Title of case study: The Dynamics of Long Slender Continua in Vertical Transportation Installations

1. Summary of the impact

Ropes and cables as well as other types of long slender continua (LSC) are key components of vertical transportation (VT) systems such as traction lifts and elevators. The research programme led by Stefan Kaczmarczyk determines how resonance conditions induced by various sources of excitation, and in particular by adverse environmental conditions such as strong winds acting upon the building structure, influence the dynamic behaviour of LSC structural integrity and performance of elevator systems in the modern built environment. This research programme was carried out in partnership with ThyssenKrupp Elevator (TKE) AG and involved experimental testing, numerical and analytical modelling and computer simulation. The research has produced the following key impacts:

- has provided TKE and the lift industry with important design guidelines;
- has led to new product development impacting on elevator safety;
- has strengthened the research and innovation capacity of ThyssenKrupp Elevator.

2. Underpinning research

In the modern high-rise built environment vertical transportation systems employ LSC such as ropes and cables of variable length moving at speed as a means of car and counterweight suspension and for the compensation of tensile forces over the traction sheave. Long cables are also used in overspeed governor and safety gear systems provided to bring the elevator car safely to rest in the event of emergency and failure of the normal stopping system. The significance of the underpinning research programme is the understanding of how various deterministic and stochastic excitations, resulting due to the irregularities of the system as well as due to environmental phenomena such as strong winds and earthquakes, affect the operation of a VT installation.

The research involved in this area concerns fundamental studies of nonlinear, time-varying systems. The underpinning work was initiated by S. Kaczmarczyk (currently Professor of Applied Mechanics). Between 2002 and 2013 Kaczmarczyk, responsible for research led new research to investigate the performance of elevator systems deployed in high-rise buildings subjected to adverse environmental phenomena conditions that cause the buildings to vibrate (sway) at low frequencies and large amplitudes.

At the initial stage mathematical models to predict transient resonance conditions and the coupled nonlinear lateral-longitudinal dynamic responses of LSC moving at speed during the system operation were developed [1]. This was followed by TKE-sponsored research into the structural integrity of an elevator suspension system [2] and a PhD project to investigate autoparametric coupling effects and nonlinear modal interactions in an elevator suspension system [3].

The results have demonstrated that LSC deployed in VT systems display a range of complex dynamic phenomena that affect the entire installation with resonance vibrations being transmitted to the elevator car and passengers. The natural frequencies of the system change with the speed of the transport motion. The length variation results in the change of the mass, stiffness and damping characteristics of the system. Consequently, slow variation of the natural frequencies occurs rendering the entire system non-stationary. Due to the non-linear nature of these systems major exchanges of energy between various modes of vibration take place. An adverse situation arises when the host (building) structure is excited near its natural frequency. When one of the slowly varying rope/cable frequencies approaches the natural frequency of the structure passages through primary and nonlinear resonances take place. The lateral in-plane and out-of-plane modes are coupled through non-linear cubic terms. Since the corresponding natural frequencies are the same, this creates conditions for passage through autoparametric (internal) one-to-one (1:1) resonance. This in turn results in a non-planar response (*whirling* motions). Furthermore, the longitudinal mode and the lateral modes are coupled through quadratic non-linear terms. Subsequently, two-to-one (2:1) internal resonance might take place when the longitudinal mode is activated, and its natural frequency is near twice that of any of the lateral frequencies.

Concurrent international collaborative research with R. Iwankiewicz (of the University of the Witwatersrand, South Africa) in the area of stochastic dynamics [4], and with Y. Terumichi (of Sophia University, Japan) in the area of tether dynamics [5] led to the development of new efficient numerical algorithms to study the dynamic behaviour of LSC with time-varying length. This informed the development of the active stiffness control algorithm to mitigate the effects of passage through resonances when a slender continuum, such as an elevator wire rope or cable, moves at speed and comes to rest, exhibiting large dynamic displacements [6].

3. References to the research

1. Kaczmarczyk, S., Andrew, J.P., Adams, J.P., The modeling and Prediction of the Influence of Building Vibration on the Dynamic Response of Elevator Ropes. 2003, *Materials Science Forum,* Vols. **440-441**, pp. 489-496.
2. Kaczmarczyk, S., Prediction of the Influence of Vibration on Structural Integrity of Elevator Suspension Ropes. 2005, *Key Engineering Materials,* Vols. **293-294**, pp. 761-770.
3. Salamaliki-Simpson, R., Kaczmarczyk, S., Picton, P., Turner, S., Non-linear modal interactions in a suspension rope system with time-varying length. 2006, *Applied Mechanics and Materials,* **5-6**, pp. 217-224.
4. Kaczmarczyk, S., Iwankiewicz, R., Dynamic Response of an Elevator Car Due to Stochastic Rail Excitation. 2006, *Proceedings of the Estonian Academy of Sciences: Physics Mathematics,* Vol. **55**, No. 2, pp. 58-67.
5. Kawaguti, K., Terumichi, Y., Takehara, S., Kaczmarczyk, S., Sogabe, K., The Study of the Tether Motion with Time-Varying Length Using the Absolute Nodal Coordinate Formulation with Multiple Nonlinear Time Scales. 2007, *Journal of System Design and Dynamics,* **1**, (6), pp. 491-500.
6. Kaczmarczyk, S., Picton, P., The Prediction of Nonlinear Responses and Active Stiffness Control of Moving Slender Continua Subjected to Dynamic Loadings in A Vertical Host Structure. 2013, *International Journal of Acoustics and Vibration* **18**(1), pp. 39 – 44.

