Case Study of Two Capstone Student Projects from Canada and the United Kingdom

Carlo A. Ferlisi*, Clément-François Mazzini†, and Éric Laurendeau‡

Polytechnique Montréal, Montreal, Quebec, H3T 1J4, Canada

Danny Raj Ramasawmy§ and Andrea Da Ronch¶

University of Southampton, Southampton, S017 1BJ, United Kingdom

The differing methodologies employed by Canadian and United Kingdom universities in similar capstone projects is presented. Polytechnique Montréal, from Canada, employs the Conceive, Design, Implement, Operate approach in its teachings. Its aerospace engineering undergraduate students are tasked with an integrative project every year, culminating into a capstone project. The presented project's goal was the design and prototyping of a dynamic test bench of a free motion, three degrees of freedom, 2D airfoil with a full-span flap for wind tunnel testing at Toulouse, France. The project was conducted in a multidisciplinary environment, under the supervision of local and international collaborators (Institut Supérieur de l'Aéronautique et de l'Espace) and received industry in-kind support (Bombardier Aerospace). Similar to Polytechnique, the students at the University of Southampton were tasked with designing and testing a transferable wind tunnel test rig. The experimental test rig was designed to provide a flexible finite-span wing free motion in either a vertical translation or a rotation of the root point. Different numerical modeling approaches were undertaken for comparison with experimental results. The project was developed by consecutive Integrated Masters students with the help of industry specialists and international faculty advisors.

*Student, Polytechnique Montréal. Email: carlo.ferlisi@polymtl.ca

†Student, Polytechnique Montréal. Email: clement-francois-2.mazzini@polymtl.ca

‡Associate Professor, AIAA Senior Member. Email: eric.laurendeau@polymtl.ca

§Student, University of Southampton. Email: drr2g11@soton.ac.uk

¶New Frontiers Fellow & Lecturer, Faculty of Engineering and the Environment, AIAA Member. Email: A.Da-Ronch@soton.ac.uk

Nomenclature

CAD	Computer Aided Design (Model).
CDIO	Conceive, Design, Implement, Operate.
CEASIOM	Computerized Environment for Aircraft Synthesis and Integrated Optimization Methods.
CG	Center of Gravity.
CSA	Canadian Space Agency.
DAQ	Data Acquisition Card.
DoF	Degree(s) of Freedom.
GDP	Group Design Project.
ISAE	Institut Supérieur de l'Aéronautique et de l'Espace.
NACA	National Advisory Committee for Aeronautics, now NASA.
NES	Nonlinear Energy Sink.
Pitch	Rotation of Airfoil at Root Point(s).
Plunge	Vertical Translation of Airfoil.
RVIT	Rotary Variable Inductive Transducers.
SABRE	Low Reynolds Wind Tunnel at ISAE (France).
UVLM	Unsteady Vortex-Lattice Method.

I. Introduction

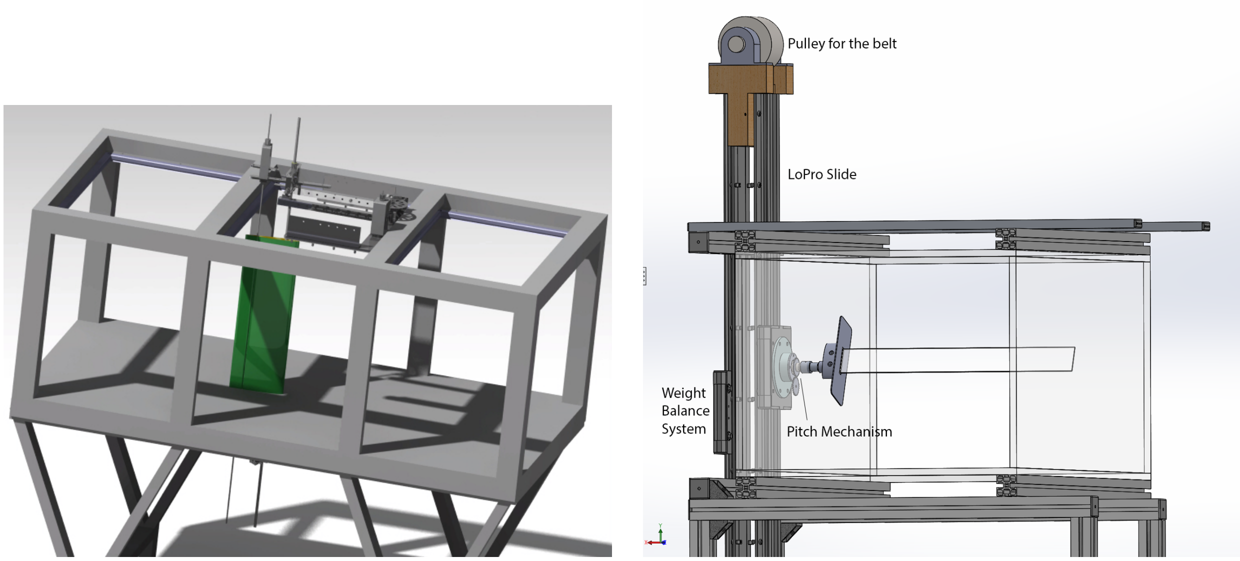
A comparative study of final year capstone projects in two aerospace engineering programs, one in Canada, the other in the United Kingdom, is made by discussing the two specific projects. They are similar in their overall objectives, methodologies, tools and multidisciplinary content. Both projects design a flutter test bench for a wind tunnel.

Polytechnique Montréal's Bachelor of Aerospace Engineering program will be presented, followed by a presentation of one of the school's capstone projects: Design of a Dynamic Test Bench of an Aircraft Wing for a Wind Tunnel. The University of Southampton's aerospace program will then be presented, followed by a similar capstone project: Design, Test and Build of an Aeroelastic Wind Tunnel Model.

