Institution: Keele University

Unit of Assessment: B10 Mathematical Sciences

Title of case study: Modelling and control of curve squeal

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

Rail transport is the greenest form of transport in that it produces the least pollution of the environment. However, the noise from squealing trains has been a major factor preventing the wider use of rail transport in populated areas, especially in cities, where trains have to traverse tight curves in built-up areas. Research carried out at Keele University on curve squeal gave crucial input to developing an effective control method (KELTRACK friction modifier, developed by the company LB Foster Friction Management). This is a device by which a thin film is applied at the wheel-rail interface, which in turn destroys the generation mechanism of curve squeal. The KELTRACK friction modifier is now used in transport systems all over the world, especially in underground systems, such as the metros of Tokyo, Beijing and Madrid.

2. Underpinning research (indicative maximum 500 words)

The research that provided the basis for this impact was carried out at Keele University from 1993 to 1999. It was initially funded by the EPSRC (£ 94,726 on 'Development of active control of wheel squeal from a nonlinear dynamical systems analysis', grant number GR/H73776). The key researchers were: Dr Maria A. Heckl (principal investigator, at Keele since 1992), Professor I. David Abrahams (co-investigator, at Keele until January 1998), Dr Xiao Yang Huang (researcher from Singapore, visiting Keele for 4 weeks in May/June 1993).

Curve squeal is the noise produced by train wheels when they traverse a tight curve, giving rise to a lateral friction force in the wheel-rail contact point. This friction force excites bending oscillations of the wheels, which in turn affect the friction force, and this feedback is responsible for high-amplitude wheel oscillations that are radiated into the environment as high-amplitude sound waves. We developed a sophisticated mathematical model to understand in detail the physical mechanisms that play a key role in the generation of squeal. Our work was published in a series of three papers in 2000, and their content is summarized below.

Our mathematical model is described in Heckl and Abrahams (2000). The train wheel is modelled as an annular disc (Kirchhoff plate) with a hub in the centre; the friction force between rail and wheel is modelled by a stick/slip friction characteristic, which is nonlinear. We developed a Green's function approach, which can deal with this nonlinearity and predict the time-history of the velocity of an individual wheel. This allows one to identify the stability behaviour, transient oscillations, limit cycles and other nonlinear features that lead to wheel squeal. In Heckl (2000), we use this model to make predictions about the dynamics of individual wheel modes. Typically only one wheel mode is unstable, and we determined which wheel properties make that mode unstable. In Heckl and Huang (2000), we extended our mathematical model to incorporate an active control system. The effect of key control parameters was predicted, and the parameter range was identified, where an unstable mode could be successfully controlled. We verified our findings with a laboratory test rig.

The idea of modelling a feedback instability by a Green's function approach works not just for a friction-driven instability such as squeal. The underpinning research in train wheel squeal has led to its application in thermo-acoustic instabilities, which occur in certain combustion systems, in particular gas turbine engines. Such instabilities can lead to catastrophic engine failure and are a serious problem in the development of clean combustion technologies. Building on our experience gained in the squeal project, we have managed to secure two major European grants (LIMOUSINE and TANGO) for collaborative research in this area.

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

Heckl, Maria A. & Abrahams, I.D. (2000) Curve squeal of train wheels, Part 1: Mathematical model for its generation. *Journal of Sound and Vibration* 229, 669-693.
DOI: **10.1006/jsvi.1999.2510**

Heckl, Maria A. (2000) Curve squeal of train wheels, Part 2: Which wheel modes are prone to squeal? *Journal of Sound and Vibration* 229, 695-707.
DOI: **10.1006/jsvi.1999.2511**

Heckl, Maria A. & Huang, X.Y. (2000) Curve squeal of train wheels, Part 3: Active control. *Journal of Sound and Vibration* 229, 709-735.
DOI: **10.1006/jsvi.1999.2512**

The Journal of Sound and Vibration (JSV) is an established international journal with an impact factor of 1.588, publishing 50 issues per year.

Grants:

£ 94,726 from EPSRC for research on 'Development of active control of wheel squeal from a nonlinear dynamical systems analysis'. Principal investigator: Maria A. Heckl, co-investigator: I. David Abrahams. 1993-1996.

