Institution: De Montfort University		
Unit of Assessment: 12		
Title of case study: Enhancing Pilot Training and Flight Safety Through Improved Aerodynamic Modelling and Prediction of Nonlinear Flight Dynamics		
Period when the underpinning research was undertaken: 2000–2020		
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:**
Mikhail Goman	Professor of Dynamics	October 1997–present
Period when the claimed impact occurred: August 2013–July 2020		
Is this case study continued from a case study submitted in 2014? N		

1. Summary of the impact

Flight simulation models for the extended flight envelope of class-specific transport aircraft developed at DMU are being used in Europe’s only centrifuge-based flight simulator (Desdemona) and the world’s first commercial Upset Prevention and Recovery Training (UPRT) flight simulator (AMST-Systemtechnik’s Airfox UPRT). DMU’s flight models and computational methodology to study nonlinear aircraft dynamics were used by TsAGI, Russia, to support UPRT research and development in Russian civil aircraft programmes. A flight simulation model for a generic tailless aircraft, developed by DMU in collaboration with Council of Scientific and Industrial Research-National Aerospace Laboratories (CSIR-NAL), India, was used to train Indian Air Force pilots for critical flight conditions, and a DMU software system for investigation of nonlinear aircraft dynamics was used by CSIR-NAL for computational clearance of flight control laws.

2. Underpinning research

Loss of control in flight (LOC-I) is the main cause of fatal accidents in civil aviation. Over the period 2009-2018, there were 64 LOC-I accidents, 94% of which involved fatalities (IATA 2019, https://www.iata.org/contentassets/b6eb2adc248c484192101edd1ed36015/loc-i_2019.pdf). To tackle this problem, the European Union Aviation Safety Agency has recently consolidated the existing requirements for UPRT (Decision 2019/005/R). UPRT aims at providing pilots with skills to prevent and recover from situations in which an aeroplane unintentionally exceeds the parameters for line operation. An important part of the training is based on the use of flight simulators, which should be equipped with flight models that extend the flight envelope.

Prof. Goman and his team at DMU have made important contributions [R1, R3, R5, R6] to the principles of aerodynamic modelling for out-of-the-envelope scenarios characterised by aerodynamic stall and LOC-I. The aerodynamic modelling is complemented with an efficient computational methodology and software tools, which have been developed to investigate nonlinear aircraft dynamics, allowing an efficient validation of out-of-the-envelope flight simulation models and computational clearance of flight control laws [R2, R4].

(1) NONLINEAR AERODYNAMICS: COHESION OF EXPERIMENTAL WIND TUNNEL DATA AND CFD SIMULATIONS

The approach to aerodynamic modelling draws on the use of experimental data obtained in wind tunnels and complementary simulations using Computational Fluid Dynamics (CFD) methods. Such a blended approach allows improved fidelity of the aerodynamic model in the stall region due to the elimination of interference effects in the experiment and extrapolation of the results for higher Reynolds numbers typical for real flight conditions [R6]. The key features of this approach include an adequate phenomenological modelling of aerodynamic hysteresis in dynamic conditions based on the so-called ‘Goman-Khrabrov model’ and CFD predictions for the intensity of aerodynamic autorotation in the stall region, which is required for realistic simulation of lateral aircraft departures at high Reynolds numbers [R3, R6].

(2) INNOVATION IN WIND TUNNEL TESTING

The development of new experimental techniques is important for correct phenomenological modelling of aerodynamics in the stall region. The existing experimental rigs for static, rotary-balance and forced oscillation wind tunnel tests do not address the effect of transient motions and presence of interference from a support system. An innovative five degree-of-freedom wind tunnel manoeuvre rig proposed by Prof. Goman was built at the Aerospace Department of the University of Bristol in collaboration with Prof. Lowenberg [R5]. This virtual-flight-in-wind-tunnel experimental rig enables a large set of conventional and extreme aircraft manoeuvres to be performed in the controlled environment of a wind tunnel, allowing improved physical simulation of aircraft dynamics in the stall region. The obtained observations of the asymmetric aerodynamic loads and static aerodynamic hysteresis phenomenon made possible important improvements in the aerodynamic structure of the flight simulation models.