Capstone projects teach the students to integrate different skills learned throughout their engineering classes. This self-taught method of learning prepares the students for the engineering industry, where one must build his own competence. Students are expected to identify issues before they arise andto have obtained sufficient theoretical knowledge to design a solution to their problem. The freedom of design usually motivates the students to complete the challenge themselves. Universities around the world use this method to educate the next generation of engineers.[1]

Polytechnique Montréal's test bench allows the airfoil to move in 3 DoFs and measure its displacements. It uses a four-bar linkage to allow movement in plunge of a carbon fiber airfoil and full-span flap. The measurements recorded by the test rig are the plunge, pitch and flap motion DoFs. RVITs and accelerometers were used to obtain these measurements. They are read by a DAQ and relayed to a LabVIEW program to store and display the data. Figure 1a illustrates the Polytechnique Montréal test rig. The project was conducted in a multidisciplinary environment, under the supervision of local (Polytechnique Montréal) and international (ISAE) collaborators. Local industry (Bombardier Aerospace) also supported the effort by providing lectures throughout the project and feedback during project reviews.

Southamptons' test bench allows a forced position and angle for the airfoil or a free displacement driven by aerodynamic loads to simulate a flight dynamic prototype problem. Southampton uses a belt-like mechanism to control the plunge of the airfoil and a cam follower controls the pitch of the rigid airfoil. A combination of accelerometers and strain gauges send the required data to an Arduino board for acquisition. The final test rig can be seen on Figure 1b.



(a) Polytechnique's Design

(b) Southampton's Design

Figure 1. Final Design of the Flutter Test Benches Developed by Both Universities

II. Polytechnique Montréal's Capstone Project

A. Overview of B. Eng. Aerospace Program

The CDIO Approach

Polytechnique Montréal, from Canada, employs the CDIO approach in its teachings.[2] Its Aerospace Engineering students are tasked with an integrative project every year, culminating to a capstone project. As per the CDIO vision, students are taught using a design approach by formulating questions and examples around design problems. All of Polytechnique Montréal's capstone projects have objectives in line with the CDIO philosophy. Projects such as *Aircraft Design* and *Aft Fuselage Design* are supervised by industrial collaborators (Bombardier Aerospace, in this case). Another example would be the *Composite Based Lunar Rover Design* in conjunction with the CSA.

Throughout these projects, students are encouraged to use an industry standard design approach. Their designs are based off criteria given by their professors. These requirements are formulated as client requests, written to resemble what a client with little to no engineering background may ask for. The students then complete a specifications document to be reviewed and accepted. Once completed, various solutions and design concepts are formulated as part of the conceptual design phase. These concepts are then studied for practicability and are scored based on how well they respond to the clients requests. Having whittled down the possible solutions, those left standing continue to be scrutinized in the preliminary design phase. This phase consists of initial sizing of the main elements of the project, as well as justifying design choices through required analyses. These designs are then presented to the clients (professors in most cases) to receive feedback and to ensure all requirements are met. Once completed, a final concept is chosen and the detailed design phase begins. This phase details the sizing of all parts. During this phase, the final design is iterated to ensure the final products success. The students are then tasked with creating a prototype of the design.

Students are generally aided by faculty members and industry specialists. This helps the students see the methodology employed by the industry. Figure 2 graphically shows the design process. The size of the base represents the relative level of detail required at each phase. Client requirements only need a coarse level of detail, whereas detailed design needs a very fine amount of detail.

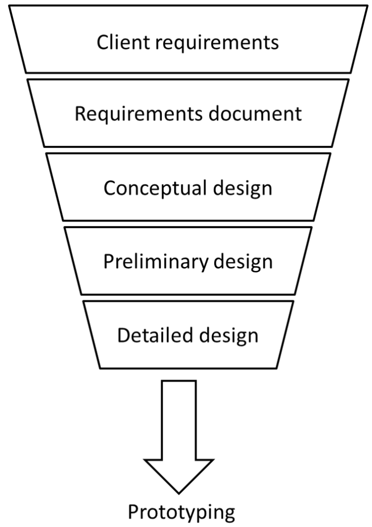


Figure 2. Design Process Employed at Polytechnique Montréal

Capstone Projects

The capstone project puts the students in a situation where they deal directly with actual clients, with minimum academic support, over a full academic term (fall and winter semesters, totalling 8 months). Since no precedent is set between the clients and the students of Polytechnique Montréal, the client only accepts the students' design if it proves successful and if it respects financial and technical constraints. Thus, students need not only work on the technical aspects of their project, but must also take into account financial factors (working with a budget) as well as human factors (team management), forcing them to become entirely self sufficient. Technical support from professors is minimized to allow the students to take full control of their project and immerse them in an industry setting. Professors take the role of project managers, helping students identify roadblocks during design reviews and obtaining access to the school's resources. The help provided by industry specialists, collaborators and clients is invaluable, as it enriches the projects' final outcome.

B. Design of a Dynamic Test Bench of an Aircraft Wing for a Wind Tunnel in Collaboration with ISAE

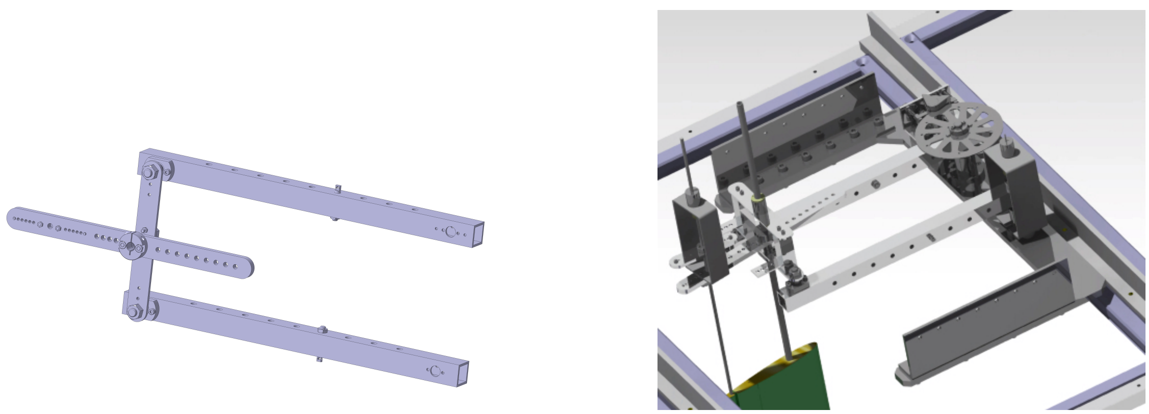
The presented project's goal was the design and prototyping of a dynamic test bench of a three DoF 2D airfoil for testing at the SABRE atmospheric wind tunnel in Toulouse, France. The prototype was to allow free movement in the plunge and pitch degrees of freedom. A full-span flap provided the third degree of freedom. The test bench is to be used as a platform to test the effect of a NES on the dynamics of the airfoil, in the context of a PhD candidate's research. The purpose of the NES is to control and lessen the effects of flutter on an airfoil. If the NES design proves successful, it may eventually provide airframe manufacturers the opportunity to decrease the overall structural weight of aircraft and correspondingly increase fuel economy.

