

Institution: University of Warwick		
Unit of Assessment: B12 – Engineering		
Title of case study: Warwick Acoustics: using ultrasonic technology to produce the world's finest sound systems		
Period when the underpinning research was undertaken: 2003 – 2020		
Details of staff conducting the underpinning research from the submitting unit:		
Name(s):	Role(s) (e.g. job title):	Period(s) employed by submitting HEI:
Duncan Billson	Associate Professor	1998 – Present
David Hutchins	Professor	1988 – Present
Period when the claimed impact occurred: Aug 2013 – Dec 2020		
Is this case study continued from a case study submitted in 2014? N		
1. Summary of the impact (indicative maximum 100 words) <p>Research into airborne ultrasound by Dr Duncan Billson and Professor David Hutchins led, via a spinout now known as Warwick Acoustics (WA), to a revolutionary electrostatic audio system that is ultra-light, super-thin, multi-directional and capable of being mass-produced inexpensively in any shape or form. This technology was used in two exclusive models of headphones, the Sonoma M1 in 2017 and the APERIO in 2019, aimed at the high-end audiophile market; strong sales led to a six-fold increase in turnover for WA [text removed for publication], who then doubled their production space and workforce based on GBP8,000,000 further investment. The state-of-the-art headphones not only won many industry awards and earned praise from seasoned Grammy-winning music producers and engineers, but also provided a vital demonstrator for highlighting the technological possibilities in other applications. In 2020 and with Billson's guidance, further investment and several proof-of-concept projects led to WA pursuing development opportunities in the automotive industry, where the technology's energy-efficient characteristics are keenly sought in the push towards greener transport.</p>		
2. Underpinning research (indicative maximum 500 words) <p>Since the 1990s, research into airborne ultrasound led by Dr Duncan Billson and Professor David Hutchins (Ultrasonics Laboratory in the School of Engineering) has predominantly focused on using and developing devices which generate and detect ultrasound in air (micro-machined electrostatic ultrasonic transducers) [3.1]. Billson and Hutchins' comprehensive research in this area investigated the transduction physics of the transducers (improving the performance of the transducers), the acoustic fields emanating from the transducers [3.2], detection and measurement of the ultrasound and acoustic fields [3.3], as well as using the transducers to test materials and structures [3.4].</p> <p>Billson and Hutchins' insight into airborne ultrasound, developed for non-destructive testing, resulted in a new, revolutionary type of electrostatic audio loudspeaker. They took the principle of the ultrasonic transducer and adapted it to work at acoustic frequencies by sandwiching in a sheet of insulating material between two sheets of conducting material. The structure comprised a micro-machined solid backplate attached to a thin metallised-polymer membrane and used a combined DC/AC signal of about 200V which gave a highly efficient source of ultrasound, generating large, undistorted sound fields in air with exceptionally broad bandwidths [3.5].</p> <p>This research led to a spinout company, Warwick Audio Technologies, being incorporated in 2002; it became Warwick Acoustics (WA) in 2018. The expertise of Billson and Hutchins is still used to guide and inform the development of WA's technology. Billson continues as a non-executive company director, and contributes to the management and direction of the company. Between</p>		

2014 and 2020, a significant amount of modelling (some of which used the well-established COMSOL software package) of the acoustic system resulted in the production of unique High Precision Electrostatic Laminate (HPEL) transducers which are capable of being inexpensively and reliably mass-produced (unlike other electrostatic loudspeakers, which are hand-built). These are optimised for acoustic quality and amplitude for headphones, and use the resonance of hexagonal elements to optimise their acoustic output [3.6-3.7].

The unique HPEL transducers, together with their bespoke drive electronics, are the heart of WA's technology. Their ongoing development has generated a great deal of valuable IP which is protected by a range of patents filed by the company. Ownership of this portfolio of patents is fundamental to the value of the company, and has been essential for raising capital investment.

The technology is now being re-engineered for the bigger, more lucrative automotive market. A new generation of HPEL transducers - double-sided 'push-pull' rather than single-sided 'pull' loudspeakers - have twice the acoustic power output as well as extremely low distortion outputs, meaning that the quality of sound coming from them is literally second-to-none. As the loudspeakers are thinner, significantly lighter and more electrically efficient than conventional loudspeakers, they are seen as an obvious technology to be adopted by the next generation of electric vehicles. This has resulted in significant interest from many automotive companies. A further substantial collaboration between the University and WA was established in May 2020, funded by Innovate UK Smart Grant, to develop a new, global standard for delivering in-car entertainment in plug-in hybrid and zero and low emission electric vehicles [G1].

