Institution: Keele University

Unit of Assessment: UoA10 Mathematical Sciences

Title of case study: Multi-parametric dynamic analysis of lightweight car parts

Period when the underpinning research was undertaken: 2016-2020

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
Dr Danila Prikazchikov	Senior Lecturer	2013 - present
Dr Ludmila Prikazchikova	Lecturer	2015 - present

Period when the claimed impact occurred: 2016-2020 (TPV)

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

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

Collaborative research between Keele applied mathematicians and TPV Automotive (Slovenia) has led to improved design by TPV Automotive of lightweight car parts essential for the stability, control, and safety of a vehicle, as well as a lower carbon footprint, through reduced energy consumption and emissions. The work has changed the Research and Design approach within TPV as well the upskilling of TPV staff through applying the research on methodologies for advanced modelling into a programme of training. These impacts have been realised through development of a new and highly practical approach to multi-parametric analysis of strongly inhomogeneous elastic structures.

2. Underpinning research (indicative maximum 500 words)

Inspired by the major industrial challenge of designing lightweight parts for environmentally friendly vehicles, the underpinning research was carried out within a collaborative industrial partnership between Keele and TPV Automotive (EU) during 2016-2020. Addressing this challenge is a priority due to the global importance of CO2 emission reductions. However, despite environmental benefits, introduction of lightweight components often results in an increase in noise and vibration, presenting an important engineering requirement to model and mitigate their harmful, and even dangerous effects.

To meet this requirement, Keele Applied Mathematicians (KAM), involving Professor J.Kaplunov, Dr D.Prikazchikov, Dr L.Prikazchikova, and Professor G.A.Rogerson, developed a robust methodology for modelling of lightweight, laterally and longitudinally inhomogeneous thin elastic structures. The focus was on multi-parametric dynamic analysis of lightweight high-contrast structural elements, including complex layered structures containing both stiff and soft parts. Breakthrough designs were found through systematic study of a variety of material configurations; the aim, successfully achieved, was to find optimal designs as required by engineers, incorporating overall weight reduction.

The KAM group established a novel asymptotic methodology for dynamic modelling of strongly inhomogeneous elastic structures. Apart from the basic small parameter corresponding to the presence of lightweight components, extra parameters related to small/large ratios of stiffnesses, and linear sizes of components were taken into consideration. Resonant phenomena caused by the excitation of harmful low-frequency vibrations, due to high contrast, were thoroughly

investigated. Powerful new methods were developed, including a two-mode asymptotic theory for the bending vibrations of a sandwich plate, replacing the conventional single-mode asymptotic formulation and various ad hoc approximations.

The approach developed at Keele originated from asymptotic analysis of a high-contrast three-component rod [1], extended to rods with arbitrarily many components [2]. In such structures, the stiff components perform almost rigid body motions, whereas the compliant components undergo nearly homogeneous deformations. Explicit formulae for the lowest resonant frequencies and corresponding mode shapes were derived. Keele's analysis in [1] was then extended to low frequency bending of a multi-component beam [3], as well as to an advanced treatment of three-layered laminates [4]. This treatment accounted for the almost-rigid-body motions of the stiffer parts of transverse components, which made possible the detailed engineering analysis of many practically important lightweight configurations. Further progress was made in [5], relating to the anti-plane problem of elasticity for a three-layered high-contrast laminate. Two-mode expansions of the full dispersion relation were derived, along with the associated reduced equations of motion. The results in [4] became the starting point for the multi-parametric analysis presented in [6], especially focused on lightweight structures. The transition from uniform to non-uniform asymptotic expansion was examined, which is of great importance in practice as the volume of stiff components is steadily reduced.

The research findings of the Keele group contributed to the modelling of specific lightweight car components within the EVA4green project, supported by the European Regional Development Fund (ERDF). Keele's methodology for evaluation of the lowest vibration modes for inhomogeneous structures was also later adopted in the project EAGLE (ERDF).

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

All the papers [1-5] are published in top-ranking international journals and contain fundamental results beyond the scope of the initial engineering applications to lightweight cars. The refereed conference proceedings [6], written in collaboration with industrial partners, further explain Keele's underpinning research in the project, with an industrial engineering audience in mind.

1. Kaplunov, J., Prikazchikov, D., & Sergushova, O. (2016). Multi-parametric analysis of the lowest natural frequencies of strongly inhomogeneous elastic rods. *Journal of Sound and Vibration*, *366*, 264-276. https://doi.org/10.1016/j.jsv.2015.12.008
2. Kaplunov, J., Prikazchikov, D. A., Prikazchikova, L. A., & Sergushova, O. (2019). The lowest vibration spectra of multi-component structures with contrast material properties. *Journal of Sound and Vibration*, *445*, 132-147. https://doi.org/10.1016/j.jsv.2019.01.013
3. Sahin, O., Erbas., B, Kaplunov, J., Savšek, T. (2020) The lowest vibration modes of an elastic beam composed of alternating stiff and soft components. Archive of Applied Mechanics, 90, 339–352. https://doi.org/10.1007/s00419-019-01612-2
4. Kaplunov, J., Prikazchikov, D. A., Prikazchikova, L. A. (2017). Dispersion of elastic waves in a strongly inhomogeneous three-layered plate. *International Journal of Solids and Structures*, *113*, 169-179. https://doi.org/10.1016/j.ijsolstr.2017.01.042
5. Prikazchikova, L., Ece Aydın, Y., Erbaş, B., Kaplunov, J. (2018). Asymptotic analysis of an anti-plane dynamic problem for a three-layered strongly inhomogeneous laminate. *Mathematics and Mechanics of Solids*, 25(1), 3-16. https://doi.org/10.1177/1081286518790804
6. Kaplunov, J., Prikazchikov, D.A., Prikazchikova, L.A., Nikonov, A., Savšek, T. Multiparametric dynamic analysis of lightweight elastic laminates. IOP Conf. Series: Materials Science and Engineering, 683 (2019), 012014 https://iopscience.iop.org/article/10.1088/1757-899X/683/1/012014/meta