(3) NONLINEAR FLIGHT DYNAMICS: COMPUTATIONAL METHODOLOGY

To address the validation problem for flight models, an efficient computational methodology for investigation of nonlinear aircraft dynamics has been developed. The combination of nonlinear aerodynamic dependencies with nonlinear inertial coupling in rigid body dynamics, as well as nonlinearities and constraints in the control system, leads to the study of a nonlinear system of large dimensions. The methodology is based on the use of Attainable Equilibrium Sets (AES) and classical methods of nonlinear dynamical systems theory, including a standard linearisation procedure and local stability analysis, which are complemented with computation and analysis of two-dimensional cross-sections of regions of attraction against disturbances in state variables and control inputs [R2]. The key element of the proposed methodology is the sequential consideration of the open airframe and a closed-loop system with nonlinearities due to control constraints. The methodology was implemented as an interactive computational system in MATLAB/Simulink. This development has allowed bifurcation and continuation techniques that are popular in academia to move to a level where exhaustive qualitative and quantitative computational studies of nonlinear aircraft dynamics can be carried out without overly simplifying the flight simulation models used in flight simulators [R4].

(4) IMPLEMENTATION

The research results outlined in the previous sections have allowed the development of realistic flight simulation models tested and tuned by experienced test pilots for an extended flight envelope. DMU has successfully implemented [R3] the approach in the EU FP7 'Simulation of Upset Recovery in Aviation' (SUPRA) project (Grant Agreement ID:233543) for a typical airliner, in the first commercial UPRT flight simulator (AMST-Systemtechnik's Airfox UPRT, https://www.amst.co.at/en/aerospace-medicine/training-simulation-products/airfox/airfox-uprt/) for a class-specific transport aircraft, and for a manoeuvrable generic tailless aircraft (GTA) [R4].

3. References to the research

[R1] Abramov, N., Goman, M. and Khrabrov, A. (2004) 'Aircraft dynamics at high incidence flight with account of unsteady aerodynamic effects', AIAA Atmospheric Flight Mechanics Conference and Exhibit, Providence, Rhode Island, August 2004; https://doi.org/10.2514/6.2004-5274

[R2] Goman, M.G., Khramtsovsky, A.V. and Kolesnikov, E.N. (2008) 'Evaluation of aircraft performance and maneuverability by computation of attainable equilibrium sets', *Journal of Guidance, Control, and Dynamics*, 31(2): 329–339; https://doi.org/10.2514/1.29336

[R3] Abramov, N.B., Goman, M.G., Khrabrov, A.N., Kolesnikov, E.N., Fucke, L., Soemarwoto, B. and Smaili, H. (2012) 'Pushing ahead – SUPRA airplane model for upset recovery', AIAA Modeling and Simulation Technologies Conference, Paper AIAA 2012-4631, 13–16 August 2012, Minneapolis, Minnesota, USA; https://doi.org/10.2514/6.2012-4631

[R4] Abramov, N., Bommanahal, M., Chetty, S., Goman, M., Kolesnikov, E. and Murthy, P.V.S. (2014) 'Flight envelope expansion via active control solutions for a generic tailless aircraft', 29th Congress of the International Council of the Aeronautical Sciences, ICAS paper 2014-0591, St Petersburg, Russia, 7–12 September; https://www.icas.org/ICAS_ARCHIVE/ICAS2014/data/papers/2014_0591_paper.pdf

[R5] Gong, Z., Araujo-Estrada, S., Lowenberg, M.H., Neild, S.A. and Goman, M.G. (2019) 'Experimental investigation of aerodynamic hysteresis using a five-degree-of-freedom wind-tunnel maneuver rig', *Journal of Aircraft*, 56(3): 1029–1039; https://doi.org/10.2514/1.C034995