3. References to the research (indicative maximum of six references) **Warwick = Bold**

All research papers were published in peer-reviewed journals

- [3.1] Hutchins, D. A., McIntosh, J. S., Neild, A., Billson, D. R. and Noble, R. A. (2003) *Radiated fields of capacitive micromachined ultrasonic transducers in air*. The Journal of the Acoustical Society of America, 114 (3). pp. 1435-1449. doi:[10.1121/1.1604120](https://doi.org/10.1121/1.1604120)
- [3.2] Neild, A., Hutchins, D. A., Robertson, T. J., Davis, L. A. J. and Billson, D. R. (2005) *The radiated fields of focussing air-coupled ultrasonic phased arrays*. Ultrasonics, 43 (3). pp. 183-195. doi:[10.1016/j.ultras.2004.04.006](https://doi.org/10.1016/j.ultras.2004.04.006)
- [3.3] Medley, A. P., Billson, D. R., Hutchins, D. A. and Davis, L. A. J. (2006) *Properties of an electrostatic transducer*. The Journal of the Acoustical Society of America, 120 (5). pp. 2658-2667. doi:[10.1121/1.2357702](https://doi.org/10.1121/1.2357702)
- [3.4] Medley, A. P., Billson, D. R., Hutchins, D. A. and Neild, A. (2007) *Acoustic fields of nonplanar radiators*. The Journal of the Acoustical Society of America, 122 (5). pp. 2587-2593. doi:[10.1121/1.2783117](https://doi.org/10.1121/1.2783117)

Patents

6 related patents were filed, including the following exemplars:

- [3.5] Billson, D. R. and Hutchins, D. A.: 'Electrostatic Audio Loudspeakers'. US Patent [US7095864B1](https://patents.google.com/patent/US7095864B1), August 2006 (granted in a further 4 patent offices)
- [3.6] Billson, D. R., Atkins, B. and Walsh, K.: 'Electrostatic transducer'. US Patent [US10785575B2](https://patents.google.com/patent/US10785575B2), September 2020 (UK IPO priority date February 2014, granted in a further 4 patent offices)
- [3.7] Billson, D. R., Atkins, B. and Walsh, K.: 'Improved Electrostatic Transducer'. EPO Patent [EP3105940B1](https://patents.google.com/patent/EP3105940B1) May 2019 (UK IPO priority date February 2014, granted in a further 4 patent offices)

Key Grant

[G1] Billson, D. R. (PI) and Hutchins, D. A. *Developing a new, global standard for delivering in-car entertainment in Partial Hybrid and Zero and Low Emission Electric Vehicles (PHEVs & ZLEVs)*. **Sponsor:** Innovate UK [\[48489\]](https://www.innovateuk.com/grants/48489) **Duration:** Jul 2020 – Sep 2021 **Award:** GBP372,246

4. Details of the impact (indicative maximum 750 words)Impact on commerce and the economy: a resounding success for a growing West Midlands firm

Billson and Hutchin's research into and early development of ultrasonic transducers played, and still plays, a key role in the success of Warwick Acoustics; in particular, the associated patents provided *"underlying commercial protections which enabled Warwick Acoustics to develop this disruptive audio technology further"* [5.1]. This 'disruptive' technology has allowed this promising West Midlands company to break into the highly saturated headphones market, dominated by giants such as Apple, Sony, Philips and JVC, with an exclusive offering. Based on the translation of fundamental research, WA have developed products that are technologically superior to those developed by firms with significantly larger R&D budgets. Once WA had proved out the potential of the technology and built an effective brand proposition, the firm was set to pursue development opportunities in the lucrative automotive industry, which spends USD8,000,000,000 a year on in-car entertainment [5.1].

