Institution:
University of Cambridge

Unit of Assessment:
UoA15

Title of case study:
The Inerter

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

The "Inerter" is a completely new mechanical device and suspension component that was conceived by Professor Malcolm Smith at University of Cambridge Department of Engineering (DoEng), as a result of his fundamental study of the possible behaviour of passive mechanical systems. Penske Racing Shocks purchased a license to produce versions of the Inerter for sale to Formula 1 (F1) teams and in IndyCar racing in 2008, once the Inerter's use in the McLaren cars that won 10 out of 15 races in the 2005 F1 season was widely known and McLaren's exclusive licence had lapsed. The use of the Inerter is now endemic in F1 and IndyCar racing.

2. Underpinning research (indicative maximum 500 words)

Professor Malcolm Smith became a lecturer in the University of Cambridge Department of Engineering (DoEng) in 1990 and was promoted to Professor in 2002. Following some consulting work on the control of active suspensions for a Formula 1 (F1) team in 1991-93, he initiated an academic research programme on active suspension systems. In 1994, active suspensions were banned in F1. This provided motivation for Smith to extend his fundamental academic work to the behaviour of passive mechanical systems with EPSRC support.

It is well-known that a circuit will be passive if its impedance is positive real. Furthermore, elegant circuit theory from the 1940s had shown that any such impedance could be realised by a network of resistors, inductors and capacitors. The standard analogy between electrical and mechanical circuits relates current to force and voltage to velocity, which then gives the following correspondences: spring with inductor; damper with resistor; and mass with capacitor. It was known, but only rarely mentioned, that the electrical-mechanical correspondence is not exact, because all the elements have two terminals except the mass, which has only one terminal and so really corresponds to a capacitor with one terminal connected to ground. Hence the elegant electrical circuit synthesis results could not be directly applied.

Smith observed that to complete the analogy there needed to be an element whose force was proportional to the relative acceleration between its two terminals. Smith's inventive step was to demonstrate that such a device could be constructed, whereupon a patent was filed by Cambridge Enterprise in 2001 [1] and later granted, and a paper was published in 2002 [2], describing a number of embodiments of the invention. This new component, coined the "Inerter", makes possible the physical realisation of any passive network impedance. In particular, it gives suspension designers an additional passive component, with very different characteristics to springs and dampers, which can be used to deliver enhanced performance.

Smith's further research, leading a team of Research Associates with EPSRC funding**, has developed theory on how to deploy Inerters in suspension systems to best advantage (e.g. [3-5]) and solved a number of fundamental open questions in circuit synthesis (e.g. classification of Ladenheim networks using a new concept of regularity [6], proof of necessity of the Bott-Duffin construction for circuit synthesis, and derivation of criteria for the required number of components of a given type).

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

[1] Patent. Smith, M.C., "Force-controlling mechanical device", US patent no: 7,316,303 granted 8 January 2008
[2]* Smith, M.C., "Synthesis of Mechanical Networks: The Inerter", IEEE Transactions on Automatic Control, Vol 47, No 10, pp 1648-1662, DOI: 10.1109/TAC.2002.803532, October 2002.
[3] Smith, M.C. and Wang, F-C., "Performance Benefits in Passive Vehicle Suspensions Employing Inerters", Vehicle System Dynamics, Vol 42, No 4, pp 235-257, DOI: 10.1080/00423110412331289871, 2004.
[4]* Scheibe, F. and Smith, M.C., "Analytical Solutions for Optimal Ride Comfort and Tyre Grip for Passive Vehicle Suspensions", Vehicle System Dynamics, Vol 47, No 10, pp 1229-1252, DOI:

10.1080/00423110802588323, 2009.
[5] Papageorgiou, C. and Smith, M.C., "Positive Real Synthesis using Matrix Inequalities for Mechanical Networks: Application to Vehicle Suspension", IEEE Trans. on Contr. Syst. Tech., Vol 14, No 3, pp 423-435, DOI: 10.1109/TCST.2005.863663, 2006.
[6]* Jiang, J.Z. and Smith, M.C., "Regular Positive-Real Functions and Five-Element Network Synthesis for Electrical and Mechanical Networks", IEEE Trans. on Automat. Contr., Vol 56, No 6, pp 1275-1290, DOI: 10.1109/TAC.2010.2077810, 2011.

