Institution: Keele University

Unit of Assessment: UoA10 Mathematical Sciences

Title of case study: Advanced mathematical modelling of longitudinal forces in freight trains

Period when the underpinning research was undertaken: 2013-2019

Details of staff conducting the underpinning research from the submitting unit:

Name(s):	Role(s) (e.g. job title):	Period(s) employed by submitting HEI:
Prof Julius Kaplunov	Professor	2012 – present
Prof Graham Rogerson	Professor	2006 - 2019
Prof Peter Andras	Professor	2014 - present
Dr Danila Prikazchikov	Senior Lecturer	2013 - present
Dr Liudmila Prikazchikova	Lecturer	2015 - present

Period when the claimed impact occurred: 2013-2019

Is this case study continued from a case study submitted in 2014? N

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

Keele Applied Mathematics (KAM) group's world-class expertise in the mathematical modelling of elastic structures has been applied in a programme of collaborative research and knowledge exchange with industrial partners, Amsted Rail and GHD, resulting in a new methodology for computing longitudinal forces between freight cars. This methodology has been incorporated by Amsted into a comprehensive software package as part of a product offering. It has provided major corrections to the evaluated longitudinal forces in about 6-8% of the analysed operational scenarios, thus reducing the risk of derailment. The evaluative methodology has also been implemented within a US patent.

2. Underpinning research (indicative maximum 500 words)

Much of the underpinning research was developed through an industrial partnership with Amsted Rail (2013-2019). The original technical problem in railway engineering was concerned with the mathematical modelling of longitudinal forces in freight cars. This was subsequently generalised by Keele's Applied Mathematicians (KAM), and finally resolved in a revised concept of 'almost rigid body motion'. This revised concept was built on the evaluation of low-frequency corrections to conventional computational models in which freight cars are modelled as rigid bodies governed by Newton's second law. Keele's revised concept allows for the incorporation of several key features in the evaluation of longitudinal forces, including the effect of self-equilibrated end loads as well as internal energy dissipation, deformability and inhomogeneity of freight cars.

The new underpinning methodology is within the mainstream of the research activities of KAM, including Prof. Kaplunov, Dr Prikazchikov, Dr Prikazchikova and Prof. Rogerson, which is concerned with multiscale modelling of deformable structures; and is also aligned to world-leading research on various modifications of Newton's second law (e.g., the influential work of G.W. Milton and J.R. Willis, Proc. R. Soc. A 463 (2007)). However, in contrast to previous work on high-frequency phenomena, notably micro-resonances, the focus of Keele's research group is explicit low-frequency refinements to rigid-body models, as required for railway engineering.

The new procedure was presented in [1] (see also [2]) dealing with low-frequency motions of an inhomogeneous viscoelastic bar. A perturbation scheme was developed for general constitutive relations in linear viscoelasticity. In-plane translations and rotations were studied, starting from structural theories of extension and bending, and the timescale characterising relaxation was assumed to be much greater than the time taken for the waves to propagate the distance between the ends of the bar.

Explicit low-frequency corrections to the equations of rigid body dynamics were obtained in the form of extra terms, expressed through prescribed end forces and moments. In implementing the new theoretical framework, KAM, with the help of Keele Computer Science colleagues, created a software platform broad enough to accommodate the use of AI neural-network machinery [5] adapted for the interpretation of accelerometer data.

The example of a homogeneous bar was addressed in greater detail, for verification purposes. A comparison with the engineering benchmark solutions of the original time-harmonic problems for extension and bending for a bar successfully demonstrated the high efficiency of the approach. For the Voigt bar, extensive numerical data were calculated.

The new approach was extended to the crucially important practical case of elastic contact between stiff and soft components [3], delivering a wealth of new engineering detail about the effect of couplers. As before, explicit low-frequency corrections to the rigid body motions of stiff components were calculated, with Keele's new approach taking account of material contrast. The KAM theory for a bar was then extended to 2D configurations in plane elasticity in [6]. Furthermore, a new specialised thin shell theory was developed [4], starting from a related concept of an almost inextensible mid-surface; this resulted in a robust procedure for the analysis of longitudinal forces in fluid-filled tank wagons.

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

The developments [1,3,4,6] expounding Keele's new concepts of almost-rigid dynamics were published in highly regarded journals.

1. J. Kaplunov, A. Shestakova, I. Aleynikov, B. Hopkins, and A. Talonov. Low-frequency perturbations of rigid body motions of a viscoelastic inhomogeneous bar. – Mechanics of Time-Dependent Materials 19 (2015), 135–151.
2. Kaplunov, J., Shestakova, A., Aleynikov, I., Hopkins, B. (2014). Perturbed rigid body motions of viscoelastic structures. – Proceedings of 9th International Conference on Structural Dynamics EURODYN-2014, Porto, Portugal, 3461–3464
3. J.Kaplunov, D.A. Prikazchikov, and O. Sergushova. Multi-parametric analysis of the lowest natural frequencies of strongly inhomogeneous elastic rods. – Journal of Sound and Vibration 366 (2016), 264-276.
4. J.Kaplunov, L.I.Manevich, and V.V. Smirnov. Vibrations of an elastic cylindrical shell near the lowest cut-off frequency. – Proceedings of Royal Society A: Mathematical, Physical and Engineering Sciences, 472.2189 (2016), 20150753.
5. P. Andras. High-dimensional function approximation with neural networks for large volumes of data. IEEE Trans Neural Netw Learn Syst, 29 (2018), 500-508.'
6. Kaplunov, J., Şahin, O. (2020). Perturbed rigid body motions of an elastic rectangle. Zeitschrift für angewandte Mathematik und Physik, 71(5), 1-15.