The team consisted of 20 students studying in mechanical and aerospace engineering, as well as one student in electrical engineering. In the first phase of the project (lasting four months), the team was split into two groups in a design competition, representing the conceptual design phase. Preliminary concepts were developed and presented to the clients. Once feedback was received, the two teams were merged in a joint effort to produce the preliminary and detailed design of the product and to build the prototype over the following four months. The team was divided into four main groups: the structural team (10 members), the sensors team (4 members), the simulation team (4 members) and the management team (3 members). The structural team was tasked with designing the test bench's structure and NES. The sensors team was tasked with selecting the necessary sensors to collect data, creating a user interface for testing, creating a post-processing script for the data, as well as designing the test bench's security system. The simulation team was tasked with creating a MATLAB simulation of the 3 DoF system and validating the simulation data against experimental data and with similar simulations. The management team kept a global view of the design and supervised the team's spending. An amount of \$4200 CAN was allocated to the project by Polytechnique Montréal's funding (\$200 CAN per student). ISAE allocated an additional budget of €10 000 for the construction of the final test bench in France.

Mechanical Design

The overarching objective of the research project is to examine flutter as a function of various mechanical linkages between the main wing element and the flap. The overall theoretical framework is Nonlinear Energy Sinks (NES).

The airfoil is attached to a four-bar linkage that allows the plunge DoF. The linkage is connected to the wind tunnel by a set of linear springs, providing stiffness in plunge, simulating an aircraft wings structural stiffness. A bracket is placed on this linkage and is connected to the airfoil. It is free to pivot around its axis, placed at the airfoils quarter-chord length. Linear springs are placed between the bracket and the four-bar linkage, providing a torsional stiffness in the pitch degree of freedom, simulating the aircraft wing's torsional stiffness. The initial tension of all the springs can be balanced by placing them in the different holes seen on figure 3a.



(a) Airfoil Bracket on Four Bar Linkage

(b) Four Bar Linkage

Figure 3. Test Bench Mechanisms

These holes enable the clients to modify the stiffness properties of the test bench and evaluate the effect of the NES on a range of flutter speeds. Figure 1a shows the assembled concept inside the wind tunnel's test section. A mock-up of the SABRE wind tunnel was made at Polytechnique Montréal during the prototyping phase. Figure 3b presents the four-bar linkage and the airfoil bracket. The linkage's motion is limited by the security system to keep the system intact and free of material failure when flutter is attained. The material used for this linkage was aluminum for its high resistance, low cost, low weight and ease of machining. For the airfoil, a NACA0012 profile was chosen and was designed to be made with a carbon fiber skin and polystyrene core. The stiffness of each spring was chosen to ensure flutter would be attainable in the wind-tunnel's speed range $\left(20\frac{m}{s}\right)$.

Instrumentation and Data Acquisition

The sensors group chose to use RVITs[3] to measure the position of the three degrees of freedom. RVITs have the property of having an excellent resolution, being limited mainly by the DAQ[4] resolution and the noise present in the reading. As a secondary measurement system, accelerometers[5] were placed on the four-bar linkage and the airfoil brackets to receive acceleration readings. The coupling of the degrees of freedom makes it difficult to interpret results from the accelerometers. The data captured from the RVITs and accelerometers is read by the DAQ and presented through a LabView interface. The interface was designed to ease the viewing of critical information and system health. It also gives remote control of the emergency braking system to the user.

A customer requirement was the presence of an automated system that could stop the four-bar linkage in the eventuality that the system reaches flutter. This system was to be fail-safe in case of power failure to the circuitry. Furthermore, the system needed to be redundant in the plunge DoF, and also needed another system for the pitch DoF. The solution was to use three disk brakes in a "normally braking" state. Brake pressure is relieved by pulling on a steel wire, releasing the brakes. To allow movement in the three degrees of freedom, a tray attached to an electric actuator is retracted, pulling the steel wires and releasing the brakes. Each wire is attached to a panic snap linked to a solenoid. If divergence is detected or power to the circuitry is lost, the solenoid is deactivated and the panic snap releases the cable, reapplying braking pressure on the disc. To detect divergence, two infrared proximity sensors and two limit switches are attached to an independent logic circuit (see figure 4). The DAQ also monitors the position in each degree of freedom. If a critical displacement is reached, power to the solenoids is cut and braking is triggered.

