Institution: Keele University

Unit of Assessment: UoA 10 Mathematics

Title of case study: The reduction of sound from aircraft engines

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

In response to many EU directives (e.g. 89/629/EEC, 2002/30/EC), and to the threat of financial penalties, the aircraft industry has long considered it a matter of the utmost importance to develop tools for the reduction of aircraft noise. Chapman's ray theory of aeroengine noise, created and developed in 1994-2000, provided such a tool. The impact of this work has extended through aircraft industry giants such as Rolls-Royce to consumers and the general public worldwide, because of its influence on the design of quieter aircraft.

Following application of the same theory to broadband underwater acoustics, the impact now extends to the government's plans for the next generation of nuclear submarines. This is a £25 billion project to design and build the Successor class, to replace the Vanguard class of Trident submarines. Chapman's ray theory has been used in the current Assessment Phase leading to Main Gate in 2016, when the Government will decide on production.

2. Underpinning research (indicative maximum 500 words)

The impetus to create a ray theory of aeroengine noise arose from two key aspects of the state of aircraft noise research in the early 1990's:

1. The prevailing theory of fan-generated sound in aeroengine ducts contained a fundamental error, in that sound rays were mistakenly believed to lie on smooth helices, rather like the stripes on a barber's pole, winding around a cylinder of fixed radius. In fact, the sound field has a very different structure.
2. Advances in theoretical understanding were urgently needed, for development and certification of new engines, to account for the high-frequency, short wavelength sound field produced by a rapidly rotating fan with many blades. Such fans were by then the norm in large high-bypass aeroengines, as used in all large commercial aircraft throughout the world.

The error (1) was catastrophic for prediction methods, because 'barber's pole' rays (if they really existed) would send net energy in the duct direction only, with no provision for the enormous sideways propagation of sound energy which actually occurs from the front face of an aeroengine. Although barber's-pole type rays do not exist, this did not stop sketches of them appearing in some research papers.

No real progress with research program (2) was possible until Chapman demonstrated that the sound rays are not smooth helices at all, but are piecewise-linear helices, consisting of a sequence of straight-line segments joined up at sharp corners. In consequence, the rays all have a sideways, i.e. radial, component in their direction. This fact has an enormous impact on the sound produced by an aircraft engine, because it implies that in an aeroengine duct the sound rays bounce repeatedly from the duct wall, to emerge from the front face of the duct at definite sideways angles, which Chapman calculated explicitly as a function of the parameters specifying the modes in the duct.

An immediate development was that within two years Chapman obtained a complete theory of aeroengine fan noise, which not only modelled the source of the noise on the fan, but also tracked the energy flow all the way through the duct and out into the far field, where the energy is perceived as noise. Within a few more years, Chapman elucidated various intricate patterns of focusing in the sound field, and his research student Hocter calculated many complete directivity patterns of aeroengine sound fields, hence determining the sound received in all directions from an aircraft.

The programme of research on aircraft engine noise occupied a major part of Chapman's research time as a Lecturer and then Reader at Keele University in the period 1994-2000, and resulted in his promotion to a Professorship. As part of this programme, Chapman supervised a PhD student, S. T. Hocter from 1996-1999, with funding provided by an EPSRC Doctoral Grant, to work on the sound radiation from the front face of the aeroengine duct. Also as part of the programme, Chapman supervised C. J. Powles, who obtained a Nuffield bursary in 2000 to work on energy paths within the duct. The following year, Powles began an EPSRC-funded PhD at Keele under Chapman's supervision, on the generation of sound rays by the leading edges of the fan blades in the duct, completing his PhD in 2004.

In the period 2010-2012, Chapman extended the theory to broadband noise in an MoD research project, with Thales Underwater Systems Ltd and other universities, on the next generation of nuclear submarines, the Successor class. The theory determines the ray directions of underwater sound from the propulsor.

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

JFM: Journal of Fluid Mechanics; JSV: Journal of Sound and Vibration; PRSLA: Proceedings of the Royal Society of London A.

