Institution: University of Bristol

Unit of Assessment: 10 – Mathematical Sciences

Title of case study: Bristol's research in dynamical systems methods are adopted and made operational within Airbus UK to develop cost-saving, high-precision modelling platforms

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

Evaluating the ground-based manoeuvrability of large aircraft is time consuming and costly if explored though industry-developed complete models of ground dynamics. Research by Krauskopf and colleagues from the University of Bristol has shown that applying methods from dynamical systems allow these dynamics to be investigated efficiently and with considerable precision. This approach, and the related purpose-developed software, *Dynamical Systems Toolbox*, have been adopted by Airbus. It is now fully incorporated in the Airbus *Methods and Tools* portfolio as a supported tool for the evaluation of proposed works and new designs. The research delivers considerable savings in time and costs for the company. Additionally, this programme of research has delivered research training for Airbus employees and one, who studied for PhD with Krauskopf, now leads the Airbus development and implementation of these mathematical techniques which are being disseminated more widely within the company. There continue to be Bristol EPSRC CASE PhD studentships in collaboration with Airbus co-supervised by Krauskopf (7 in the assessment period).

2. Underpinning research (indicative maximum 500 words)

Aircraft are designed to fly and, hence, are not optimised for ground operations in the way a car or other ground vehicles may be. Nevertheless, a passenger aircraft needs to operate fast, reliably and safely on the ground in order to ensure its overall commercial success. Prior to this research, the standard methodology of aircraft manufacturers was to conduct massive and expensive numerical simulations of industry-tested and parametrised models for aspects of aircraft motion to evaluate the ground performance of aircraft as part of their design, evaluation and certification.

The underpinning research consists of the systematic mathematical analysis of several of these models using dynamical systems techniques to study their nonlinear dynamics and the stabilities of particular aspects of their motion. This methodology avoids expensive brute-force numerical simulations. The models studied represent different features of ground manoeuvres and were developed in collaboration with Airbus. The behaviour of these nonlinear mathematical models was evaluated using both analytical and numerical techniques and their parameter dependence was analysed using software, purpose-developed by Krauskopf and colleagues, the *Dynamical Systems Toolbox,* which runs under MATLAB (a widely used numerical computing environment and programming language). This enabled the introduction of numerical continuation to follow solutions and their changes of stability with varying parameters. Importantly, this approach could be used within an industrial setting.

Specific projects were as follows (references from section 3 in parentheses):

- a fully parameterized model of a mid-size aircraft was used to evaluate aircraft ground turning and provide guidelines for the safe operation limits and maximum load factors under different conditions. The main motivation for this work was to evaluate the suitability of the existing Federal Aviation Regulations for lateral loads experienced during turning maneuvers [3].
- bifurcation studies of shimmy oscillations of an aircraft nose landing gear. A mathematical model with torsional and lateral bending modes that are coupled through a wheel-mounted elastic tyre was developed and studied. The bifurcation analysis was performed in terms of the forward velocity & vertical force and was used to find regions of stable torsional and stable lateral shimmy oscillations [1].

- research on ground handling studies of aircraft with more than three sets of wheels, in particular, the Airbus A380 model. This led to the development of the *Dynamical Systems Toolbox* and demonstrated its usefulness with the evaluation of low-, medium- and high-speed ground manoeuvers of an A380 in comparison with an A320 [2,5,6].

- treatment of the dynamics of a deployment cycle of an aircraft landing gear, showing the usefulness of dynamical systems methods with a study of actuator placement for nose and main landing gears [4].

The various strands of this research programme were undertaken in Bristol from 2006 onwards and have led to a series of scientific publications in which the underlying mathematics, and its application to aircraft dynamics, are explained. The publications appeared in high quality applied mathematics journals. The research was led by Krauskopf (University of Bristol until 2011, University of Auckland from 2011), Lowenberg (University of Bristol) and Neild (University of Bristol), together with Bristol postgraduate students and postdoctoral research assistants Rankin, Knowles, Thota and Desroches, and industrial contacts and supervisors at Airbus [b,c]. There are currently three EPSRC Case students in Bristol still co-supervised by Krauskopf.