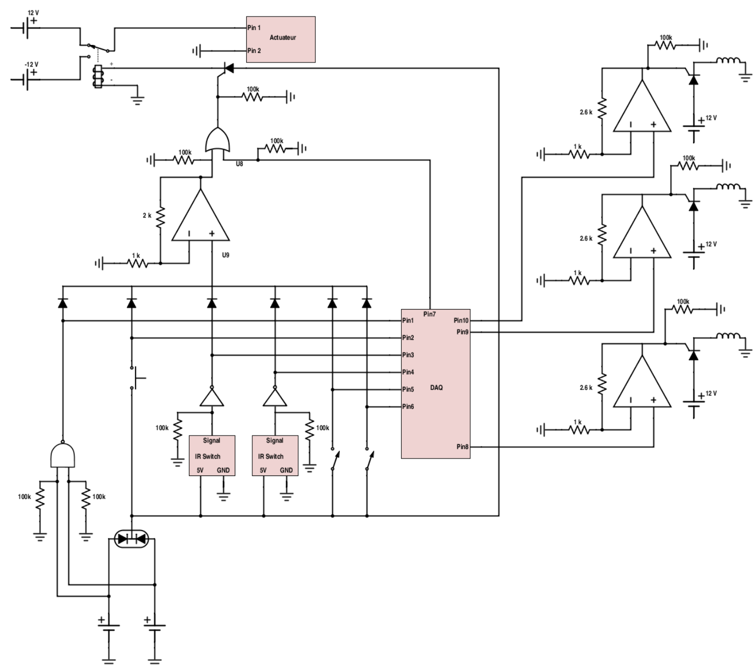


Figure 4. Logic Diagram of the Security Circuit

Simulation

In order to size the design, simulations were run to find the induced dynamic and aerodynamic loads on the structure. Utilizing Lagranges method, the formulae for the potential and kinetic energy of the system were used to develop the system's equations of motion. The system was not modeled as a perfect system and various dissipation sources from friction was taken into account. For the aerodynamics simulation, UVLM[6] code was employed and improved.[7,8] The resulting simulation creates a time-stepping model of the system. The simulation was created in MATLAB with Simulink. To ensure validity of the simulation, the results were validated by comparing with a Theodorsen model and linearized UVLM model provided by graduate level students. The simulation was also tested against results found in articles.[9] Figure 5 shows a sample output of the simulation.

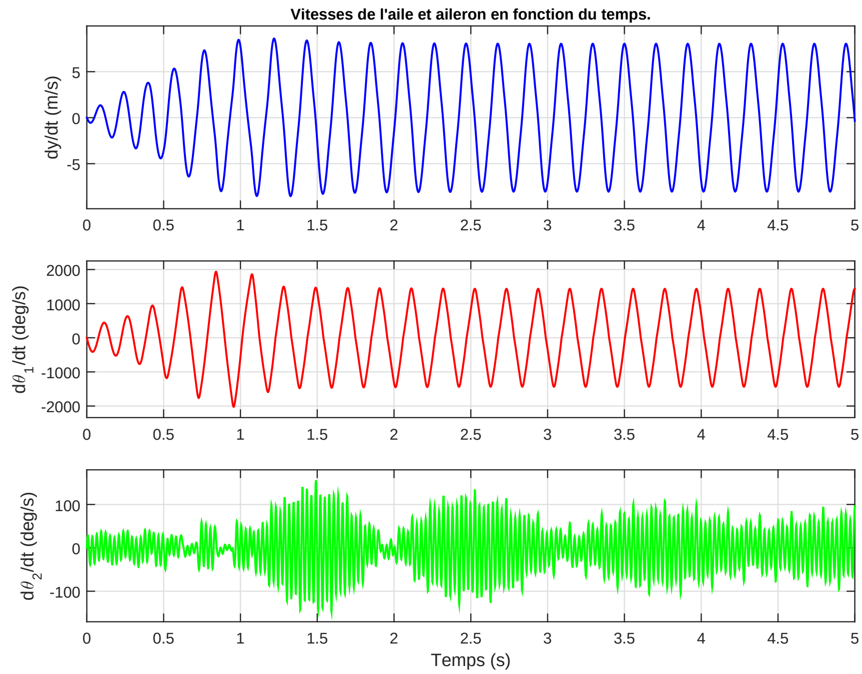


Figure 5. Sample Output of Simulation at Limit Cycle Oscillations (Flutter Limit) - Speed in the Plunge, Pitch and Flap Motion Degrees of Freedom (from top to bottom)

Project Deliverables and Experimental Results

While the complete test bench is to be built in France, the team prepared a prototype for demonstration in Montreal. The prototype included the four-bar linkage, the spring system the sensors and security system. The wing was made from laser-cut balsa wood instead of composite to lower the prototyping cost. The wind-tunnel test section was reproduced with a wooden frame to demonstrate the final assembly to the client. Polytechnique Montréal's wind tunnel was incompatible with the test bench, therefore no testing in a wind tunnel was possible. Although integrated test could not be achieved, sub-system tests have proven successful.

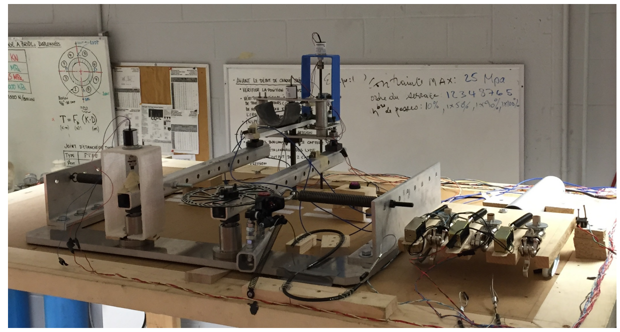
After calibrating the RVITs, the spring system was tested to ensure it was within design parameters. The prototype was imperfect, as free-play between critical assemblies created unexpected degrees of freedom in the model. To save money, parts were machined by the students. Mistakes during machining created zones where some moving parts would rub together, dissipating the system's energy. It is expected that the final assembly with accurately machined parts by the technicians at ISAE would be free of the extra DoFs and the excess friction.

The security system was proven to work as intended. The emergency brakes were tested with vigorous motion and proved to stop the wing immediately. The infra-red sensors and end-stops proved their ability to detect and stop the four-bar linkage whenever its angles exceeded the limits set.

The data acquisition was functional, but the signals received were very noisy, degrading the post-processing results. With a proper signal conditioning circuit and electromagnetic shielding, this effect will be diminished.

The prototype is presented in figure 6.

(a) View Underneath the Wind Tunnel Mock-Up



(b) View Above the Wind Tunnel Mock-Up

Figure 6. Polytechnique Montréal's Assembled Prototype

III. University of Southampton's Capstone Project

A. Overview of Southampton engineering programs

The University of Southampton requires every Integrated Masters student to undertake a group design project (GDP) in partial fulfillment to their degree. During the GDP, the students design and build projects within tight deadlines; testing the student's ability to work as a team and the effectiveness of the implementation and learning of skills from their previous studies. GDPs are used to help academics and external companies further their research and development by allowing students to work on their projects. The projects are continued in the following year by a new set of students, allowing the design to be pushed further. There is no set structure of how each GDP is undertaken, and it is up to the students to self-organize, with guidance from supervisors when appropriate. However during the preceding years of study, multiple group projects are undertaken to give a good basis and experience on how they should be approached.

