Institution: University of Southampton

Unit of Assessment: 15 General Engineering

Title of case study: 15-24 Identification and Active Control of Multiple Sources of Sound

1. Summary of the impact

Work at the Institute of Sound and Vibration Research (ISVR) has led to a sophisticated new understanding of a number of multiple-input multiple-output (MIMO) problems in acoustics. The effects are wide ranging, attracting heavyweight industry sponsors and driving valuable new innovations in home entertainment, construction, aviation and defence. In particular, research has led to the deployment of new "active" methods for controlling noise and vibration within aircraft. Systems have been installed in over 200 propeller aircraft since January 2008, giving a total number of 1000 aircraft treated to date and benefitting 177 million passengers worldwide. Noise reduction systems based on patents resulting from the unique ISVR methods are being developed for maritime use by BAE Systems. The underpinning science has significantly cut the cost of noise tests on Rolls-Royce jet engines, saving US$4 million to date and reducing their environmental impact. It has led to the development of mass-produced systems for living-room 3D sound, global sales of which have reached US$7.2 million.

2. Underpinning research

ISVR's Stephen Elliott, Professor of Adaptive Systems, and Philip Nelson, Professor of Acoustics, began working together to identify and control multiple sources of sound following their appointment as lecturers in ISVR in 1982. They have since developed their own approaches and applications to a wide range of practical problems. As an example, the inner surface of an aircraft in flight vibrates and radiates unwanted noise into the passenger cabin. This noise problem is particularly acute in propeller-driven aircraft where the surface vibrations are driven by the repetitive passage of the propellers. Early work, undertaken before 1993 and outside the REF period, involved the introduction into the cabin of multiple loudspeakers whose outputs could be controlled to cancel the radiation of the sound from the surface vibrations. Digital filters were used to generate the signals applied to the secondary sources in response to measurements made of the unwanted sound by microphones in the aircraft cabin.

A more sophisticated and practical approach to the cabin noise problem, led by Elliott and developed during the REF period since 1993, was to control the surface vibrations by adding other "secondary" vibration sources. The underpinning research that describes both the physics of the processes involved and the means for controlling the secondary vibration sources was detailed in two significant texts [3.1, 3.2] in 1997 and 2001. Further research then demonstrated the effectiveness of inertial actuators in reducing noise in propeller aircraft [3.3]. Similar "active" approaches are being used to reduce noise and vibration in ships and submarines, building on the original research involving aircraft. The focus has been on the design of practically viable, low power, active vibration isolation mounts and effective control algorithms. Steve Daley, Professor of Industrial Active Control (2010ff), has led the marine vibration control work. Funded by BAE Systems, it has enabled the development of truly effective and practical systems for the maritime sector.

A deep understanding of multiple input/multiple output (MIMO) acoustical systems is also required when noise control engineers wish to identify the number and strength of the component sources associated with a distributed source of sound (like the inlet of a jet engine). In principle, the measurements of a sound field can be used to determine the characteristics of the source of that sound. But in practice, solving this "inverse problem" poses several difficulties. An example of such a problem was presented by Rolls-Royce, who sought a way to measure the noise from gas turbine engines in a test-cell environment. In 1999, with Rolls-Royce backing of over £1.6 million, the University Technology Centre in Gas Turbine Noise was founded at ISVR to pursue this line of research and advance other noise reduction technologies.

While indoor test cells are a lot more cost-effective than outdoor rigs they rarely provide ideal

acoustics, as unwanted reflections from the surfaces of the cell interfere with microphone measurements. The challenge was to remove interferences and characterise the various noises produced by different parts of the engine. Work led by Nelson [3.4] resulted in a further programme of work with Dr Keith Holland, Lecturer (1999-2007) and Senior Lecturer (2007ff), which began in 2002 with a series of laboratory experiments using large microphone arrays to isolate and quantify the strength of multiple acoustic sources. Once tests had proved feasibility, in 2005 the team first deployed large, carefully designed microphone arrays in real test-cell environments. Novel processing methods yielded reliable predictions of outdoor engine noise levels [3.5]. These measurements are now regularly used in Rolls-Royce engine development programmes.

Another problem requiring an understanding of MIMO acoustical systems is that of accurately reproducing a sound field. This research, also initiated by Nelson during the late 1990s, dealt with the problem of transmitting sound from a number of loudspeakers in order to deliver accurately specified signals to the ears of a listener [3.6]. This allows, for example, a listener to hear a piece of music almost exactly as it would sound if played in a concert hall. There is clear potential for commercialisation and already the work has led to the formation of a spin-out company, the licensing of the intellectual property and the development of 3D-effect sound systems for the home.