* References which best reflect the quality of the underpinning research.

**EPSRC grants related to this research: "System design fundamentals for passive and active suspensions", 1996-1998, GBP80k; "The Inerter concept in mechanical networks: control, design and implementation", 2002-2004, GBP215k; "Theory and application of Inerters for mechanical control", 2008-2011, GBP290k; "Control for energy and sustainability", Programme Grant, 2009-2014, GBP5.5M (shared with Imperial College). Smith was the Principal Investigator for all these grants except the Programme Grant for which Professor RB Vinter at Imperial College was the Principal Investigator with Smith as the lead Co-Investigator for the University of Cambridge.

The Inerter invention and associated academic work has been widely recognised as a fundamental innovation. It has led directly to Smith delivering over 20 plenary, invited or named lectures since 2008 at many locations around the world including: Hyderabad, Kyoto, Budapest, Nanjing, Gent, Boston, Wuerzburg, Hong Kong, London, Tokyo, Oberwolfach, Toronto, Athens, Koblenz, Tel Aviv and elsewhere. Smith was elected to become a Fellow of the Royal Academy of Engineering and this research was referenced in his citation.

4.1 Context

In motor racing, car performance is ultimately limited by the ability of the car to grip the road while transferring power through the tyres, and suspension design is a critical area differentiating one team from another. Earlier innovations to improve grip, such as active suspension and tuned mass dampers had been developed, and in F1 were subsequently banned by the Federation Internationale de L'Automobile (the FIA: which is the governing body for world motor sport and the federation of the world's leading motoring organisations including F1 and the World Rally Championship). Nevertheless, the quest for competitive advantage in such a high-profile sport is unrelenting.

4.2 Technology transfer and development

Based on his previous experience with active suspension design in F1, Smith realised that the Inerter could give performance advantages in this area and in 2001 presented his work to McLaren Racing (with whom DoEng had an established relationship). Smith worked through Cambridge Enterprise to arrange a joint development agreement granting exclusive rights in F1 to McLaren in 2002 for a limited period. Understanding how to make optimal use of one or more Inerters required extensive analysis, simulation, experimentation and track testing. It was also necessary to develop light-weight and reliable components. In due course, a clear lap-time advantage was demonstrated by the McLaren team with Smith working as a consultant.

4.3 Significance of the Inerter

The first use of an Inerter in an F1 race was in Kimi Raikkonen's McLaren MP4-20 at the 2005 Spanish Grand Prix which he won. McLaren cars then won 10 of the remaining 15 races of the 2005 season. The significance of the invention is further evidenced by McLaren's efforts to keep it secret under the code name "J-damper", the efforts of others to discover the design and use of this new component, and the subsequent case of spying brought by McLaren against the Renault engineering team in 2007. This spying case also shows the radical and subtle nature of the invention, because the FIA found that "*Renault fundamentally misunderstood the operation of the system"* even after seeing the drawings for the J-damper (Paragraph 8.7, FIA World Motor Sport Council Decision, 7 December 2007).

4.4 Impact from 2008

During the December 2007 hearing, neither the World Motor Sport Council nor McLaren made

public what the J-damper was. Thereafter, speculation increased on internet sites and blogs about the function and purpose of the device and there were many amusing and erroneous guesses. Finally, the truth was discovered by a motor sport correspondent from the Autosport magazine, Craig Scarborough. Autosport ran an article on May 29, 2008, page 33, *"Mark Hughes on... A genius idea, and why McLaren hasn't tried to stop others using it"*, which revealed the Cambridge connection and that the J-damper was an Inerter. The exclusive license with McLaren was then allowed to lapse and, in 2008, Penske Racing Shocks was granted a non-exclusive license to design, develop, and produce generic and team specific Inerter designs as well as future embodiments and enhancements. To quote from the Penske Racing Shocks press release [7]: *"The benefit of the Inerter to the handling characteristics of all racing vehicles is undeniable in both theory and practice. We are confident that the ingenuity of Cambridge now combined with Penske product quality, performance, and customer service, will promote greater exposure of the Inerter in Motorsport."*

Publicity about the Inerter and its use in motorsport has continued at a high level in the popular press and magazines [8, 9]. The Inerter featured in a report by the IEEE Control Systems Society presenting success stories in control engineering [10]. At the same time, its use has spread beyond the F1 grid to IndyCars and several other formulas (with customer names remaining confidential in many cases). Cambridge Enterprise is receiving royalties for direct licenses from several F1 teams and, through Penske, from several more (the values remain confidential). It is widely assumed that all 12 current F1 teams are using Inerters [11].

