process, Engineers evaluated the impact of different types of absorptive materials and traded off their benefits against their costs. They

quantified the impact of main paths and flanking paths so that they didn't waste money reducing main paths in situations where the flanking paths would be controlling. The result was that noise on the Cascadia tractor was reduced by 5 to 6 dB below the previous generation and tests show that the Cascadia is one of the quietest cabs in North America", Craig Birkett, Product Validation/Engineering Analysis, Freightliner LLC. [11]

"By using ESI's vibro-acoustic software we were able to obtain up to 15 dB reduction in the interior sound pressure levels in one of our vehicle platforms. The software is now used in production as part of our standard vehicle design process", Kazuki Fukui, Nissan Motor Company. [11]

"Ensuring that our structures survive the harsh environments encountered during launch and liftoff is essential to our missions. Using VA One we can now predict the dynamic stress, strain and force in key components. This will help us to ensure that our structures are qualified for the acoustic and vibrational environments encountered during launch and liftoff", Ben Tsoi, Senior Dynamics Environmental Engineer, NASA Jet Propulsion Laboratories. [11]

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

[7] Product manager of VA One from 2003 to 2013

[8] Boeing Technical Fellow

[9] Manager, Acoustics and Vibration, Bombardier Transport

[10] Technical Director, ESI International Business Unit

[11] VA One success stories on the ESI website at http://www.esi-group.com/products/vibro-acoustics/va-one/success-stories