Institution: Loughborough University

Unit of Assessment: B12 Aeronautical, Mechanical, Chemical and Manufacturing Engineering

Title of case study: Drivetrain noise and vibration refinement for automotive applications

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

Reducing vehicle noise and vibration is a key quality objective in the automotive industry. Historically, the approach has been costly palliation late in the manufacturing process; now a new approach applied earlier in the vehicle development cycle has been devised by Loughborough University and Ford and implemented at Ford that has led to savings of $7 per vehicle with respect to clutch in-cycle vibration (whoop). Ford has reported savings of $10M over 5 years, whilst reductions in transmission rattle have led to 5% fuel efficiency gains **[5.1]**. Ford has made an investment of £240M in its engine and transmission work at Bridgend, which includes aspects of work reported here and has created 600 new jobs **[5.2]**.

2. Underpinning research (indicative maximum 500 words)

Fuel efficiency and reduced emissions are key drivers for vehicle development, whilst customer-driven demand is for improved efficiency and enhanced performance. These conflicting requirements lead to higher levels of noise, vibration and harshness (NVH) **[3.1, 3.2]**. In the 1990s, the industry was unprepared to deal with this in a fundamental, scientific and cost effective manner. Ford, the UK's leading volume manufacturer (19% of the UK market) had the vision to develop a fundamental and generic approach to powertrain refinement, dealing with specific concerns such as clutch take-up judder **[3.4]**, in-cycle vibration (whoop) **[3.3]**, driveline shuffle and elasto-acoustic response (clonk) **[3.5, G3.1]** and transmission rattle **[3.1,3.6]**. Under the auspices of the then Vice President of Ford Global Development, Richard Parry-Jones, a team of Ford specialists, led by Michael Menday and Patrick Kelly, joined a programme of research with Homer Rahnejat (at the University of Bradford from 1996 and at Loughborough University since 2000) with the objectives of developing an overall methodology for refinement and then specifically reducing NVH issues. The research spanned 1996-2010, with a methodology being developed and applied by Ford since 2008, including palliation of: (i)- whoop in Fiesta, Focus and Galaxy (since 2008) and in all Fiesta 3-cylinder Ecoboost (since 2012), Ecosport models (2013) and planned for new Ka model (2015), (ii)- Gear rattle palliation in all low cost diesels; Fiesta and 1.6 Ltr. Focus (2010) and 1.5 Ltr. Diesel (2013). Prior to 2010, the concepts were also used by companies belonging to the Premier Automotive Group (PAG), viz. Ford, Jaguar, Land Rover, Lincoln, Mercury, Aston Martin and Volvo. The PAG was dissolved in 2010.

The 2-phase approach included: (1) down-cascading from system level (vehicle) to rig-based correlation, multi-scale multi-physics modelling and definition of performance metrics, and (2) up-cascading from metrics to component and system level implementation. This approach yielded many beneficial impacts (section 4).

The multi-scale, multi-physics approach integrated constrained Lagrangian dynamics, modal analysis and elasto-acoustic coincidence (using inverse boundary element method) with contact mechanics, with elastohydrodynamics of concentrated contacts or lightly loaded hydrodynamics **[3.1,G3.2-G3.4]**. It dealt with refinement issues, integrated with other vehicle measures. The approach was combined with vehicle measurements: acoustic evaluation and laser vibrometry **[3.1]**.

All the NVH research was led by Rahnejat (Loughborough, 2000 – to date) and Kelly and Menday (Ford). For whoop there was extended collaboration with Prof. Biermann (Aachen) within a research consortium that included the companies Raybestos and Fichtel & Sachs. For transmission rattle, the research team at Loughborough included Theodossiades (Reader, 2002 – to date), King (Senior Lecturer, 1989 – to date) and Rothberg (Professor, 1990 – to date) together with the companies AVL, Getrag and GKN. For shuffle, clonk, and rattle, the researchers included

Mavros (Research Associate, 2004-2005, now Senior Lecturer), Kushwaha (Research Fellow, 2001-2004, now at Magna), Gnanakumarr (PhD student: 2001-2005, Research Associate: 2009-2011, now at Ford), Perera (PhD student: 2004-2007, Research Associate: 2009-2010, now at Bentley), Tangasawi (PhD student, 2006-2011, now at AVL), Centea (PhD student, Bradford: 1997-1999, now at McMaster) whilst the consortium included Mechanical Dynamics, UK.

3. References to the research (indicative maximum of six references)
Note: The overall methodology, described in section 2, culminated in the publication of a reference volume with worldwide participation from academe and industry, under the editorship of Homer Rahnejat (2010) who also contributed 8 out of 33 chapters; this is 3.1 below.

