



History of the Acoustics Research Unit at the University of Liverpool

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Abstract – Acoustics research was established at the University of Liverpool in the middle of the 20th century in the department of physics which led to the formation of the Acoustics Research Unit (ARU) in the mid-1970s as part of the department of building engineering and then architecture. This article reviews the history and legacy of the research group that has worked on airborne and structure-borne sound over a 70 year period.

Keywords. Acoustics Research Unit, University of Liverpool, history

1 Introduction

The Acoustics Research Unit (ARU) at the University of Liverpool in the United Kingdom specialises in research, supervision of postgraduate research studies (PhD and MPhil), training, knowledge exchange and consultancy. Over a 70 year period, the research has focused on airborne and structure-borne sound in the fields of engineering acoustics, building acoustics, room acoustics, psychoacoustics, speech intelligibility, privacy and security, human vibration, environmental noise and industrial acoustics. In these areas, particular emphasis has been placed on the development of prediction models with validation using laboratory experiments, experimental studies on subjective evaluation, and the development of new measurement procedures. The first part of this paper reviews the history of the ARU and the lead researchers with the second part giving an overview of the main research areas.

2 History

2.1 1949–1977

In 1949, an Acoustics Research Laboratory was established in the Department of Physics under the headship of Derrick Parbrook. With Tempest, Parbrook worked on the absorption of ultrasound in light gases [1]. Under the supervision of Parbrook, Michael Bryan obtained his PhD in the area of audiology and carried on to work on threshold measurements and loudness evaluation. Under

Parbrook, the acoustics group transferred to the newly-established Department of Building Science in 1967, which later became the Department of Building Engineering in 1973. The relocation involved the construction of a suite of measurement facilities: anechoic chamber, reverberant chamber, large and small transmission suites (see Fig. 1), and other fully-instrumented spaces. Research then began to focus on the sound insulation of lightweight building elements which required a double leaf construction to achieve a high performance. The theories employed travelling wave analysis for sound transmission through cavity walls. Building on the development of Statistical Energy Analysis (SEA) by Richard Lyon (MIT, USA) for aerospace applications, the team of Malcolm Crocker, Arnold John Price, Ken Mulholland, Derrick Parbrook and Mahendra Bhattacharya developed applications with greater relevance to buildings. The seminal work by Crocker and Price on the prediction of sound insulation using SEA for single and double walls paved the way for its use in the field of building acoustics. Parbrook was instrumental in the formation of the British Acoustical Society, which became the Institute of Acoustics in 1974. Throughout this period of research, doctorates were awarded to Ken Mulholland, Malcolm Crocker (later at Auburn University, USA), Alan Cummings (later at Hull University, UK), Roger Utley (later at BRE, UK), John Price, Stuart Flockton, (later at University of London, UK) and Richard Guy (later at Concordia University, Canada).

2.2 1977–2007

In 1977, Barry Gibbs was appointed to take over the Acoustics Research Unit (ARU) with emphasis on research into structure-borne sound transmission in the

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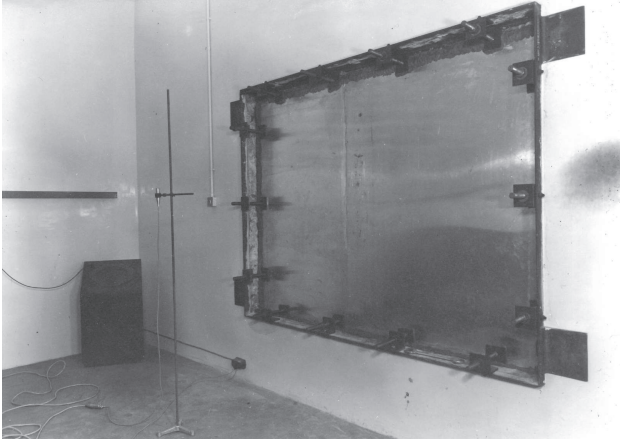


Figure 1. ARU transmission suite (1968): One of the panels used in the seminal work by Malcolm Crocker on the prediction of sound insulation with Statistical Energy Analysis.