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

KAM group have developed advanced methodologies for the mathematical modelling of longitudinal forces between cars in freight trains. The methodologies developed are based upon the concept of almost rigid body dynamics, as outlined in section 2. In two funded collaborative projects with Amsted Rail, one of the largest global railway engineering companies, the methodologies have been applied to:

- Predicting of end-of car systems performance when subjected to longitudinal forces [5.1]
- Modelling of low-frequency dynamics for fluid-filled tank cars [5.2]
- Optimising the use of accelerometer data in telematics monitoring systems [5.3]

Gutteridge, Haskins & Davey Ltd (GHD), a multi-national professional service company focusing in particular on railway engineering, has been working with KAM through continuous Knowledge Exchange, through their senior consultant, Dr Anzhela Shestakova, who worked on the Amsted Rail project [5.3] for her PhD at Keele [5.5]. Dr Shestakova has applied the advanced methodologies developed at Keele to address a variety of challenging problems in e.g. Mine-Rail-Port operations and sustainable development of British and international railways [5.4].

Improving workforce skills

KAM's expertise has also been utilised to improve the mathematical modelling knowledge and skills within the Amsted Rail's workforce [5.1]. Specifically, KAM has supported the training of rail and track engineers at Amsted Rail to understand the theory of almost rigid body dynamics and mitigation of impact as vibrations travel through rail car components [5.1], including regular online sessions with R&T staff. This training includes a bespoke workshop to learn about the application of the almost rigid body dynamics in evaluating the impact of longitudinal forces in rail car components [5.1].

Creating a new methodology

"Keele's group has developed a robust methodology considering the railway car deformability in a quite simple and elegant manner." Former Director of Research and Development for Amsted Rail (2008-2017) [5.6].

Since 2015, Amsted Rail's Research & Design (R&D) department have collaborated with KAM on projects related to the modelling of longitudinal forces during the coupling of rail freight cars [5.6]. The ends of heavy-haul rail cars need to be able to withstand high impact contact when coupling takes place, and when in motion as the rail car is pushed and pulled [5.7]. Amsted Rail use an advanced custom modelling system to evaluate the performance of the end-of-car systems, including friction draft gears and hydraulic cushion units [5.7]. Amsted Rail began to collaborate with KAM to improve the robustness of the evaluative methodology for modelling end-of-car systems. The existing methodology was enhanced by incorporating the concept of almost rigid body dynamics to ensure that rail cars can withstand high energy impacts [5.1].

Improving modelling and testing

The resulting advanced evaluative methodology has provided Amsted Rail with a more powerful, efficient and economical way of modelling longitudinal forces taking into consideration the deformability, internal dissipation and inhomogeneity of freight cars [5.1]. Amsted Rail have found that applying the improved methodology, "results in major corrections to the evaluated longitudinal forces in about 6-8% of the analyzed operational scenarios. This leads to the reduction in risk of derailment" [5.1]. The evaluative methodology developed by KAM has been implemented within a US patent by Amsted Rail in a US patent (10551257, issued 4th February 2020) as 'railway freight car coupling force monitoring system' [5.1, 5.8]. KAM have also worked to optimise and reduce the expenses of experimental tests, which cost up to $10,000 for each coupling system test [5.4].

The advanced methodologies for the modelling of freight cars using artificial intelligence (neural network) technologies created at Keele have been applied by Amsted Rail [5.4, 5.5]. KAM worked together with Amsted Rail to create a software platform broad enough to accommodate the use of AI neural-network machinery adapted for the interpretation of accelerometer data [5.5].

The advanced methodologies have been applied in the improvement of Amsted Rails telematics monitoring system, involving IONX (a subsidiary of Amsted Rail), to prevent railway accidents and derailments [5.6]. Within the telematics system sensors monitor trains movements and track condition, this data is used to highlight repairs reducing long term maintenance costs as they can be tackled early. The project has improved modelling longitudinal forces using real-time accelerometer data, by applying the concept of almost rigid body motion to calculations. The effective modelling longitudinal forces by KAM posits to save Amsted Rail millions of dollars in impact damage annually [5.6]. Overall, this work has a “significant impact on many innovations for monitoring impact damage in the railroad industry in North America” [5.6].

These developments are fundamental in nature and scope, with the potential to underpin many engineering applications beyond those already implemented in KAM’s partnerships with Amsted Rail and GHD.

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

5.1. Letter of support from Chief Research Engineer at R&T Amsted Rail, USA

5.2. Contract on modelling of low-frequency dynamics for fluid-filled tank cars

5.3. Contract on analysis of data from accelerometers for evaluating of the longitudinal forces between freight cars

5.4. Letter of support from Technical Director at Gutteridge, Haskins & Davey Ltd (GHD)

5.5. A. Shestakova. Development of mathematical models for freight cars subject to dynamic loading. – PhD Thesis, Keele, 2015.

5.6. Letter of support from former Director of Research and Development for Amsted Rail from 2008-2017

5.7. Amsted end-of-car brochure https://www.amstedrail.com/wp-content/uploads/2019/08/EndofCar-Brochure.pdf

5.8. Patent “Railway freight car coupling force monitoring system”. Amsted Rail Inc., Patent number 10551257**,** Feb. 2020. https://patents.justia.com/patent/10551257