€ 876,858 from the European Commission (FP7) for the Marie Curie Initial Training Network LIMOUSINE (Limit cycles of thermo-acoustic oscillations in gas turbine combustors). Deputy Coordinator: Maria Heckl. The total award for all partners in the network was € 4.1 million. 2008-2012.

€ 3.73 million from the European Commission (FP7) for the Marie Curie Initial Training Network TANGO (Thermo-acoustic and aero-acoustic nonlinearities in green combustors with orifice structures). Coordinator: Maria Heckl. The award for the activities at Keele is € 1.13 Million. 2012–2016

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

Researchers, both academic and industrial, from all over the world (Netherlands, Belgium, Italy, France, USA, Canada, India, Korea) made use of our work as evidenced from the citations made to our papers listed above. One paper that cited our work is by a group in the Vancouver-based company LB Foster Friction Management.

Eadie D.T., Santoro M. and Kalousek J. (2005) Railway noise and the effect of top of rail liquid friction modifiers: changes in sound and vibration spectral distributions in curves. *Wear* 258, 1148-1155.

LB Foster used our work to gain crucial insight into the fundamental mechanisms of wheel squeal, in particular the role of stick slip and the shape of the traction-creepage curve. Armed with this insight, they developed a commercial product, the KELTRACK ® Top of Rail Friction Modifier, which has revolutionised the wheel/rail interface dynamics and has achieved unsurpassed reduction of squeal noise. http://www.lbfoster.co.uk/_pdf/Portec-Keltrack.pdf

KELTRACK is a water-based suspension of proprietary solids, which is pumped to the top of the rail by a trackside delivery system, prior to a curve where squeal is of particular concern. The water component evaporates and the material remains as a thin dry film. This film alters the coefficient of friction to a value between that of dry friction and that of a lubricated contact, and hence changes the lateral friction force between wheel and rail. In this way, the stick/slip feedback between wheel oscillations and friction force is disrupted, i.e. the mechanism that generated the squeal noise has been deactivated. This technique allows KELTRACK to dramatically reduce squeal noise as trains negotiate a curve. The noise abatement levels (up to 27 dB) are almost immediate. Other benefits (not found in traditional lubricants such as oil or grease) of this system include reduced lateral forces, reduced wear, decreased potential for derailment, no effect on traction and breaking, environmentally safe (non-contaminating).

The Top of Rail Friction Modifier is now used on railways around the world, for example on Tokyo Metro, Beijing Metro, New York City Transit Authority, Madrid Metro and numerous others which transport billions of passengers daily. Within the UK, KELTRACK is applied on London Underground, and on sites on Network Rail. For example there are a number of application systems controlling curve squeal around Euston Station in London. (see the e-mail by Dr Don Eadie, Vice President, Technology and Innovation, LB Foster Friction Management dated 6 June 2012). The impact world-wide has been and continues to be massive, benefitting millions of commuters and city-dwellers.

Another paper that cited our work was produced by a European research consortium focussing on active squeal attenuation.

Cigada, A. Fehren, H., Manzoni, S., Redaelli, M., Schiedewitz, M. and Siebald, H. (2008) Investigations on the attenuation of squeal noise from a resilient railway wheel by means of piezo-actuators. Proceedings of ISMA 2008, 2709-2723.

Cigada et al applied our work within the FP6 – funded project InMAR (Intelligent Materials for Active Noise Reduction, see http://www.inmar.info/start.htm). In an e-mail dated 29/6/2012, they write "we have studied your research in order to fully comprehend the squeal phenomenon and its generation mechanism and to find suggestions on the way to actively control it. Finally we have been able to control squeal". One of the partners of the InMAR consortium was the company ERAS GmbH (Göttingen, Germany), which has a commercial interest in controlling squeal noise (and other unwanted vibrations) by active methods.

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

The Vice President, Technology and Innovation at LB Foster Friction Management, Canada, can corroborate the claim that LB Foster have gained valuable insight through our work and that this was crucial for the development of their KELTRACK ® Top of Rail Friction Modifier, which now controls curve squeal in public transport systems around the world.

An Associate Professor at Politecnico di Milano can corroborate the claim that my work was used in the FP6 – funded project InMAR to develop an active squeal control method.