<u>Key collaborators from within the University of Northampton</u>

Andrew, J.P., Head of Division of Engineering (currently retired) [1];
Adams, J.P., Senior Lecturer (currently Head of Department of Engineering and Technology) [1];
Picton, P., Professor of Intelligent Computing Systems [3,6];
Salamaliki-Simpson, R., PhD researcher (doctoral studies completed in 2010, funded by the University of Northampton) [3];
Turner, S., Senior Lecturer (currently Associate Professor) [3].

4. Details of the impact

The impact involves TKE AG, the commercial partner, which is a leading international elevator company responsible for the ThyssenKrupp Group’s global activities in the area of elevators and escalators and other passenger transportation systems with more than 46,000 employees, sales of 5.3 billion Euros and customers in 150 countries.

New Design Guidelines

The theory and models developed within the research programme led by Prof. Kaczmarczyk have provided TKE AG with robust design guidelines that were used to solve technical problems in a number of prestigious elevator/ passenger transportation projects worldwide. These projects involved a broad range of technical challenges. For example, the One World Trade Center tower is the tallest building in the Americas and will have the fastest elevators in the Western Hemisphere. The project involved the design and analysis of 73 traction elevator installations equipped with steel wire cables with an overall length of 198 miles. The design guidelines provided within the research programme, and their implementation in the above projects, served as development and market enablers improving the company’s international competitive advantage and helping to secure new markets.

New product development

The theory, mathematical models and computer simulation tools developed to predict the dynamic behaviour high-rise elevator systems equipped with long suspension and compensating ropes have informed the development of innovative control strategies to mitigate the effects of resonance conditions caused by environmental loadings such as wind and earthquakes.

Subsequently, the TKE R&D centre commissioned research into the development of an active control system. Two international patents have been awarded so far for this work. The patents protect proprietary technologies currently being developed. It is anticipated that the patented technologies will result in significant economic returns. They will lead to new product development impacting on the company's sales growth as well as on its profitability.

Furthermore, the impact created has resulted in the development of safer and improved passenger VT systems operating in the modern built environment. For example, the design of an active roller guide (ARG) system to suppress vibrations in high-rise elevator installations, developed with Prof. Kaczmarczyk's input, reduced the amount of vibrations transmitted to the elevator cars, improved efficiency of the system and has led to improved ride quality and increased passenger safety and comfort.

Impact on the research and innovation capacity

Following the research programme the School of Science and Technology, University of Northampton and TKE AG agreed in 2012 to establish a Strategic Partnership for Cooperation in Research and Innovation. The Partnership has strengthened the research and innovation capacity of ThyssenKrupp Elevator and has helped them to develop new technologies. The impact and importance of the Partnership on the company performance was emphasised by the Senior Vice President, Corporate Department Research and Development (CD R&D) at ThyssenKrupp Elevator AG, who stated:

"The Partnership has strengthened the innovation capacity of ThyssenKrupp Elevator and will help to develop new technology-based products. This additional cooperation allows us to continue to leverage the University resources to develop our teams and provides a platform for Open Innovation. We are excited and proud to have an opportunity to work with such a prestigious University within our industry".

The Lift Engineering Group (LEG) led by Prof. Kaczmarczyk delivers the MSc in Lift Engineering (LE) postgraduate course leading to a higher-level qualification award, which provides a detailed advanced study of engineering and R&D related management issues for technical staff employed in lift making companies and allied industries. The research programme together with the MSc provision informed the TKE's R&D programme designed to raise technical expertise of the company's R&D staff.

The Engineering Training Manager, CD R&D ThyssenKrupp Elevator AG, commented:

"Sustainable innovation calls not only for highly qualified specialists, but increasingly for extensive knowledge sharing between industry and research institutions. Joint events, with the University, for example as part of our 'Accelerated Engineering Training' programme, give us the opportunity to discuss specific topics with specialists and find out whether and how we can apply the ideas and principles developed in our future global research and development activities."

The research training and knowledge sharing impacted on TKE global research and innovation results and led to the completion of a PhD programme by a senior member of their management. Three additional PhD projects, sponsored by TKE, are underway. This has fulfilled the overall aim to embed the University's expertise within the TKE organization to raise technical qualifications of their R&D staff and to achieve optimized designs for their new products.

This research programme has not only contributed to knowledge transfer within the company. The results and outputs have been disseminated through an international conference series, the annual *Symposium on Lift and Escalator Technologies*, organized jointly by the LEG led by Kaczmarczyk and the Chartered Institution of Building Services Engineers (CIBSE) Lifts Group. The symposium has reached its third edition in 2013 and has attracted over 90 delegates from the national and international lift industry community. This has extended the breadth of the beneficiaries and potential users.

5. Sources to corroborate the impact

Beneficiaries who could be contacted to corroborate the claims made

Senior Vice President - CD R&D, ThyssenKrupp Elevator AG, Essen, Germany
Engineering Training Manager - CD R&D, ThyssenKrupp Elevator AG, Essen, Germany
Manager, ThyssenKrupp Elevator Innovation GmbH, RIC Pliezhausen, Germany
Director, Strategic Development Americas, ThyssenKrupp Elevator AG, USA
Manager, Research Center (TRIaD), ThyssenKrupp Elevator AG, Horn Lake, USA

Patent information

Smith R., Kaczmarczyk S., Nickerson J., Bass P. M., *Elevator Rope Positioning Apparatus.* 28 February 2012, United States Patent. Patent No. US 8,123,002 B2. http://www.google.co.in/patents/US8123002

Smith R., Kaczmarczyk S., *Actively Damped Tension Member*. 07 February 2012, United States Patent. Patent No. US 8,110,050 B2. http://www.google.com/patents/US8110050