For all NVH Phenomena

[3.1]: H. Rahnejat (Editor)
***Tribology and Dynamics of Engine and Powertrains: Fundamentals, Applications and Future Trends,* Woodhead Publishing, Cambridge, 2010 1056 pp. (ISBN 978-1-84569-361-9 online version ISBN 978-1-84569-993-2)**

In its Introduction, Prof. Richard Parry-Jones CBE FREng (Chief Technical Officer and Head of Global R&D Operations for Ford worldwide until retirement in 2007 and now Co-Chairman of Automotive Council, Department for Business, Innovations and Skills) wrote: "*The book covers many important practical engineering and technological issues that the industry faces in design and development today and into the future. .... established academics and promising researchers make this a rather unique and comprehensive volume"*. In the preface, Prof. Duncan Dowson CBE FRS FREng (Past President of IMechE and pioneer of the field of tribology) noted: "*This is a fascinating and comprehensive book on current developments in the fields of tribology and multi-body dynamics related to vehicle problems".* This volume includes key outputs from all the refinement concerns and impacts made.

[3.2]: H. Rahnejat and S.J. Rothberg (Editors)
Multi-body Dynamics: Monitoring and Simulation Techniques, Professional Engineering Publishing (IMechE), **2004** 522 pp. (ISBN 1 86058 463 2)

This was an earlier volume, also containing applications of the overall methodology. It was edited by Rahnejat and Rothberg and resulted from the 3rd International Symposium on Multi-Body Dynamics, held at Loughborough University in July 2004.

For clutch vibration problems (judder and whoop)

[3.3]: M. Kushwaha, S. Gupta, P. Kelly and H. Rahnejat, "Elasto-multi-body dynamics of a multicylinder internal combustion engine", *Proc. Inst. Mech. Engrs., J. Multi-body Dynamics*, **216** (2002) 281-293 (doi: 10.1243/146441902320992374), Journal Impact factor: 0.721

[3.4]: D. Centea, H. Rahnejat and M.T. Menday, "Non-linear multi-body dynamic analysis for the study of clutch torsional vibrations (Judder)", *Applied Mathematical Modelling,* 25 [3] (2001) 177-192 (doi:10.1016/S0307-904X(00)00051-2). Journal Impact Factor: 1.706

For driveline elasto-acoustic coupling (clonk)

[3.5]: S. Theodossiades, M.M. Gnanakumarr, H. Rahnejat and M. Menday, "Mode identification in impact-induced high-frequency vehicular driveline vibrations using an elasto-multi-body dynamics approach", *Proceedings of the Institution of Mechanical Engineers, Part K: Journal of Multi-body Dynamics*, **218** [2] (2004) 81-94 (doi: 10.1243/146441904323074549). Journal Impact Factor: 0.721

For transmission rattle

[3.6]: S. Theodossiades, O. Tangasawi and H. Rahnejat, "Gear teeth impacts in

hydrodynamic conjunctions promoting idle gear rattle", *Journal of Sound and Vibration,* 303 [3] (2007) 632-658, (doi:10.1016/j.jsv.2007.01.034) Journal Impact Factor: 1.613

Grants: These NVH phenomena were investigated under various research grants and contracts, a representative sample of which are highlighted below:

For Driveline shuffle and clonk

G3.1: *OPTRAREF*; EPSRC/DTI Foresight Vehicle with Ford & Mechanical Dynamics; 2000-2004; £286,000 (from all sources), Rahnejat (PI)

For Transmission rattle

G3.2: *Automotive Transmission Rattle: Root Causes to Innovative Solutions*; Rahnejat (PI), Rothberg, Theodossiades and King; EPSRC with Ford, Getrag, GKN & AVL; 2006-2010; £205,000 (EPSRC) + £42,500 (Ford) plus in kind contributions.

G3.3: *Transmission Drive Rattle*; Rahnejat (PI), Rothberg, Theodossiades & King; Ford University Research Program; 2007-2010; £72,000.

G3.4: KTP for transmission refinement; Theodossiades, Rahnejat & King; DTI/TSB and Romax Technology; 2007-2009; £199,000.