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

[1] Thota., P., Krauskopf, B and Lowenberg, M. 2009, Interaction of torsion and lateral bending in aircraft nose landing gear shimmy, *Nonlinear Dynamics* **57**(3) 455-467; DOI: 10.1007/s11071-008-9455-y
*[2] Coetzee, E., Krauskopf, B. and Lowenberg, M.,2010 Application of bifurcation methods for the prediction of low-speed aircraft ground performance, *Journal of Aircraft (American Institute of Aeronautics and Astronautics)* **47**(4) 1248-1255; DOI: 10.2514/1.47029
*[3] Rankin, J., Krauskopf, B., Lowenberg, M. and Coetzee, E. 2010, Nonlinear analysis of lateral loading during taxiway turns, *Journal of Guidance, Control, and Dynamics (American Institute of Aeronautics and Astronautics)* **33**(6) 1708-1717; DOI:10.2514/1.50626
*[4] Knowles, J.A.C., Krauskopf, B. and Lowenberg, M. 2011, Numerical continuation applied to landing gear mechanism analysis, *Journal of Aircraft (American Institute of Aeronautics and Astronautics)* **48**(4) 1254-1262; DOI: 10.2514/1.C031247
[5] Coetzee, E., Krauskopf, B. and Lowenberg, M. 2011 Analysis of medium-speed runway exit manoeuvres, *Journal of Aircraft (American Institute of Aeronautics and Astronautics)* **48**(5) 1553-1564; DOI: 10.2514/1.C031276
[6] Rankin, J.,Desroches, M.,. Krauskopf, B. and Lowenberg, M. 2011, Canard cycles in aircraft ground dynamics, *Nonlinear Dynamics* **66**(4) 681-688; DOI: 10.1007/s11071-010-9940-y

* references that best indicate the quality of the underpinning research.

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

The introduction of dynamical systems methods, which are implemented in the *Dynamical Systems Toolbox,* into the industrial practice at Airbus provides the company with new capability for the evaluation of aircraft ground performance and the potential of considerable savings in time and costs (estimated at 80% of staff time compared to current practice within the aircraft industry [c]). Airbus has fully adopted this methodology and has developed a strategy for the continued future use of dynamical systems methods in an internal document, *Strategic Research into Dynamical Systems Methods: A roadmap from 2009 to 2013* [a].

The software, *Dynamical Systems Toolbox (DST)*, has transitioned within Airbus from its Research portfolio into its Methods and Tools portfolio. This is a mandatory stage of Airbus for institutionalisation of new operational engineering methods. Further evidence of the integration of these techniques into Airbus is the development of the *Dynamical Systems Toolbox* interface to Airbus' own software tools was sub-contracted and internal training sessions have been held. The new tool is presently in use by members of the Future Project Office, the Process, Methods & Tools Department and the Landing Gear group; the latter work on current aircraft projects, as well as the exploration of new landing gear and aircraft concepts. It is estimated that the new tool has

made significant savings in terms of man hours during 2012[c]. Airbus UK have described the impact of the research as approximately 80% reduction in time and associated costs [c] for ground maneuverability analysis and specified that the estimate of the saving is made by comparing the time taken to conduct global assessments using bifurcation and other dynamical systems techniques versus the time to obtain exhaustively a large number of point solutions. This is important because it allows the efficient use of numerical simulations for new designs. The engineer from the Modelling & Simulations Methods and Tools group writes, "The tool provides a method for de-risking design-decisions; the trade-off being between the impact of a risk occurring versus the likelihood of the risk occurring" [b].

The research formed the basis of the enhanced capability introduced by Airbus Process, Methods & Tools via the development of fully parameterized and validated models, the development of the *Dynamical Systems Toolbox* and the demonstration of the approach via dedicated case studies. The research has been supported and sponsored by Airbus, via direct interaction between the industry and university based researchers. The research has grown considerably in reaction to demand from the company - now also including novel testing strategies and the characterization of aircraft upset scenarios in flight. Regular research meetings (about every six months) were conducted at University of Bristol and at Airbus at which further dissemination could occur, together with the identification of new projects. Additionally, there have been several subsequent PhD students associated with this research project who have each spent extended placements at the company. Evidence of the value of this project to Airbus comes in part from the large number of grants and support they have provided (£415K in direct funding, plus funding in kind) [d].