B. Capstone Project - Design, Test and Build of an Aeroelastic Wind Tunnel Model

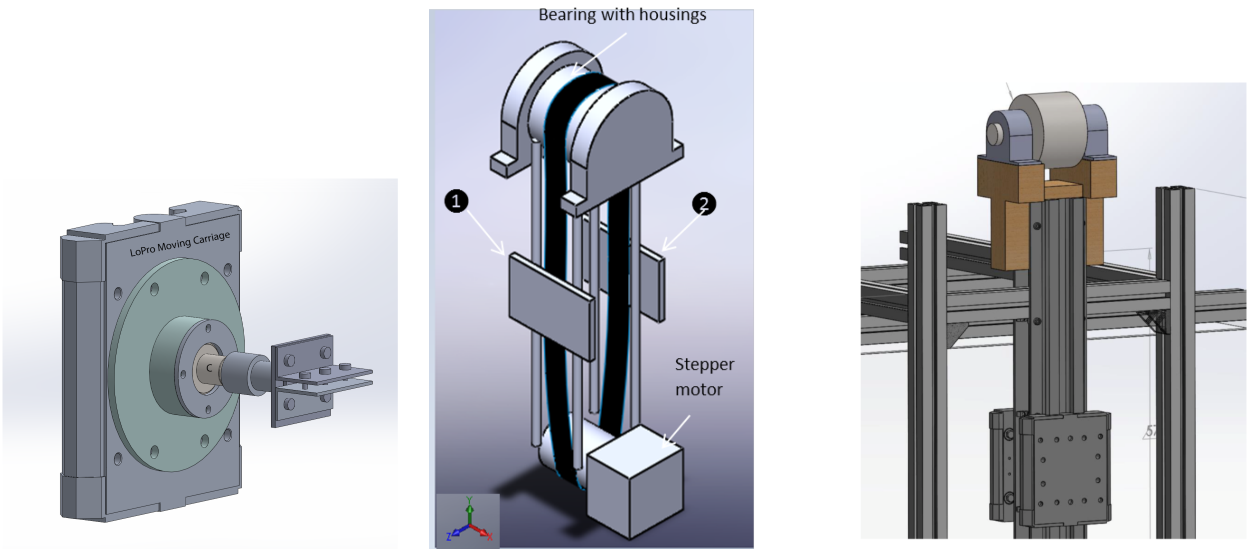
University of Southampton's project consisted of the design and testing of an aeroelastic wind tunnel model, for use in the University's wind tunnels. The model to be tested was to have two DoFs for a flat plate, or airfoil section. Simultaneously, different numerical approaches were undertaken to provide estimates of the expected frequencies, displacements and flutter speeds to compare with the wind tunnel model.

The group of seven students was divided into two sub-teams in order to pursue numerical and experimental research methods. At the start of the project, both groups worked together to research and understand aeroelasticity. Then, the three members of the numerical group each explored different methods of simulating aeroelastic phenomena in order to be able to predict or simulate the experiments. The experimental group took to the initial design of the testing rig. These designs were then developed throughout the project duration. This ensured that the next group of students to work on the project would have a 2 DoF rig to help develop their project.

While designing the testing rig, a temporary flat plate mount was manufactured, tand fully-parametric CAD models of various 3D wing structures were created. The test plan was then produced and experimental tests took place in March. In order to achieve the objective of the project, a number of resources had to be used. For aeroelastic analysis, the numerical group acquired three software packages: P2Strip, NeoCASS[10] and Nastran.[11]

Mechanical Design

The testing rig is transferable between different wind tunnels of different sizes and air speeds. The rig was designed to withstand greater forces than was required within the accompanying experiments, where the wind tunnel was limited to a maximum airspeed of $20\frac{m}{s}$. The testing rig has the ability to prescribe motion or have free motion in the pitch and plunge degrees of freedom. Motion in the 2 DoF have adjustable stiffness to help with modeling purposes. The plunge mechanism consists of two linear rails back to back, with a pulley and belt system. Two carriages are attached to the belt on alternate sides. One holds the mechanism for pitching, and the other acts as a counterbalance, as in some circumstances the wing may not produce sufficient lift to sustain the weight. At the bottom of the system, there is a linear stepper motor connected to a rotating bearing, to prescribe motion to the belt. Alternatively, this could be disconnected to allow free motion of the belt. The pitch mechanism uses a cam follower to provide the rotation which attaches to the plunge mechanism carriage. This cam follower and the sliding mechanism for plunge motion are purchased off-the-shelf. The cam follower is attached to the carriage as shown in figure 7a. On the opposite side of the attachment is a mount for wing or flat plate. The design was made as simple as possible and has screwed and bolted attachments. The purpose was to allow easy replacement, and larger cam followers to be attached depending on the loading conditions of the wind tunnel and wing.



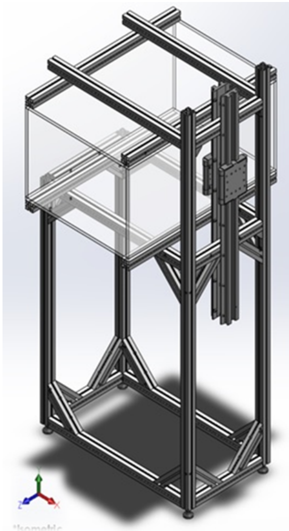
(a) Pitch Mechanism (b) Plunge Motion (c) Plunge Mechanism

Figure 7. CAD Models of DoF Mechanisms

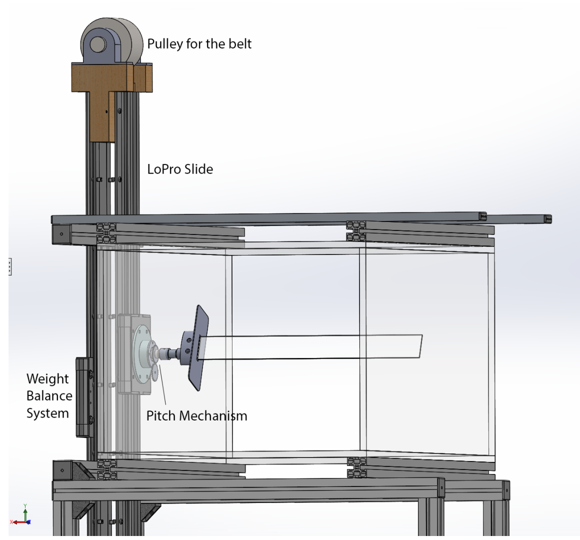
The external frame was designed with extruded sections and fasteners from the MiniTec framing company. It is designed to support the mass of the rig, to prevent inducing motion in the rails or wind tunnel and to be easily assembled and disassembled, for transport to alternative wind tunnels and storage. Representations of the design can be seen in figure 8a.