built environment. This led to novel measurement methods to quantify wave transmission across junctions of plates [2] alongside a body of work to predict structure-borne sound transmission at junctions for both bending and in-plane waves [3–5]. During this period, Gibbs supervised 20 PhD students to successful completion. As a research theme, the experimental quantification of structure-borne sound power from machinery and mechanical sources led to seven of these PhDs, the first being by Andy Moorhouse (later at Salford University, UK). Many of the research projects stemmed from collaborations with Chinese, Brazilian and European acoustics groups. These included Huang Yizhu from the Nanjing Institute of Architecture and Civil Engineering (China), Qiu Shuye, Chen Jialing, Su Jianxin, Qiu Guiming, Li Shaohui from Shantou University (China) under The British Council collaboration Scheme, Visting Professor Bjorn Petersson from Lund University (Sweden), and later the Technical University Berlin) and Professor M. A. Sattler from the Universidade Federal Do Roi Do Sol (Brazil) – see Figure 2.

In 1982, Gary Seiffert started his career as research support in the ARU. Under the supervision of Gibbs, he carried out his PhD on the interaction of sound with powdered material which led to links with the horn manufacturer Primasonics on acoustic cleaning and promotion of fluidising powder in industrial settings. In later years, Seiffert became examiner and moderator for the Laboratory School of the Institute of Acoustics (IOA) Diploma in Acoustics by distance learning as well as Chair of the IOA committee for the Certificate of Competence in Environmental Noise Measurement.

David Oldham came to Liverpool in 1990 to head the Department of Building Engineering and continue his research on room and building acoustics. With a sizeable cohort of PhD students, his research focussed on ventilation, factories, facades, airflow noise in ducts and sustainable materials.



Figure 2. Even during the 1980s, research meetings were still held in black and white, occasionally in sepia! From left to right: Gary Seiffert, Rory Sullivan (PhD student), Jean-Michel Mondot (Chalmers University of Technology, Sweden), Richard Lyons (PhD student), Barry Gibbs, Bjorn Petersson (Chalmers University of Technology, Sweden), David Oldham, Simon Pepper, John Goodchild.

During the 1990s, many government-funded laboratories in Europe that worked on building acoustics were privatised and more building acoustics research moved into university departments. Liverpool played a key role in the dissemination of this research when Professors Gibbs and Oldham became founding co-editors of the *Journal of Building Acoustics (Multi-Science)* from 1993 to 2009; the journal currently continues into its fourth decade. The *Internoise* conference came to Liverpool in 1996 for which it had the largest number of attendees up to that point-in-time; this might have been due to Liverpool’s famous architecture, the legacy of The Beatles and its football clubs, but it would be nice to think that the tour of the ARU helped to draw a few attendees too!

In the 1990s and early 2000s, Gibbs became involved with Standardisation when Visiting Professor Heinz-Martin Fischer, Stuttgart University of Applied Science (Germany), introduced Barry Gibbs to the CEN working group TC126/WG7 that was concerned with developing standards on the measurement of structure-borne sound from mechanical sources in buildings. European groups had previously developed a version of SEA based on path analysis to estimate sound transmission in the field. Whilst there were accepted methods of characterizing mechanical services as airborne sound sources, there was still a need to characterise structure-borne sources [6]. This was recognised by European Standards working groups, and the ARU became actively involved in a series of collaborative research projects towards treating vibrating mechanical installations as noise sources [7]. Noteworthy, was a measurement method applicable to a whole range of machines in all building types [8, 9].

Undergraduate teaching on acoustics was incorporated into the Building Engineering (BEng) degree in

the 1980s and 1990s and subsequently into Architecture (BA) and Architectural Engineering (BEng) degrees from mid-2000s to the current day.

2.3 2007–Present

Carl Hopkins joined the ARU in 2007 from a research and government advisory role at the Building Research Establishment (BRE). His PhD was on structure-borne sound transmission across coupled plates which was supervised by Professor Bob Craik at Heriot-Watt University. In 2007, Hopkins published his monograph on sound insulation [10], a comprehensive guide to sound and vibration theory and its application to the measurement and prediction of sound insulation in buildings. Building up the cohort of PhD students, Professor Hopkins became Head of the ARU whilst focussing on extending the application of SEA in buildings and broadening the group's research into other areas such as vibrotactile perception and speech security.