There is also impact from the work in terms of staff training in research and recruitment in Airbus. For example, a member of staff was seconded from Airbus to perform PhD research at the University of Bristol. He is now one of the main advocates of the use of dynamical systems methods and is helping to lead their introduction within Airbus. In addition, a former postdoctoral research assistant (held 2007-2010) at Bristol was hired by Airbus and now works as Airbus Model Developer – Physical Systems at Airbus' Design Analysis.

A further impact of this research has been the embedding of nonlinear dynamics approaches within Airbus. It is expected that usage of the DST will increase amongst other departments when research through currently on-going PhD projects near completion (there are several on-going Bristol EPSRC Mathematics CASE studentships in partnership with Airbus). There are plans for further training courses within Airbus and improvements in the DST interface. Airbus also plans to set up a more extensive training course with the University of Bristol.

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

[a] Airbus internal report *Strategic Research into Dynamical Systems Methods: A roadmap from 2009 to 2013*. Details from this report are available from a Future Projects Engineer, Airbus Operations Ltd.
Corroborates contribution of methodology developed at the University of Bristol to Airbus's strategy for the continued future use of dynamical systems methods.

[b] Expert (Modelling & Simulation Methods and Tools, Airbus Operations Ltd.
Can be contacted to corroborate the contribution of the research to Airbus' decision making around risk.

[c] Future Projects Engineer, Airbus Operations Ltd.
Can be contacted to corroborate claim of 80% reduction in time and cost for Airbus.

[d] This research activity received a total of £805K of funding, of which £415K from industrial partner Airbus, as follows:
(i) PI: Krauskopf, Co-I: Lowenberg. Title: Bifurcation analysis of nonlinear ground handling of aircraft. Sponsor: EPSRC Maths Case Award with Airbus in the UK. Period: October 2006 - March 2010 to support PG Rankin. Value: £65K (EPSRC) plus £25K (Airbus)
(ii) PI: Krauskopf, Co-I: Lowenberg. Title: Analysis of nonlinear ground handling models.

Sponsor: Airbus in the UK. Period: April 2007 - March 2010 to support PDRA Thota. Value: £220K
(iii) PI: Krauskopf, Co-I: Lowenberg. Title: Modelling and nonlinear analysis of landing gear and airframe interactions. Sponsor: Airbus in the UK. Period: March 2007 - June 2011 to support PhD work of Coetzee (while full-time employee of Airbus). Value: salary cost for Coetzee plus £25K (research support)
(iv) PI: Krauskopf, Co-I: Lowenberg. Title: Dynamics of statically indeterminate landing gear systems. Sponsor: EPSRC Maths Case Award with Airbus in the UK. Period: October 2008 - March 2012 to support PG Knowles. Value: £65K (EPSRC) plus £25K (Airbus)
(v) PI: Krauskopf, Co-I: Lowenberg. Title: Dynamics of aircraft main landing gears. Sponsor: EPSRC Maths Case Award with Airbus in the UK. Period: October 2009 - March 2013 to support PG Howcroft. Value: £65K (EPSRC) plus £30K (Airbus)
(vi) PI: Neild, Co-I: Krauskopf. Title: Dynamic substructure testing strategies in aerospace. Sponsor: EPSRC Industrial Case Award with Airbus in the UK. Period: August 2010 - January 2014 to support PG Terkovics. Value: £65K (EPSRC) plus £30K (Airbus)
(vii) PI: Lowenberg, Co-I: Krauskopf. Title: Investigation of airliner upset and upset recovery dynamics using bifurcation analysis. Sponsor: EPSRC Maths Case Award with Airbus in France. Period: October 2010 - March 2014 to support PG Gill. Value: £65K (EPSRC) plus £30K (Airbus)
(viii) PI: Krauskopf, Co-I: Lowenberg, Neild. Title: Investigation of coupled landing gear and fuselage vibrations. Sponsor: EPSRC Maths Case Award with Airbus in the UK. Period: October 2011 - March 2015 to support PG Kewley. Value: £65K (EPSRC) plus £30K (Airbus).

Corroborates Airbus's investment in underpinning research.