C. J. Chapman 1994 Sound radiation from a cylindrical duct. Part I. Ray structure of the duct modes and of the external field. *JFM* **281**, *293-311*.
C. J. Chapman 1996 Sound radiation from a cylindrical duct. Part II. Source modelling, nil-shielding directions, and the open-to-ducted transfer function. *JFM* **313**, 367-380.
C. J. Chapman 1999 Caustics in cylindrical ducts. *PRSLA* **455**, *2529-2548.*
S. T. Hocter 1999 Sound radiation from a cylindrical duct. *PhD thesis, University of Keele.*
S. T. Hocter 1999 Exact and approximate directivity patterns of the sound radiated from a cylindrical duct. *JSV* **227**, *397-407.*
C. J. Chapman 2000 Similarity variables for sound radiation in a uniform flow. *JSV* **233**, *157-164.*
S. T. Hocter 2000 Sound radiated from a cylindrical duct with Keller's geometrical theory. *JSV* **231**, *1243-1256.*
S. T. Hocter 2000 Sound reflection into a cylindrical duct. *PRSLA* **456**, *2707-2716.*
C. J. Powles 2002 Energy paths in sound fields. *PRSLA* **458**, *841-855.*
C. J. Powles 2004 Supersonic leading-edge noise. *PhD thesis, University of Keele.*

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

The impact of this work has taken place via Rolls-Royce, the second largest maker of aircraft engines in the world, and a world leader in gas turbine technology, and via the MoD and Thales Underwater Systems. A large number of research contracts between Rolls-Royce and university research groups have exploited Chapman’s ray theory of aeroengine noise; this research has concerned the design of new aeroengines, and has greatly reduced the risk that certain types of aircraft might be banned. The work has also been exploited in EU projects arising from EU directives. The exploitation has taken place outside of Keele, most notably through the long-standing connections of Rolls-Royce with the Department of Applied Mathematics and Theoretical Physics, Cambridge University, and the Institute of Sound and Vibration, Southampton University. The exploitation in underwater acoustics took place via consultancy for the Successor class nuclear submarine project, initiated by DSTL, and led to the report Broadband Hydroacoustic Research (ref. 9).

Two recent articles co-authored by senior Rolls-Royce engineers are explicit about the impact of Chapman's work on noise reduction. The first, co-authored by Dr A. B. Parry, is the survey article `Modern Challenges Facing Turbomachinery Aeroacoustics', published in 2012 in the Annual Review of Fluid Mechanics (ref. 1). The second article, co-authored by Dr A. J. Kempton and published in 2010, is explicit about the way in which Chapman's work is needed for prediction of the far-field directivity of broadband noise using measurements made in the duct (ref. 2).

A world-class group which has exploited Chapman's ray theory is that led at Cambridge University by Professor N. Peake, working jointly with Rolls-Royce over a period of many years. The impact trail from Chapman's work to industrial practice in Rolls-Royce lies in a series of EPSRC CASE awards between Rolls-Royce and Cambridge University in which Chapman's ray theory explicitly plays an underpinning role. A long-lasting contact at Rolls-Royce is Dr A. B. Parry, an engineering specialist in aerothermal methods, aeroacoustics, and aerodynamics.

Full details of four of the above-mentioned research awards are given in refs. 2-6, in which the published papers noted refer to the collaboration with Rolls-Royce and explain the relation of the results to Chapman's work. These details provide the impact trail which leads from Chapman's work to Rolls-Royce. The young researchers who worked with N. Peake include E. J. Brambley, A. J. Cooper, C. J. Heaton, G. M. Keith, and B. Veitch. The areas investigated in these research projects were

1. Resonant phenomena in gas turbines,
2. Aeroacoustic models of fan noise,
3. Wave propagation and resonance in aeroengines,
4. Turbomachinery broadband noise.

The research awards cover the period 1998-2009. Given that Chapman's ray theory provides basic underpinning science, and aeroengine development is a long-term process, this continuity of use over an extended period is an essential part of the impact which the work has to the present day. In detail, the above research awards have led, via Chapman's ray theory, to advances at Rolls-Royce relating to the acoustic effects of

1. the rotor, stator, and guide vanes in the aeroengine duct;
2. the precise shape of the duct, including for example the non-circular cross-section, the curvature of the centre-line, the variation in duct-liner properties, and angling of the front face of the duct; and
3. the interaction of the effects in (1) and (2), which occurs because of scattering and diffraction.