Since 2016 WA has attracted an estimated GBP8,000,000 in funding for further R&D, including from Birmingham-based Mercia Fund Managers, who provide venture capital to businesses focused on innovative technologies, and Shenzhen listed Guoguang Electric Company Ltd of Guangzhou, China. In 2017, the company moved to a unit at the Motor Industry Research Association (MIRA) Science Park near Nuneaton, following 9 years at Warwick Science Park. In 2020 WA doubled both its office and production space (from 3,200 sq.ft to 7,000 sq.ft) and its engineering team (from 10 to 20), with further workforce growth expected. [5.1]

WA has two models of headphones: the Sonoma M1, released in May 2017 at a retail price of GBP4,995; and the flagship APERIO, released in October 2019 at a retail price of GBP20,000. The APERIO was designed to be the world's best headphone system, a claim supported by many awards and extensive industry praise (see *Impact on culture*). The first production run sold out within four weeks of release. Both models have over 70 distributors in 20 different countries, including the US, Japan, Germany and Australia. In June 2020, a 24k gold-plated APERIO, sold in the UK exclusively by Harrods in Knightsbridge for GBP30,000, was launched to much excitement [5.1].

Based on total sales, in the financial year 2019/20 there was a more than six-fold increase in revenue over the previous year [text removed for publication], despite the onset of the COVID-19 pandemic just six months after the APERIO's release. In 2020/21, WA is on-target to secure revenue of [text removed for publication] primarily through engineering services provided to the automotive industry, and this is expected to continue to grow exponentially in the coming years. The CEO of the business stated, *"While Warwick Acoustics' growth, commercial successes and innovation in the automotive sector are driven firmly by the company, these advancements would not have been possible without the basic research into electrostatic transducers by Dr Billson and the University of Warwick."* He added that Billson, who occupies a non-executive position on the board, remains *"important to the products and successes of the company"* [5.1].

Impact on innovation: ultrasonic technology in the automotive industry's 'green mobility' agenda

Warwick Acoustics' ultra-light (~20g), super-thin (~10mm), shape-versatile and multi-directional speaker system gives it significant advantages over traditional – and necessarily bulky – magnet/coil and conventional electrostatic sources. These characteristics, plus the fact that the technology is inexpensive to produce in any quantity, would suit a variety of applications, such as an in-car sound system, where a more personalised experience might mean drivers can still hear navigation instructions while passengers listen to music.

More important, though, is its reliability and recyclability: the technology is establishing itself as highly disruptive in the automotive audio market as it dovetails with the industry's 'green mobility' agenda which aims to reduce both air and noise pollution from transport, and to address climate change in the transport sector through mitigation and adaptation. The industry is investing billions

of pounds in environmentally and socially sustainable hybrid (PHEV) and full electric (BEV) vehicles. In order to minimise CO₂ emissions per km driven and make those vehicles attractive to consumers, new lightweight, power-efficient technology solutions are being sought for every system in the vehicle.

WA's audio solutions offer a number of key advantages which offer 'material and valuable savings' [5.1] for original equipment manufacturers (OEMs):

- A 50% weight saving and 75% power saving compared to other solutions. Put in context, a traditional audio system weighs up to 22kg, and will consume up to 2kW of power; a typical car weighs around 2,000kg and will have a battery pack of 30-100kWh. Light-weighting and energy efficiency are of high importance to an industry with constraints on carbon emissions, and these properties also result in a significantly extended range for electric vehicles.
- A group delay (a measurement, in seconds, of the time taken by the modulated signal to get through the system) that is an improvement of more than 20 times that of existing transducers, and dramatic improvements in signal purity, which are key requirements in noise cancellation and which are of ever-increasing relevance in quieter electric vehicles.
- No use of rare-earth metals, elimination of which is a major goal of car manufacturers committed to delivering on a 'green mobility' agenda. [5.1]

These USPs resulted in the award in 2020 of three Proof of Concept contracts by OEMs within the automotive sector in the EU and US, [text removed for publication] [5.1]. A GBP500,000 industry-facing grant from Innovate UK has attracted keen support from the automotive sector, [text removed for publication] [5.2].

Impact on culture and music industry: improving the listening experience for audiophiles and industry producers

Aimed at the high-end audiophile market, to date the Sonoma M1 and APERIO have won 14 and 5 awards respectively, from trendsetting audiophile magazines such as HiFi+, Absolute Sound and Tone Audio with a combined international readership of over 300,000 [5.1].