Pyoung Jik Lee joined the ARU in 2014 bringing expertise in human perception and response to sound and vibration in the built environment. Lee's PhD was at Hanyang University (Korea) supervised by Professor Jin Yong Jeon on the subject of impact sound insulation of floors and human perception. In personal research and alongside PhD students, Lee also broadened the research portfolio of the ARU to include psychophysiological responses to sound and vibration as well as annoyance due to impacts inside buildings, the role of community psychology and hospital acoustics.

Gibbs was President of the International Institute of Acoustics and Vibration, IIAV (2002–2004) followed by President of the Institute of Acoustics (2016–2022) and, although retired, remains an Emeritus Professor at the ARU.

2.4 Collaboration with International research groups and links to Standardisation

ARU research on sound transmission led to new developments and improvements in Standards on building acoustics that prescribe measurement methods, prediction models and evaluation (e.g. see [11, 12]). This provided the scientific basis and experimental validation needed to establish new approaches in nine International and European Standards. These Standards are adopted in over 34 countries where they are used by accredited test laboratories, consultants, manufacturers and government regulators for buildings, ships and offshore structures. Participation in Standards committees and Working Groups continues as it ensures the research addresses the needs of industry and government stakeholders. Korea and Japan assess impact sound insulation using measurements with a heavy impact source, and in the last few decades there has been interest in using this source in Europe. However, there was no internationally

agreed method to calculate a single-number rating that could be used to assess annoyance and identify acceptable levels of impact sound insulation for building regulations. Research using subjective evaluation studies by Lee [13] assessed different ratings developed in Korea and Japan to identify the most suitable rating method, which was subsequently included in EN ISO 717-2.

2.5 Collaboration with industry, international institutes and learned societies

Since the 1980s the ARU has provided acoustics consultancy and short courses to industry. This initiative began with John Goodchild and Andy Moorhouse and continues to this day, being headed up by Gary Seiffert. Clients are typically government departments, acoustic product manufacturers, mechanical and manufacturing industries, museums, local authorities, architecture and construction companies.

In the 1990s, the ARU started to provide training courses for Continuing Professional Development in the field of acoustics that were accredited by the IOA. These courses covered topics including environmental noise measurement, workplace noise and hand-arm vibration. At present, the focus is on running the certificate of competence in environmental noise measurement for the IOA and the laboratory and experimental methods module of the IOA diploma.

3 Research areas

3.1 Vibroacoustic prediction models

The majority of research to develop vibroacoustic models at Liverpool has been based on the use of Statistical Energy Analysis (SEA) alongside Finite Element Methods (FEM). For direct sound transmission, Crocker and Price published two seminal papers on experimentally-validated SEA models to predict sound transmission across single and double walls [14, 15]. This work formed the foundations for the development of SEA in building acoustics in the 1970s and 1980s. In the late 1990s, Gibbs and Maluski [16] pushed the limits of finite element calculations to calculate airborne sound insulation for direct transmission between two rooms based on what was achievable with the computing power available at the time.

Accurate prediction of sound transmission in buildings requires consideration of flanking as well as direct transmission. In the early 1980s, Gibbs and Craven developed theory for the transmission of bending and in-plane waves across L -, T - and X -junctions of walls and floors [4], taking advantage of the computing power available at the university to carry out parametric studies [5]. Later work by Hopkins and Robinson validated the use of Transient SEA (TSEA) to predict L_{Fmax} for sound and vibration in buildings [17]. This enabled the prediction



Figure 3. ISO rubber ball drop used for experimental validation of prediction models on impact sound insulation.

of impact sound insulation with heavy/soft sources such as the rubber ball and tyre machine, which are used in Korea and Japan [18, 19] – see Figure 3. To account for spatial filtering and the existence of non-diffuse vibration fields, Heron’s theory for Advanced SEA (ASEA) that incorporated ray tracing was experimentally validated for structure-borne sound transmission across ribbed plates [20], periodic box-like structures [21] and frameworks of beams [22] – see Figure 4.