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

The KAM research group have applied the almost rigid body dynamics concept through international collaboration with the TPV automotive group. In 2016, KAM began working with TPV

group to develop lightweight multi-component elastic structures for car parts in partnership with the TPV Group using the methods of multi-parametric dynamic analysis [5.1]. The TPV Group is a multi-national company, based in Slovenia, producing car parts for most European car brands with an annual turnover around €150 million. Keele's collaborative research with TPV has been within the framework of two ERDF grants, including the projects "Environmentally Safe Green Mobility Car" (EVA4green) and "Advanced sensor system for 3D control of the geometry of complex objects in the factories of the future". Professor Kaplunov was specially invited to take part in these projects via the affiliated Faculty of Industrial Engineering (FINI) Novo Mesto, Slovenia [5.2], bringing to bear the unique expertise of the KAM group.

The collaboration has resulted in several benefits for TPV, including securing new funding streams from the European Regional Development Fund (ERDF), European Cohesion Fund and Government of Slovenia. One project to benefit from the ERDF was project EAGLE, involving the development of an advanced 3D sensor system enabling frequency visual control of geometrically complex products [5.3]. This project has led to a Slovenian Innovation Registration Certificate [5.3] and an analogue of a regional patent implemented by a collaboration with TPV, Alpineon (Tech company) [5.4], FINI [5.2] and Keele. Professor Kaplunov is a named party on this certificate, and his contribution was an evaluation of the effect of structural vibrations (5.3).

The collaborative projects with TPV, because of KAM's involvement, have also led to job creation, the expansion of R&D activities, upskilling the workforce and the application of new mathematical modelling techniques (5.1). As part of EVA4green project consortium (*see evidence* 5.5, 5.6) KAM contributed substantially to:

- 22 new products
- 40 innovations
- 16 international patent applications
- Energy consumption reduction by 10-15%
- Reduction of emissions from internal combustion engines by 13-21%
- 15% weight reduction in several structural car elements

Skills development of workforce

The KAM research group has worked with TPV to develop mathematical modelling knowledge and skills within their workforces [5.1]. TPV identified a knowledge and skills gap in advanced mathematical modelling techniques applicable to the analysis of vibrations in non-uniform structures: in response, KAM and TPV created a professional development programme [5.1, 5.3]. This programme tailored for the Research and Design (R&D) team has included a series of consultations, training workshops and a book translated into Slovenian [5.7, 5.8, 5.9]. This included a workshop titled 'Development of Lightweight Layered Structures under Low Frequency Dynamic Loading' at TPV in February 2019 [5.1]. The workshop was organized as the activity within the project EVA4green - Ecological Safe Vehicle for Green Mobility program [5.1]. The workshop introduced using the methods of multi-parametric dynamic analysis and used it as a basis to design new approaches with engineers 'for planning and controlling the dynamic response of "lightweight" structures optimizing the choice of material and geometric parameters' [5.1]. These workshops have improved problem solving skills of engineers and changed some R&D practices through the embedding of advanced mathematical modelling [5.1]. An evaluation post workshop showed that 50% of participants agreed that the workshop had supported their knowledge development [S10].

New modelling approaches

At TPV, new multi-parametric modelling approaches have enabled R&D staff to carry out dynamic analysis of lightweight materials by modelling low frequency vibrations [5.1]. These new approaches have allowed R&D staff to "optimize the design in terms of its frequency response when developing lightweight structural elements that are exposed to dynamic loads in a sufficiently efficient and fairly quick manner" [5.1]. Also, the research has been applied to optimize

calculations, which avoids lengthy computations for choosing the right set of problem parameters and reducing the time needed for experimental setups [5.8].

Through the introduction of new multi-parametric modelling approaches, based upon the advanced plate models developed by KAM, the design of car chassis components, such as the cross-car beam and control arm, have been improved by lessening the effects of low frequency vibrations and reducing their weight [5.1]. The mid-term external evaluation of the EVA4green project specifically mentions the improvement of the cross-car beam with magnesium and steel parts that were designed and evaluated using multi-parametric modelling [5.5].

Overall, the work of KAM has made a significant impact upon TPV, as stated by the Assistant management director, "The innovative methodologies which they introduced to the project activities, ensure better optimisation of products, lower weight of car parts, lower carbon footprints and a shorter development cycle" [5.1].

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

5.1. Letter from Assistant Management Director at TPV Automotive "*The impact of the collaboration with the research group of Prof Julius Kaplunov*"

5.2. Letter from the Faculty of Industrial Engineering Novo mesto (FINI) confirming that Prof J.Kaplunov has been invited to contribute to projects EVA4green and EAGLE.

5.3. Slovenian Innovation Registration Certificate

5.4. Letter from CEO at Alpineon Ltd "*Contribution of Prof J.Kaplunov and his research group to EAGLE project*"

5.5. Mid-term evaluation report for EVA4green project

5.6. Letter from Assistant General Manager at TPV Automotive "*Contribution of Prof J.Kaplunov and his research group to EVA4green project*"

5.7. Article in Slovenian newspaper.

5.8. Letter from Assistant General Manager at TPV Automotive "*Dissemination of knowledge within EVA4green project*"

5.9. "Dinamika tankostenskih elastičnih teles", FINI Publisher, 2019, ISBN 978-961-94246-7-4.

5.10. Evaluation of workshop 'Development of Lightweight Layered Structures under Low Frequency Dynamic Loading' at TPV, in February 2019.