Design Experiments

Test rig has gone through multiple iterations and was developed during the course of the project. A static flat plate mount was designed to investigate the effects of flutter on a flat plate. Since the mount was static, motion in two DoFs came from the structural stiffness of the plate via its bending and torsional modes. The static mount had a circular design with a slot for the flat plate. The design was based on an existing component of the wind tunnel wall so the experiments could easily be set up, as seen in figure 9a. A hole was drilled through, to allow wires from the data acquisition system to pass outside of wind tunnel. As different plate materials had different thickness, small filler plates were made to provide a secure fit in the slot. The experiments that were undertaken used this static mount with a selection of different flat plate materials. They were tested in the wind tunnel at different angles of attack, increasing the tunnel wind speed until flutter occurred. The plates were designed to undergo flutter below the wind tunnel's maximum speed of $20\frac{m}{s}$. The data was collected with strategically placed accelerometers to capture the first three bending modes and first torsional modes of the flat plate. The plate can be seen in figure 9b.



(a) Rig Frame



(b) Final Design

Figure 8. Southampton's Final Design

Simulation

Three numerical approaches were used to predict the dynamic and static properties of the flat plate. Aeroelastic analysis has a combination of different disciplines, mainly aerodynamic and structural. A number of different ways were used to solve the problem. This project used P2Strip, NeoCASS and Nastran. P2Strip is a program developed to predict the dynamic behaviour for a 2D aerofoil. NeoCASS is part of the CEASIOM project and was used to help preliminary and conceptual design. Nastran is a commercial package able to perform multidisciplinary structural analysis.[12–15] All three approaches rely on different aerodynamic and structural models.

P2Strip used the classical theory of Theodorsen and a two dimensional structural model of a flat plate which is able to move in pitch and plunge DoF.[16] As the motion of the aerofoil tested was in 3D and P2Strip was 2D, the effective plunge and pitch stiffness for modeling was from the structural stiffness of the flat plate in bending and torsion. This was the simplest modeling method, hence the inclusion of two alternatives: NeoCASS and Nastran.

NeoCASS (Next generation Conceptual Aero Structural Sizing) is freeware, which employs different methods

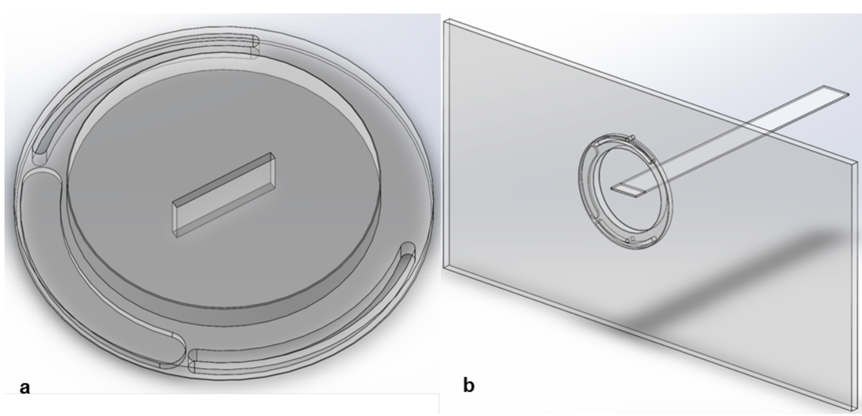
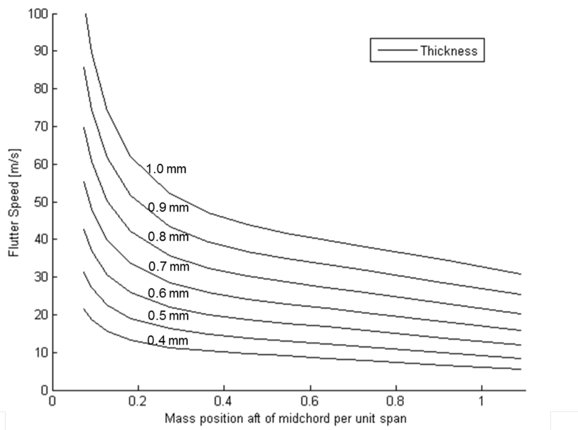
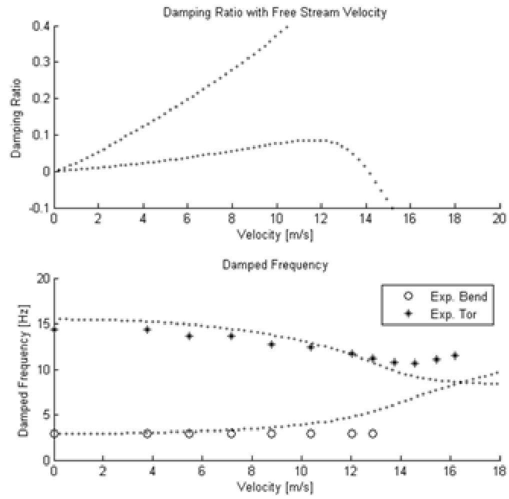


Figure 9. CAD drawing of a flat plate mount (a). CAD of flat plate mount fitted into wind tunnel, with 3mm acrylic flat plate fitted (b)

to perform aero-structural analysis upon a chosen geometry.[14] This project was originally developed as part of the CEASIOM project. NeoCASS[17] uses linear/nonlinear finite beam element methods, and the vortex lattice or doublet lattice method for its structural and aerodynamic resolution.