3.2 Structure-borne sound power

The research collaboration with Petersson, led Gibbs to focus on the problem of quantifying the power input from structure-borne sound sources [6, 23]. With Fulford, Gibbs went on to focus on multi-point connected machinery [24–26]. Until 2009 there was no generally accepted procedure to measure the vibrational power output of building machinery. This changed when the reception plate method developed by Gibbs [27–29] was used as the basis for the European Standard EN 15657-1. This Standard was initially limited to machinery installed in heavyweight buildings but was later extended to include lightweight buildings by incorporating research from Gibbs on the two-stage reception plate method. EN 15657-1 allows manufacturers of heating, ventilation, domestic appliances etc. to measure their products in laboratories and assess compliance with noise limits after installation. Subsequent research led to improvements in sampling procedures for low-frequency sources [30]. With Höller, Gibbs also investigated a source substitution method to determine structure-borne sound power as a development of the reception plate approach [31]. Through the adoption of ARU research, and its inclusion in EN 15657, at least ten laboratories and manufacturers across Europe now use reception plates for testing and product development.

Collaboration with Professor Ulrich Schanda and his team at the Rosenheim University of Applied Sciences

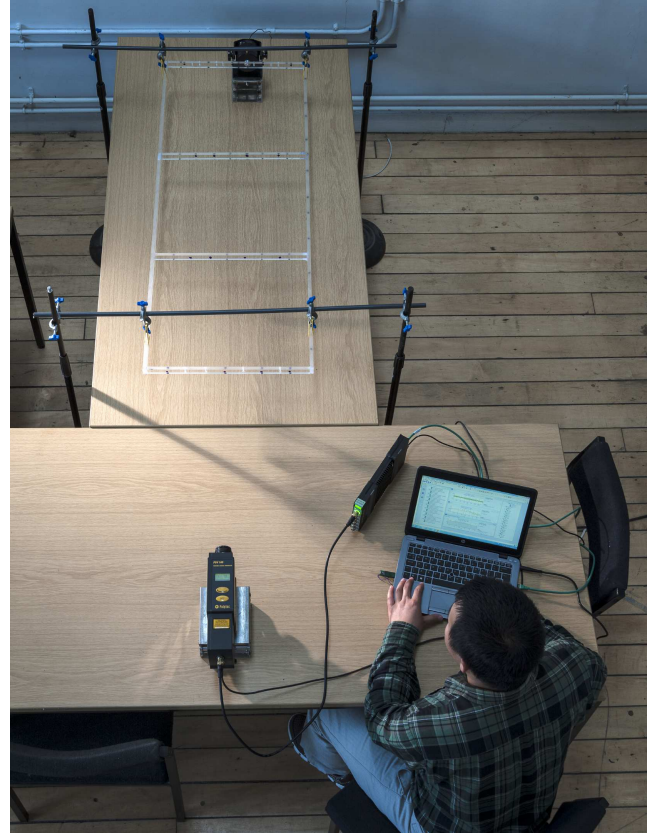


Figure 4. Laser vibrometer measurements on a framework of beams for comparison with prediction models based on Advanced Statistical Energy Analysis (ASEA).

(Germany) on timber-frame buildings led to insights into the structural dynamics of solid timber floors considered in Switzerland [32] and into transmission functions to provide an empirical basis for the prediction of structure-borne sound transmission from machinery in a simplified approach for manufacturers [33].

3.3 Human response

Lee conducted extensive research on human responses to sound and vibration where the initial focus was on floor impact noise with heavyweight floors [34], which later expanded to include lightweight structures [35]. A wide range of research methodologies have been employed, including semi-structured interviews [36], questionnaire surveys [37], and laboratory experiments [38]. In 2017, Lee pioneered the use of physiological measurements in response to building noise by introducing heart rate, electrodermal activity, and respiration rate as indicators [39]. These physiological measures have since been extended to include facial electromyography (fEMG) [40] and electroencephalography (EEG) [41]. Beyond building noise, Lee’s research has explored human responses in diverse environments such as urban soundscape [42]. The reproduction of stimuli



Figure 5. A participant engaged in a VR experiment, wearing electrodes to measure physiological responses to soundscapes.

in laboratory settings has evolved through the availability of virtual reality (VR) and spatial audio [43], allowing for immersive and more realistic experiments – see Figure 5. Research on the effects of noise on individuals and communities has been primarily conducted through questionnaire surveys. Negative emotions such as annoyance [44] and discomfort have been the focus of many investigations along with the effects of noise exposure on blood pressure [45] and voice disorders [46].