Another world-class group which has disseminated Chapman's work to Rolls-Royce and the worldwide aircraft industry is the Rolls-Royce University Technology Centre in Gas Turbine Noise at Southampton University. This is housed in the Institute of Sound and Vibration Research (ISVR). The research workers there have made frequent use of Chapman's ray theory, often making use of Hocter's papers noted in Section 3, on sound radiation and reflection from the front face of the aeroengine duct. This contribution to Rolls-Royce's research is indicated in ref. 2.

A further dissemination route of Chapman's work has been directly to the European aircraft industry, via EU projects in Frameworks 5 and 6. The EU directives 2002/30/EC and 2002/49/EC were to reduce aircraft noise, and included the setting of noise standards. Two such projects were SILENCE(R), referring to Significantly Lower Community Exposure to Aircraft noise, and

MESSIAEN, referring to Methods for Efficient Simulation of Aircraft Engine Noise. Refs. 7-8 give published papers arising from these projects which refer to Chapman's ray theory and provide a link to the European aircraft industry.

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

ARFM: Annual Review of Fluid Mechanics; JFM: Journal of Fluid Mechanics; JSV: Journal of Sound and Vibration

1. *N. Peake & A. B. Parry 2012* Modern challenges facing turbomachinery aeroacoustics*. ARFM* **44***, 227-248.*
2. *C. R. Lowis, P. F. Joseph & A. J. Kempton 2010* Estimation of far-field directivity of broadband aeroengine fan noise using an in-duct axial microphone array. *JSV* **329***, 3940-3957.*
3. Rolls-Royce/EPSRC CASE award GR/L80317, 1998-2001. A mathematical investigation of resonant phenomena in gas turbines. *A. J. Cooper & N. Peake 2001, 2005 JFM* **445***, 207-234,* **523***, 219-250; N. Peake & A. J. Cooper 2001 JSV* ***243****, 381-401.*
4. Rolls-Royce/EPSRC CASE award GR/M21638/01, 1999-2002. Development and validation of aeroacoustic models for fan noise. *G. M. Keith & N. Peake 2002 JSV* **255***, 129-146, 147-160; C. J. Heaton & N. Peake 2005 JFM* **540***, 189-220.*
5. Rolls-Royce/EPSRC CASE award RG/42494, University Gas Turbine Research Partnership Programme, 2004-2007. Wave propagation and resonance in aeroengines. *E. J. Brambley & N. Peake 2008 JFM* **596***, 387-412.*
6. Rolls-Royce/EPSRC CASE award EP/D035031/1, 2006-2009. Mathematical modelling and computational engineering prediction of turbomachinery broadband noise. *B. Veitch & N. Peake 2008 JFM* **613***, 275-307.*
7. Rolls-Royce/EU-FP5 SILENCE(R) project, 2001-2005. Significantly lower community exposure to aircraft noise. *A. McAlpine, R. J. Astley, A. J. Kempton et. al. 2006 JSV* **294***, 780-806.*
8. Rolls-Royce/EU-FP6 MESSIAEN project 502938, 2003-2007. Methods for efficient simulation of aircraft engine noise. *G. G. Vilenskii & S. W. Rienstra 2007 JFM* **583***, 45-70.*
9. Thales Underwater Systems, project DSTlx-10062650/BHAR, 2010-2012. Broadband Hydroacoustic Research (Phase II). *D. Yumashev, I. D. Abrahams, C. J. Chapman et al. 2012, 1-47.*

Source to corroborate the impact of the work on Rolls-Royce and the aircraft industry: Engineering Specialist – Aerodynamics, Rolls-Royce plc.

Source to corroborate the spin-off impact on the submarine industry (defence work): Naval Systems Department, DSTL.

Source to corroborate the impact of the work on the European aircraft industry: Institute of Sound and Vibration Research, University of Southampton.

Source to corroborate the impact of the work on the aircraft industry: Centre for Mathematical Sciences, Cambridge University.