(a) Effect of 20g Mass Position Aft of Midchord and Plate Thickness on Flutter Speed



(b) Sample Output of P2Strip, Overlayed with Experimental Results

Figure 10. Simulated and Experimental Results

Nastran was originally developed for structural analysis.[18] This is commercial software and uses similar structural and aerodynamic models to NeoCASS, finite beam elements and the vortex lattice method.[19]

Simulations were used before the experiment to help choose a suitable plate that would undergo flutter within the constraints of the wind tunnel, which was limited to $20\frac{m}{s}$. Figure 10a shows one of the simulations that were used to help determine the sizing of the plate to undergo flutter. The results from P2Strip shows that a plate by itself is stable and may not flutter when the elastic axis and CG coincide. However by adding a weight to offset the distance of the center of gravity and elastic axis of the plate, a flutter solution exists and the speed at which it occurs can be varied depending on the CG location. This information, prior to experiments, gave a rough indication of when flutter would occur, at what speeds and under what mass loading conditions.

The Nastran and NeoCass programs successfully determined the mode shapes and oscillating frequencies of the flat plate in the wind tunnel. However the solvers were not able to produce plots for flutter speed. P2Strip produced results for flutter speeds which were close to experimental results. It is important to note that the P2Strip program operates for 2D airfoils while the experimental test bench has a 3D airfoil. Nevertheless, the results were close enough to be accepted. Figure 10b is an example of P2Strip. It plots the damping ratios of the first bending and torsional mode, and their respective frequencies with free stream velocities. There are two indications of when flutter occurs. The first, when the damped frequencies of bending and torsion start to coalesce, becoming coupled. The second, when the damping ratio of one of the modes passes through zero. Overlaid on this diagram are the experimental data points for the corresponding test case.

Further simulations were investigated, such as the dynamic response of the flat plate. These preliminary studies are the basis of where the following group in the University of Southampton's system will start and develop further. Figure 11 shows the dynamic response of the plate above, below and at the critical flutter speed. Above the flutter speed the oscillations increase exponentially.

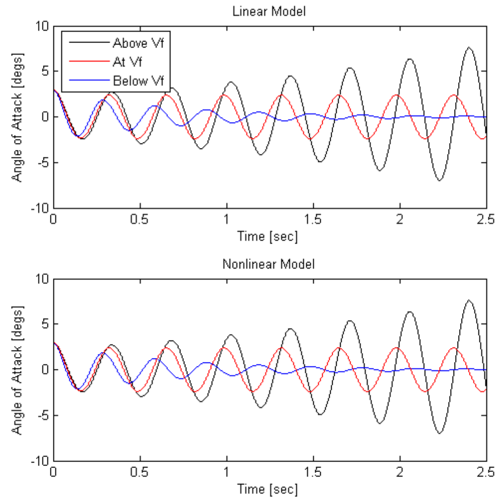


Figure 11. Sample Time Domain Simulation Response

Experimental Results

The experimental results showed distinct margins where the flutter speed would occur for different angles of attack. Figure 12 shows an initial increase in flutter speed with increasing angle of attack followed by a decrease in flutter speed for further increasing angle of attack for the aluminum, polyvinyl chloride and polycarbonate plates. The flutter speed for plate at 0 and -1 degrees angle of attack were unable to be recorded since the plate did not flutter before or at the maximum speed allowable in the wind tunnel. The peaks on the graph showing the highest flutter speed varies for each plate tested. This is likely due to the material properties of each plate and the difference in torsional stiffness between plates.

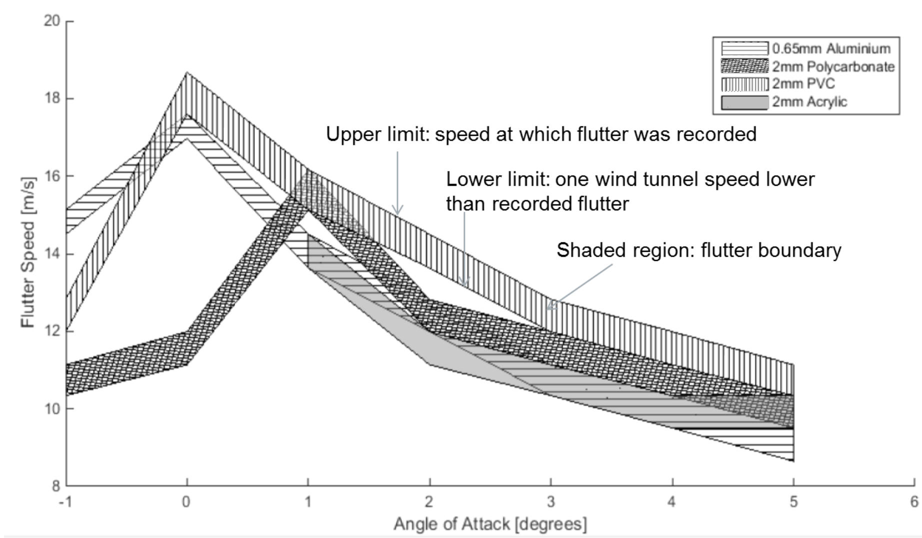
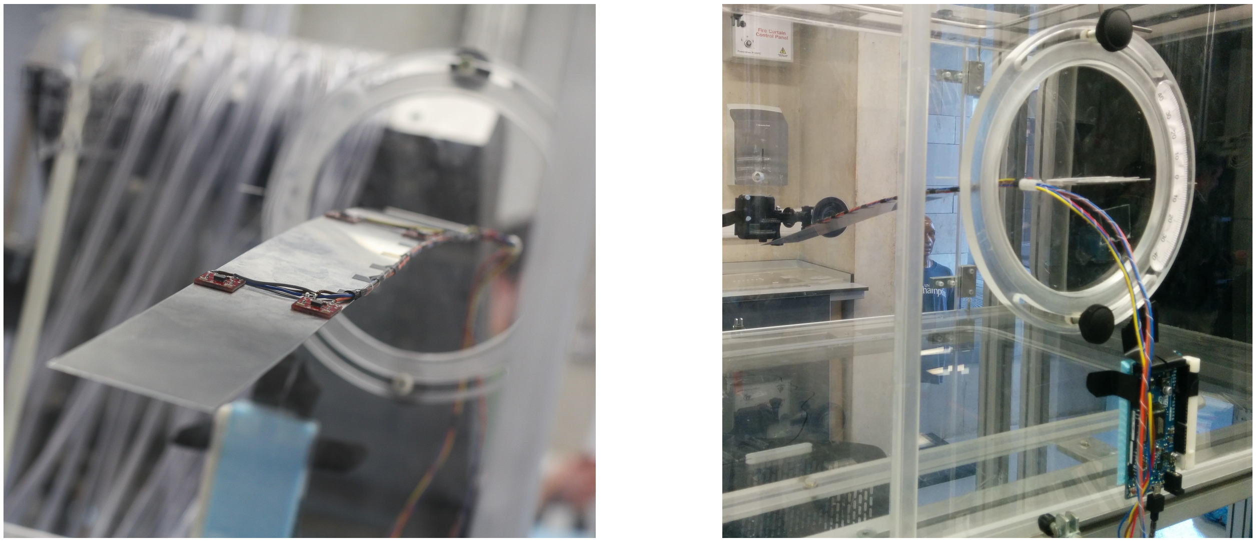