The Inerter is now permitted in the IndyCar Series Rule Book [12] with certain packaging constraints and Cambridge Enterprise is receiving royalties from Penske and another licensed supplier of Inerters, GWC Engineering, from a majority of the IndyCar teams. Royalties are also being received from Penske from a number of customers in different domains of motorsport outside of F1 and IndyCars, with details largely very confidential. Penske has continued a strong development programme in collaboration with Cambridge. In 2011, Penske launched a new product, which was covered in the technical press [13].

To quote from Penske's Director of Research and Development [14], *"Developing the use of Inerters in racing with Dr. Smith and Cambridge University has helped Penske Racing Shocks to increase our market share within the our industry, and significantly increase overall sales. The use of Inerters in race car suspension design has helped our customers to both increase grip levels and platform stability at the same time making this development a necessity to be competitive in many racing formulae."*

To quote from the McLaren Head of Vehicle Dynamics [15]: *"In McLaren Racing we have worked with Prof Malcolm Smith since 2001 when he first introduced us to the concept of suspension networks containing the Inerter. Prof Smith's work in this area was completely new at the time, so far as we know, and we worked with him for a number of years to understand the technology and optimise the Inerter for use in Formula One. We successfully applied the system to our Formula One cars and we understand it has also been used by many other Formula One teams. It has been very satisfying to see a technology born out of a highly academic study of passive electrical and mechanical networks turn into a tangible benefit in Formula One suspension."*

The significance of this work is summarised by the Technical Advisor to the President of the FIA, 2006 to 2010 [16], *"The Inerter was the outstanding technical advance that came to my attention while at the FIA. There were many clever improvements and refinements of technology every year in Formula One, but the Inerter stood apart in that it was totally new thinking coupled with real potential benefit for the automotive industry. Suspension systems although infinite in variety had always depended on springs and dampers to determine their characteristics. The Inerter allows a new fundamental component to be added. Electronics without a capacitor would be rather stunted, now suspension designers have a previously missing component."*

The significance is further underlined by Paddy Lowe, who was Engineering Director (2005-2011) and then Technical Director (2011-2013) at McLaren Racing, before becoming Executive Director

(Technical) at Mercedes Grand Prix (2013-), "*The Inerter was first introduced to F1 in 2005 and has become a standard element of F1 suspension systems, now of equal rank to the spring and the damper in our constant search for higher levels of grip and stability.*"

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

[7] Penske press release, "Penske Racing Shocks to supply Cambridge Inerter technology in F1", 19 August, 2008 (http://www.penskeshocks.com/PRESS_2008-08-19.php)
[8] "Ingenuity still brings success in Formula 1", Grandprix.com, http://www.grandprix.com/ns/ns20669.html
[9] "Toyota's Secret F1 Car", cover feature in Racecar Engineering (July 2010, Vol 20, No 7, pages 12-18)
[10] "Control for Formula One!", *The Impact of Control Technology*, T. Samad and A.M. Annaswamy (eds.), IEEE Control Systems Society, 2011, available at http://ieeecss.org/sites/ieeecss.org/files/documents/IoCT-Part2-14FormulaOne-LR.pdf
[11] "The Science of Formula 1 design" by David Tremayne, Haynes Publishing, 2009. Discusses the development and deployment of the Inerter (J-damper) in F1 racing, pages 131-4 and 186.
[12] 2013 IZOD IndyCar Series Rule Book, https://hardcards.indycar.com/Resources/pdfs/2013_IICS_Rulebook.pdf
[13] "Shocks to the system: three years on from the J-damper story Penske Racing Shocks announces its hybrid damper/Inerter for wider application", Simon McBeath, Racecar Engineering, November 2011, pages 51-56
[14] Statement received from Director of Research and Development, Penske Racing Shocks.
[15] Statement received from Head of Vehicle Dynamics, McLaren Racing.
[16] Statement received from the Technical Advisor to the President of the FIA, 2006 to 2010.
[17] Statement received from Mr Paddy Lowe, Executive Director (Technical) at Mercedes Grand Prix (who gave permission to be named).