Institution: BRUNEL UNIVERSITY (H0113)

Unit of Assessment: 12 Aeronautical, Mechanical, Chemical and Manufacturing Engineering

Title of case study: ROBUST DESIGN OF MICRO-SCALE PIEZOELECTRIC ACTUATORS

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

The research produced accurate simulation models of piezoelectric actuators for investigating sensitivities to parameter variations that led to maximum power for minimum electric field. This was the basis of design rules for determining new products at the industrial partner NXT, now named Hi-Wave Technology, headquartered in Cambourne, UK. Old design rules had led to two failed products whereas these new design rules have guided successful products with a major Japanese television manufacturer, a Japanese printer company and a Russian mobile phone company. Without this research Hi-Wave would have stopped activities in this technology. To date, licences for more than 24 million units per annum have been sold and more than 280,000 units manufactured.

2. Underpinning research (indicative maximum 500 words)

The research underpinning for this impact was carried out by Brunel University in collaboration with the London School of Economics, and supported by two grants from the EPSRC. Brunel managed the project, generated engineering simulation models and conducted experimental validations. The Brunel team comprised of Dr Mark Atherton (PI), Reader in Mechanical Engineering; Dr Matthew Oldfield, Research Fellow (2005-2007); and Dr Yijun Shen, Research Fellow (2004-2005). London School of Economics who contributed statistical methods to the sensitivity analyses, comprised of Professor Henry Wynn (PI), Professor of Statistics; Dr Mark Perry, Research Associate (2004-2006); and Dr Ron Bates, Research Associate (2007).

Piezoelectric materials (e.g. PZT-5H) are increasingly used as sensors and actuators due to their efficient coupling of energy in the electrical and mechanical domains. This project focused on Distributed Mode Actuators (DMA) that have begun to be used in televisions, tablet PCs and mobile phones for producing sound and haptic function. These small piezoelectric bimorph devices have several layers up to 100 microns thick and are highly modal, operating at frequency ranges unsupported by conventional excitation devices. This prevents the application of conventional modal analysis techniques. There is a scarcity of literature addressing modal validation of finite element (FE) models of bimorph devices that are both too small for well-established experimental techniques and too complex to be validated against 2D structural assumptions.

There are many complicating factors for an analytical prediction of the modes of a piezoelectric plate actuator (DMA): The plate is multilayered, coupling exists between the PZT material, applied voltage and mechanical behaviour and the influence of non-ideal boundary conditions is undetermined. The bimorph's scale makes it susceptible to production inaccuracies that would be within acceptable tolerances in a macro-scale device. Identifying and characterising these inaccuracies is critical to achieving validation, and illustrates the limitations of relying on FE or experimental results alone. 1D blocked force and 2D beam assumptions prove insufficient for validation due to modes both in the length and width of the device in operation.

Brunel developed a general method for validating simulation models of a device that is too small for conventional modal analysis excitation. This method is based on a simple and reliable measurement of the blocked force produced by the device rather than on measurements of surface velocity of the bimorph using a scanning vibrometer. The geometry of the device coupled with the self-actuation method requires the validation to be carried out in 3D. Only then is the model considered validated and suitable for subsequent FE experimentation on minor modifications to material and geometric properties. The lessons learned are universally applicable to the modelling of piezoelectric bimorph devices.

A finite-element-based formulation for sensitivity analysis studies of piezoelectric devices was also developed and an existing finite element piezoelectric solver was extended to implement its solution. The solver was applied to simulate the static operational and sensitivity characteristics of

a piezoelectric-based distributed mode actuator. The finite element sensitivity solutions were verified against empirical results obtained using the original system model. The sensitivity analysis was performed with respect to the material piezoelectric coupling parameters since it is these parameters that are subject to variability under operational conditions. As such, these sensitivity results are of interest from a robust design perspective.