The support of the BBC for this work has been formalised through the award in September 2013 of a £6 million EPSRC programme grant involving ISVR and the Universities of Surrey and Salford. All three are members of the new Audio Research Partnership formed by the BBC. The project is aimed at the development of the next generation 3D audio systems in broadcasting and the BBC is supporting this project with in-kind support valued at over £400k. Nelson is one of the co-investigators on this grant which begins in December 2013.

3. References to the research (best 3 are starred)

[3.1] C. R. Fuller, S. J. Elliott and P. A. Nelson 1997 *Active Control of Vibration* Academic Press. http://www.sciencedirect.com/science/book/9780122694400

[3.2] S.J. Elliott 2001 *Signal processing for active control* Academic Press. http://www.sciencedirect.com/science/book/9780122370854

*[3.3] L. Benassi, S.J. Elliott and P. Gardonio 2004 *Journal of Sound and Vibration*, **275**, 157- 179. Active vibration isolation using an inertial actuator with local force feedback control. http://dx.doi.org/10.1016/j.jsv.2003.07.019

*[3.4] P.A. Nelson and S.H. Yoon 2000 *Journal of Sound and Vibration* **233**(4) 643-668. Estimation of acoustic source strength by inverse methods: Part I, conditioning of the inverse problem. http://dx.doi.org/10.1006/jsvi.1999.2837

[3.5] K.R. Holland and P.A. Nelson 2012 *Journal of Sound and Vibration* **331**(20) 4425-4437. An experimental comparison of the focused beamformer and the inverse method for the characterization of acoustic sources in ideal and non-ideal acoustic environments. http://dx.doi.org/10.1016/j.jsv.2012.05.005

*[3.6] T. Takeuchi and P.A. Nelson 2002 *Journal of the Acoustical Society of America*, **112**(6), 2786-97. Optimal source distribution for binaural synthesis over loudspeakers. http://dx.doi.org/10.1121/1.1513363

4. Details of the impact

4.1 Quiet propeller aircraft. The commercialisation of active control systems for aircraft has been led by Ultra Electronics [5.1], a group of over 20 businesses in mainly the UK and North America that supplies electronic systems to the defence, security and aerospace industries. It employs over 3,000 people. After Southampton research made it clear that using structural actuators to drive the fuselage allowed both the vibration inside the passenger cabin and the noise level to be controlled, ISVR developed novel inertia actuator designs, which now have several international patents (e.g. WO 2005 059 397) granted to the University.

These patents were licensed in 2004 to Ultra Electronics who, in 2009, announced the installation

of their 1,000th active noise control system for a commercial propeller aircraft [5.2]. A total of 200 such systems have been installed since January 2008. These systems are now standard fit on the Bombardier Dash 8 Q400, which is the most popular type of civil propeller aircraft. Bombardier recently confirmed [5.3] that it had orders for 428 of the Q400s from 40 operators in 30 countries on six continents. These aircraft have transported 177 million passengers over 3.2 million flight hours. The new market for noise control devices in aircraft is still growing, which is confirmed by their Technical Director, Ian Stothers [5.4], who originally worked at ISVR on the very first control system under the supervision of Prof Elliott.

4.2 Vibration reduction in ships and submarines. In marine applications, auxiliary and propulsion machinery causes vibration that leads to passenger and crew discomfort and radiated noise that is harmful to marine life and creates a severe detection hazard for naval vessels. For manufacturers of military vessels, attaining contractual targets is essential due to severe penalties that can be as much as £1 million per dB of non-compliance. The distinctive technology developed by staff at ISVR is now being commercialised for wider use by BAE Systems. The following statement has been provided by Alastair Sherriff, NAVED Manager, BAE Systems Maritime [5.5]:

> *"BAE Systems have found the links we have developed with ISVR to be invaluable in progressing technology development and knowledge transfer. We regard your work in active noise control for maritime applications as a technology driver for BAE Systems and the significant developments that have taken place since your move to the ISVR have been the key to moving the technology out of the laboratory in preparation for future applications. The use of the developed toolset and the novel approach to characterising transfer paths will provide deeper understanding of the composition and contribution of noise sources not possible with legacy techniques. Our link with the ISVR is providing real capability improvement now and we hope will continue in the future."*

4.3. Jet engine noise measurement. The Rolls-Royce project on measuring noise output in an indoor test-cell environment has produced substantial financial and environmental benefits. Using methods pioneered at the University Technology Centre in Gas Turbine Noise, Rolls-Royce engineers were not only able to ensure that engines' noise levels were acceptable, they were also able to acquire the data needed to develop technologies for reducing the emissions of carbon dioxide and nitrogen oxides. By piggy-backing the noise tests in this way, Rolls-Royce avoided the need to undertake separate outdoor tests. New testing methods have been in place since 2007, delivering savings of at least US$ 4million since January 2008. The ISVR has successfully applied these methods to engines in test beds in Spain, Germany and the UK. When combined with other work undertaken at ISVR, the result is a significant reduction in engine noise and emissions. Dr Andrew Kempton, Chief Noise Specialist at Rolls-Royce, said [5.6]:

> "*The technique has allowed us to exploit noise measurements when aero-engines are tested indoors. Such indoor tests are conducted to provide understanding of other engine properties (not their noise), and rather than conducting a specific outdoor noise test (with a typical cost of $1M) Rolls-Royce, with the support of Southampton University, piggy-backs noise measurements on the indoor tests. Since January 2008, these techniques have been exploited on four such piggy-back tests. In reality, in many cases the outdoor noise test would have not been possible (for cost or logistics reasons). So piggy-backing noise measurements using your technique on indoor tests has allowed us to acquire data that is used to help us develop technologies to improve the environmental performance of our engines (for example in terms of CO2 or NOx emissions) by ensuring that the noise impact is acceptable. Technology developments at Rolls-Royce, supported by our University Technology Centre in Gas Turbine Noise at Southampton, have resulted in exceptionally quiet aircraft with low emissions; two of the new generation aircraft (such as the A380 and B787) produce the same amount of noise as one of the aircraft they are replacing, so that in the next forty years aviation can double without increasing the overall noise*."

4.4 3D sound systems. Even in the early stages of the ISVR work on sound reproduction, undertaken in the mid-1990s, there was massive interest from industry sponsors, including Yamaha, Hitachi, Samsung and Japan's largest construction company Kajima Corporation, which resulted in total funding of around £1.2 million. Kajima, with its annual turnover of $15 billion, was primarily interested in simulating the acoustical environments offered by the buildings they designed. This involves replicating sounds exactly as they would be heard in the yet-to-be-built concert hall, office or meeting room. Recognising the huge commercial potential, the University assigned a number of patents, which came out of the underpinning research, to a holding company, Adaptive Audio Ltd, who in 2004 formed a joint-venture company, Opsodis Ltd, with Kajima [5.7].

Kajima engineer Dr Takashi Takeuchi, who had completed a PhD in the late 1990s under the supervision of Prof Nelson, returned to ISVR in 2006 as visiting researcher, where he has since supported the commercialisation of the technology through Opsodis Ltd. The intellectual property was sub-licensed to several audio manufacturers including Marantz (Japan), and Inkel (Korea). Sales of the systems since 2005 by Marantz [5.8] have exceeded 6,000 units, with a total sales value of US$7.22 million [5.9]**.** These sales include a first "high-end" product known as the "ES-150", which sold 211 units and a second product known as the "ES-7001", which sold 5,198 units. As of July 2013, the total number of ES-7001 products sold since January 2008 is 2,968 (total sales value of US$3.71 million). The Inkel product was launched in the USA in May 2013 under the "Sherwood" brand [5.10]. It is anticipated that sales of this product will reach 5,000 during 2013 alone. Interest in the technology continues to expand and is being evaluated by NHK (the Japanese Broadcasting Company), the BBC as described above, and Huawei, who awarded a £420k contract to ISVR in 2013 to undertake the development of loudspeaker arrays for personalised audio. The latter is being led by Dr Filippo Fazi, former PhD student of Nelson and ISVR Lecturer (2010ff), who was awarded a Royal Academy/EPSRC Fellowship worth over £450k to undertake further work in inverse problems in electro-acoustics.

5. Sources to corroborate the impact

[5.1] Ultra Electronics web-site describing active noise and vibration control systems: http://www.ultra-controls.com/productdetails.php?productID=15

[5.2] Ultra Electronics Press Release http://www.airframer.com/news_story.html?release=4402

[5.3] Description of Bombardier Q400 propeller aircraft: http://www.bombardier.com/en/aerospace/commercial-aircraft.html

[5.4] Corroboration of number of sales of active noise control systems: Mr Ian Stothers, Technology Director, Ultra Electronics Ltd. Controls Division (Cambridge)

[5.5] Corroboration of application of active control technology by BAE Systems: Alastair Sherriff, NAVED Manager, BAE Systems Maritime – Submarines.

[5.6] Corroboration of significance of noise source characterisation to Rolls-Royce: Dr Andrew Kempton, Chief Noise Specialist, Rolls-Royce Plc.

[5.7] Corroboration of formation of Opsodis Ltd.: Dr Minoru Nakayama, Divisional Advisor, Kajima Technical Research Institute, Kajima Corporation.

[5.8] Review of Marantz product base on Opsodis technology: Cinemarium ES7001. http://www.trustedreviews.com/Marantz-Cinemarium-ES7001-Soundbar_Surround-Sound-System_review

[5.9] Corroboration of numbers of sales of licensed products from Opsodis Ltd: Mr Masami Uehara, Senior Manager, Marketing Division, Kajima USA, Inc.

[5.10] Sherwood product based on Opsodis technology: S7 and S9 3D Soundbar. http://www.sherwoodusa.com/product/view.asp