For Sonoma M1, these include the Haute Fidélité Référence Award, Tyll's Wall of Fame and Hi-Fi Choice Recommended status [5.1, 5.3]. Studio Magazin stated that "...the Model One headphone system...has achieved absolute perfection." HiFi Statement named the headphones "A new star in the sky of headphones!" and HiFi Choice awarded them 4.5/5 stars, saying, "The M1 delivers a high-end musical performance with a fantastic bass response, which is very extended and tuneful." TONE Audio concluded that: "The Model One might just be the best value in high-end audio today. Even those with mega systems will be amazed at what this system can do, revealing nuance and detail that can often be masked by the best of rooms" [5.3].

The APERIO model's high-profile awards include ToneAudio 2019 Product of the Year award, with TONE Audio's editor Jeff Dorgay stating: "Not only does it provide one of the world's finest personal audio experiences, it includes a world-class DAC and line preamplifier. In the end, one for the high-end audio's best value propositions" [5.3]. HiFi+ Magazine gave the system an Editors' Choice Award in 2020, with editor Chris Martens adding: "The APERIO is the finest headphone system I have ever had in my home, and also the finest I have ever heard (including some that cost far more than the APERIO does)" [5.3].

As a crowning achievement, in November 2020 audiophile legend David Robison of Positive Feedback gave the APERIO his 'very highest recommendation', explaining that:

*"There is no doubt about it in my mind: The Aperio Headphone Amp/up-to-DSD256 DAC/Preamp sets a new global standard for all headphone systems to aspire to. **This is world-class audio performance of the highest level of achievement**" [5.3].*

The Sonoma M1 and APERIO have garnered glowing praise from industry professionals such as Grammy Award-winning engineers Alan Silverman, David Hewitt and Bob Ludwig (the latter having worked with Bruce Springsteen, Queen, Jimi Hendrix and Daft Punk) [5.1].

Alan Silverman, owner of Aerial Sound in New York, says: *"After decades of work as a recording engineer there are very few memorable 'firsts' anymore, but my first listen to the APERIO was astonishing. The clarity and smoothness of the sound was something I could not have imagined... Listening to music with APERIO is a joy!"* [5.4].

Roy Hendrickson, veteran mixer, engineer and producer at BerkleeNYC, with 32 years' industry experience producing for the likes of David Bowie, John Lennon and Madonna, says: *"I really am so pleased with the Sonoma M1 headphone system, it's unbelievably honest and perfectly balanced. I have been able to hear elements to adjust in my mixes I would have missed in studio monitors... The Sonoma system is a breath of fresh air to my ears"* [5.4].

Bert van der Wolf, an award-winning director, producer and recording & balance engineer at Spirit of Turtle in the Netherlands, said about the APERIO: *"These are just ridiculously good. 100% accurate reproduction of what I recorded. I've never heard any headphone as brilliant as these, I did not think this level of honesty was even possible in a headphone!"* [5.4]

Warren Sokol, Mastering Engineer at the world-famous United Recording Studios, LA, who has recorded with the Foo Fighters and Iggy Pop, said: *"The APERIO is another level of headphone systems! The detail to design is impeccable, it's truly a beautiful package! The image & frequency response is amazing but I was really impressed with the speed & accuracy of the dynamics & detail of the sound!! How's it all packed in there?!?"* [5.4]

Michael Beinhorn, musician and Grammy-nominated music producer who played keyboards with Herbie Hancock on Future Shock and produced albums for Red Hot Chili Peppers, Aerosmith and Ozzy Osbourne, simply said after a two-hour session with the APERIO: *"Absolutely incredible, mind-blowing!"* [5.4]

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

[Note: Sonoma Acoustics is fully owned by Warwick Acoustics. They were selling the headphones, which is why they are mentioned in reviews. We have removed reference to them in the case study to avoid confusion]

[5.1] Statement from the CEO of Warwick Acoustics

[5.2] [text removed for publication]

[5.3] Awards and audio magazine editor praise - <https://warwickacoustics.com/reviews/> (selected awards and praise provided in PDF evidence)

[5.4] Praise from industry professionals - <https://warwickacoustics.com/headphones/studios/> (accessed 12.02.20)