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

- Perry, M., Bates, R.A., Wynn, H.P., Atherton, M.A., A finite element based formulation for sensitivity studies of piezoelectric systems, Smart Materials & Structures. Vol. 17(1), February 2008, 015015 (7pp). ISSN 0964-1726. http://dx.doi.org/10.1088/0964-1726/17/01/015015 .
- Oldfield, M.J., Atherton, M.A., Bates, R.A., Perry, M.A., Wynn, H.P., Modal validation of a cantilever plate MEMS piezoelectric actuator illustrating sensitivity to 3D characterisation, Electroceramics. Vol 25(1), August 2010, pp 45-55, ISSN: 1385-3449. http://dx.doi.org/10.1007/s10832-009-9587-6
- EPSRC GR/S63496/02, 2005-07, £116,004, Micro-scale Robust Engineering Design, PI: Dr M Atherton.
- EPSRC GR/S63496/01, 2004-05, £58,383, Micro-scale Robust Engineering Design, PI: Dr M Atherton.

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

Whereas previous design rules led to two failed products, the new design rules have informed a series of devices and products. Without the Brunel research this technology would have been dropped. Keeping the technology commercially viable led Hi-Wave to establish a subsidiary business unit in the UK called Redux Laboratories. Redux spun out from Hi-Wave in May 2013.

The sound pressure level of poorly designed phones is 10-15 dB lower than new designs based on the improved Brunel technology, which can be driven by 'real-world' electronics that enable maximum power transfer while minimising electrical field in the piezoactuator (DMA).

The follow-on is direct-drive technology using design rules developed from the original foundational design rules from this research.

There is a significant improvement in the environmental impact and energy usage in deploying these improved piezoelectric devices over conventional voice-coil loudspeakers, as they require much less electrical energy to operate, which for mobile phones means longer battery life and better user experience.

Without this project, the following opportunities would not have materialised.

Units made to date:

- DMA haptics $1.8M licence, signed with Nissha printing, Dec 2009. First product, Yota mobile phone. Estimated 10,000 units per annum; 40,000 in total.
- Toshiba 3D TV (model 12GL1), the World's first glasses-free 3D TV. Launched Dec 2010, 15,000 units sold. (http://www.hdtvtest.co.uk/news/toshiba-12gl1-glasses-free-3d-tv-20101222969.htm)
- Mobile phone, incorporating Redux/HiWave v2 DMAs, developed by Yota Corp, Oct 2011. 5,000 engineering samples sold.
- "Farina" personal audio headset developed and being commercialised by Hybra technologies and others. Released in 2013, estimated more than 250,000 units per annum.

Licensed units,

The product has been licensed to the following companies (names have been redacted)

- Company A: up to 10,000 units per annum, expected release late 2013.

- Company B: up to 20 million units per annum with next generation games machine. Release expected 2014.
- Company C: up to 2 million units per annum, release expected in 2014.
- Company D: up to 2 million units per annum, release anticipated in 2015.
- Company E has been engaged in discussions about a licensing agreement, with a release estimate 2015.

The current business strategy of Redux Laboratories is to concentrate their resources on the personal headset market.

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

- ***Press releases:***

Nissha licence 29/12/2009

http://uk.reuters.com/article/2008/12/29/uk-nxtplc-idUKTRE4BS18J20081229

HiWave launches 'soft tissue' conduction headset

http://www.trustnet.com/Investments/Article.aspx?id=201207260900015310I

- ***Trade articles on performance of devices**:*

Hybra Tech personal audio device, Jan 2010

http://deadsexymag.blogspot.co.uk/2010/01/orb-stylish-and-dead-sexy-gadget.html

- ***Patents**:*

Yota mobile phone incorporating DM: WO 2012/053939 A2

- ***Hi-Wave internal reports**:*

(a) Yota cell phone DMA Advance information. (DMA in Yota handset, designed along KPI parameters), July 2011.

(b) Farina presentation (DMA using KPI analysis), July 2012