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

(a) General Impact

The research outcomes were first adopted by Ford Motor Company, the primary sponsor of the work (specific details below). The overall methodology has also been adopted globally, with specific aspects reported by Mitsubishi, Japan (vibro-acoustic approach and metrics for evaluation of their gear rattle research, using the methodology in **[3.6]**) **[5.3]**; AVL, Slovenia (multi-body dynamic analysis with interfacial clutch friction model for their dual clutch transmissions assessment, using the methodology in **[3.4]**) **[5.4]**; DAF Trucks, Netherlands (friction and clamp load characteristics in their clutch control work, using the methodology in **[3.4]**) **[5.5]** and Valeo Transmissions, France (gear teeth impact force analysis and clutch interfacial friction representation for their drivetrain R&D, using the methodology in **[3.6]**) **[5.6]**. There have been many other industrial and university teams who have adopted various aspects of the described methodology; this has led to ~300 citations since 2000.

Graham Hoare (Vice President and Head of Ford Research and Development Centre, Dunton, Essex) has stated: "*Long term collaborative research between Ford and Loughborough's Dynamics Research [Group] has brought understanding and direct vehicle improvements with respect to NVH refinement as outlined in this impact case study*". **[5.7]**

(b) Specific impacts

Specific impacts made with respect to three NVH aspects mentioned in section 2 are:

1) Clutch in-cycle vibration (whoop):

Loughborough research identified the root cause of whoop as increased flywheel conical whirl with crankshaft flexibility because of the use of materials of lower elastic modulus alongside increased combustion power **[3.3]**. The impact of the flywheel on the clutch system during pedal actuation induced natural mode vibration of the clutch lever assembly. A mass-damper, known as the "Diehl fix", was traditionally empirically used as a method of palliation but this added 1-2 kg to the clutch weight, occupied 100-200 cm^3 in the engine compartment and had an associated cost of $7 per vehicle over an annual production volume of 2 million vehicles Using the Loughborough methodology, optimisation of the clutch cover compliance **[3.3]** eliminated whoop and the need for

the Diehl fix, saving $7 per vehicle. The solution was implemented in a range of new Ford models including the popular Fiesta and Focus brands from 2004 onwards. The modified vehicles used 4-cylinder, 1.8 litre diesels with manual transmissions. The implementation work is ongoing for other vehicle models. Ford has reported savings, conservatively put, at $10 M **[5.1]**.

(2) Driveline elasto-acoustic response (clonk):

Impulsive loading of the powertrain occurs with sudden throttle tip-in or back-out, or by abrupt release of the clutch pedal. These induce shock wave propagation onto hollow thin-walled driveshaft tubes **[3.5]**, causing elasto-acoustic response up to an unacceptable 110 dB(A). The most cost effective solution, involving spun cardboard fitted liners, has been implemented in some light trucks, vans and SUVs including some Transit models, Galaxy and Escort vans from 2004 to the present day. Technically, there is a noise level reduction of 10-20 dB(A) and improved sound quality through reduced high frequency sharp spectral content **[3.1]**.

(3) Transmission rattle:

The fundamental research through to technological innovations carried out by Ford and Loughborough for palliation of transmission rattle (2006-2010) has already resulted in the development of light weight, NVH refined, fuel efficient transmissions, including:

- 5/6 speed manual transmission (MX65) with a 5 kg reduced mass and 5% improved fuel efficiency meeting the research specified metric of impulsion ratio not exceeding unity.
- 7 speed manual transmission (MT90c) with reduced 2 dBA noise level and 5% fuel efficiency gain.
- Ford has invested in volume manufacture of these transmissions with an investment of £240 M in the UK at Bridgend **[5.2]**.

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

The following sources can be made available at request:

[5.1]: Letter by Technical Specialist – Global Transmission and Clutch Systems, Ford, November 2013
[5.2]: http://www.dailymail.co.uk/news/article-20576/Car-giants-invest-millions-UK-plants.html
[5.3]: K. Ohta *et al* , "Vibration Response and Noise Radiation of Engine Block Coupled with the Rotating Crankshaft and Gear Train", Journal of Environment and Engineering, 6(4), 2011, pp. 765-777, http://dx.doi.org/10.1299/jee.6.765: Work reported by Mitsubishi, Japan
[5.4]: T. Petrun *et al,* "A friction model for dynamic analyses of multi-body systems with a fully function clutch", Proc. IMechE, Journal of Multi-body Dynamics, 227(2), 2013, pp. 89-105, doi: 10.1177/1464419312464708: Work reported by AVL, Slovenia
[5.5]: G. Naus *et al,* "Robust control to suppress clutch judder", 9th International Symposium on Advanced Vehicle Control, Kobe, Japan, 2008: Work reported by DAF Trucks, Eindhoven, The Netherlands
[5.6]: S. Sfarni *et al,* "Finite element analysis of automotive cushion discs", Thin-Walled Structures, 47(4), 2009, pp. 474-483, Work reported by Valeo, France
[5.7]: Letter by Vice President of Ford Product Development, November 2013