Research by Hopkins and Seiffert [47, 48] on the vibrotactile presentation of music to the glabrous skin of the hands and feet tackled the barriers to music performance and education for people with a hearing impairment. Research on the perception of music using safe levels of vibration has transformed the way that music is taught at the Royal School for the Deaf in Derby where it gave an understanding of pitch, enabled group musical performances, significantly improved engagement in music lessons and helped protect the teacher’s hearing by reducing sound levels in the classroom. The music teacher noted that the equipment “...has certainly given our children greater access to sound ... particularly in the area of pitch, they are now beginning to make the connection between the vibration and the pitch of the note which before, a lot of our students would get confused”. It transpired that children with a hearing impairment often confuse pitch with the intensity of the vibration. The video documenting this work at the school [49] won the Acoustical Society of America’s 2021 Science Communication Award. In terms of participation, it has enhanced music production, and restored access to music when sudden-onset deafness occurred in mid-life.

3.4 Sound in the built environment

In terms of environmental noise, Oldham conducted extensive research on sound propagation in urban environments, sound scattering from building facades, and façade design. With Egan, Oldham investigated the performance of T-profile highway noise barriers using BEM [50]. As part of the EU 6th Framework Holiwood

project, Oldham et al. [51] investigated the sound absorption properties of sustainable acoustic absorbers from the biomass with potential application to noise barriers. Oldham and Ismail [52] investigated the effect of reflections from non-smooth building façades on sound propagation in streets which showed that the scattering coefficient is typically low for building façades. In later years, Lee continued this line of research by performing computer simulations of sound propagation in urban street canyons [53] and other environments such as hospital wards and open-plan offices. Lee subsequently investigated noise levels and sources in health-care settings [54], as well as residential buildings [55] and offices.

To evaluate rain noise inside buildings and cars it is necessary to know the force applied by rain drops at terminal velocity. Wavelet deconvolution was used to determine these forces with and without a shallow water layer on an elastic plate [56]. Validated models for point excitation of roof glazing were used to calculate conversion factors between laboratory measurements with artificial rain to other situations with natural or artificial rainfall, and between measurements on roof elements that are inclined at different angles [57]. This has allowed more meaningful assessments of laboratory rain noise measurements with artificial rain and for natural rainfall which requires assessment in practice.

3.5 Industrial acoustics

Seiffert and Gibbs [58, 59] pioneered research into acoustic cleaning for industrial applications, investigating the removal of electrostatically deposited powders using high-intensity low-frequency sound and vibration for which an important industrial application was the cleaning of electrostatic precipitator filters in coal-fired power stations. This led to work by Seiffert and Hopkins [60] on the acoustic cleaning of orthopedic components, such as the acetabular cup in total hip joint replacements. These are made from titanium powder in processes such as selective laser melting to form a porous metal implant. This demonstrated that acoustic cleaning using high-intensity sound has significant potential for use in the final preparation stages of porous metal orthopedic components to remove loose powder after manufacturing. Moving into high-temperature industrial applications, Hopkins et al. experimentally evaluated the airflow resistance of fibrous materials up to 800 °C [61].

4 Concluding discussion

To-date, acoustics research at the University of Liverpool has covered a period of over 70 years, starting in physics, then moving into the departments of building engineering and architecture. Ex-PhD students and

post-doctoral researchers have had (and continue to have) successful careers in academia, industry and consultancy where they have risen to senior leadership roles. The main research areas continue to be based around vibroacoustics, structure-borne sound, human response to sound and vibration, sound in the built environment and industrial acoustics.

Acknowledgments

Inevitably, when describing such a long period of time in a short article, it has not been possible to mention the large cohort of PhD students and post-doctoral researchers by name who contributed so much to the research activity of the ARU. Likewise, it has not been possible to name people in industry who liaised, funded and collaborated with the ARU in research which benefitted both parties. They are not forgotten and are gratefully acknowledged.

Conflicts of interest

The authors declare no conflicts of interest in regard to this article.

Data availability statement

No new data were created or analysed in this study.

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