[R6] Abramov, N.B., Goman, M.G., Khrabrov, A.N. and Soemarwoto, B.I. (2019) 'Aerodynamic modeling for poststall flight simulation of a transport airplane', *Journal of Aircraft*, 56(4): 1427–1440; https://doi.org/10.2514/1.C034790

4. Details of the impact

The impact of this case study can be summarised as follows:

(1) The flight simulation model [R3, R6] developed at DMU from 2009 to 2012 under the leadership of Prof. Goman during the European project SUPRA 'Simulation of Upset Recovering in Aviation' (www.supra.aero) was used for training pilots and flight instructors in the unique centrifuge flight simulator 'Desdemona' located at TNO, the Netherlands (https://desdemona.eu/). Since 2016, more than 235 people (airline pilots and flight instructors) from over a dozen airline companies from Germany, the Netherlands, Belgium, Luxemburg, UK, Portugal, Turkey and the United Arab Emirates (Lufthansa, German Wings, DHL, Transavia, TAP Air Portugal, AeroLogic, Shell, Cargolux, SunExpress, Corendon, Fly Dubai, Emirates Presidential Flight) have been trained for LOC-I and UPRT scenarios. The UPRT course at Desdemona continues to attract pilots following excellent feedback from the trained pilots and their companies [C1].

(2) Using the methodology presented in [R1, R2, R4, R6], DMU developed, between 2014 and 2017, a class-specific out-of-the-envelope flight simulation model, which was implemented in the first commercial flight simulator designed and built for UPRT and LOC-I training by AMST-Systemtechnik GmbH, Austria (AIRFOX UPRT, https://www.amst.co.at/en/aerospace-medicine/training-simulation-products/airfox/airfox-uprt/). DMU's flight simulation model has been thoroughly validated for operational flight conditions and in the extended flight envelope, where it inherits properties of the SUPRA model. Additionally, the model incorporates effects of icing leading to early stall, along with improved modelling of the ground effect aerodynamics for more realistic lateral-directional stability and pilot handling during crosswind landings [C2]. In December 2020, AMST's AIRFOX UPRT was available on the market as a cost-effective and high-quality training solution [C2].

(3) The SUPRA model [R3] and the methodology for aerodynamic modelling developed at DMU were used by TsAGI (www.tsagi.com) in projects funded by the Russian Federation Government (2013–2018) to build flight simulation models in the extended envelope for real aircraft (e.g., Sukhoi Superjet 100, Irkut MC-21). The DMU MATLAB/Simulink software system for study of nonlinear flight dynamics (see Section 2(3)) was used by TsAGI for validation purposes and tuning parameters in their flight simulation models. This software system allows the saving of significant resources compared to traditional computationally intensive direct time simulations [C3].

(4) From 2012 to 2015, DMU developed an aerodynamic model of a manoeuvrable GTA with an extended flight envelope in cooperation with CSIR-NAL, India (https://www.nal.res.in/en) [R4, R5]. Since September 2013, this flight simulation model has been used to train Indian Air Force pilots on the NAL flight simulator at high angles of attack in spin modes and to practice recovery techniques from spin. The interactive computational system for nonlinear flight dynamics developed at DMU (see Section 2(3)) was used by DMU to determine the critical flight modes for the

GTA. This allowed CSIR-NAL to efficiently carry out computational clearance of flight control laws over the extended flight envelope [C4].

5. Sources to corroborate the impact

[C1] Testimonial from Technical Director, Desdemona BV.

[C2] Testimonial from Managing Director, AMST-Aviation GmbH.

[C3] Testimonial from Head of Flight Safety Complex, Central Aerohydrodynamic Institute (TsAGI), Russia.

[C4] Testimonial from Chief Scientist and Head of Flight Mechanics and Control Division, National Aerospace Laboratories (CSIR-NAL), Bangalore, India.