Figure 12. Experimental results

Summary

The aim of this project was to study various numerical approaches, in conjunction with experimental tests, in order to be able to predict and control the aeroelastic mechanism of flutter. The project was split



(a) Flat Plate with Accelerometers (b) Flat Plate Mount and Arduino

Figure 13. Southampton's Flat Plate inside Wind Tunnel

into two groups numerical and experimental. Each group achieved their goal: comparing results derived from theoretical predictions with experimental results. P2Strip predicted flutter speeds of the flat plate tested. NeoCass and Nastran produced mode shapes and predicted the natural frequencies of the plate. A transferrable experimental test rig was designed to be used in the different Southampton wind tunnels. It provides free and prescribed movement in two degrees of freedom. The combination of the experimental and numerical tools developed is the starting place for the following year's students, who are taking over the project. Figure 13 shows the flat plate inside the wind-tunnel.

IV. Conclusion

[The conclusion will highlight the results of both capstone projects. Furthermore, the similarities and differences between the project will be presented.]

References

[1]Ward, T. A., "Common elements of capstone projects in the world's top-ranked engineering universities," *European Journal of Engineering Education, p. 211-218*, 2013.

[2]Crawley, E. F., Malmqvist, J., Östlund, S., and Brodeur, D., *Rethinking Engineering Education: The CDIO Approach*, Springer, 2014, 2nd Edition 2014: ISBN-13: 978-3319055602 ISBN-10: 3319055607.

[3]Measurement Specialties, "Position Sensor - R120LC Series," 2015, url: http://www.meas-spec.com/product/t_product.aspx?id=2676/.

[4]Data Translation Inc., "DT9816 Series - 16-Bit, Up to 750kS/s Low-Cost Simultaneous USB Data Acquisition," 2015, url: http://www.datatranslation.com/products/dataacquisition/usb/DT9816/.

[5]PCB Group Inc., "Platinum Stock Products; Modal Array, Ceramic Shear ICP Accelerometer," 2015, url: http://www.pcb.com/Products.aspx?m=333B50.

[6]Katz, J. and Plotkin, A., *Low-Speed Aerodynamics*, Cambridge Aerospace Series. Cambridge University Press, 2001, isbn : 9780521665520.

[7]Ali, A. H., "Computational Method for Unsteady Motion of Two-Dimensional Airfoil," *Journal of Engineering 14.4*, 2008, pp. 3136–3152.

[8]Ramesh, K. et al., "An Unsteady Airfoil Theory Applied to Pitching Motions Validated Agains Experiment and Computation," *Theoretical and Computational Fluid Dynamics 27.6*, 2013, pp. 843–864, issn : 0935-4964. doi : 10.1007/s00162-012-0292-8.

[9]Tang, D., Dowell, E., and Virgin, L., "Limit Cycle Behavior of an Airfoil with a Control Surface," *Journal of Fluids and Structures 12.7*, 1998, pp. 839–858, issn : 0889-9746. doi : http://dx.doi.org/10.1006/jfls.1998.0174.

[10]Ricci, S. and NeoCASS Team, “NeoCASS,” 2012, (Version 2.0) [Analysis program], Available at: https://www.neocass.org/.

[11]MSC Software, “Nastran,” 2014, (2014 Version) [Analysis program], Available at: http://www.mscsoftware.com/product/msc-nastran-desktop.

[12]Da Ronch, A., Badcock, K., Wang, Y., Wynn, A., and Palacios, R., “Nonlienar Model Reduction for Flexible Aircraft Control Design,” *American Insitute of Aeronautics and Astronautics*, 2012.

[13]Da Ronch, A., Tantaroudas, N. D., Jiffri, S., and Mottershead, J., “A Nonlinear Controller for Flutter Suppression: from Simulation to Wind Tunnel Testing,” *American Institute of Aeronautics and Astronautics*, 2014.

[14]Cavagna, L., Ricci, S., and Travaglini, L., “NeoCASS: An Integrated Tool for Structural Sizing, Aeroelastic Analysis and MDO at Conceptual Design Level,” *Progress in Aerospace Sciences*, 2011.

[15]MSC Nastran, “Modal Frequency Response Analysis Using MSC.Nastran,” Tech. rep., MSC Nastran, Unknown.

[16]Patil, M. J., Hodges, D., and Cesnik, C. E., “Nonlinear Aeroelasticity and Flight Dynamics of High-Altitude Long Endurance Aircraft,” *Jourlal of Aircraft, vol. 38, no. 1*, 2001.

[17]Cavagna, L., Da Ronch, A., and Ricci, S., “NeoCASS Next Generation Conceptual Aero Structural Sizing,” Tech. rep., Dipartimento di Ingegneria Aerospaziale, Politecnico di Milano, 2009.

[18]Singh, A., “Applications of Nastran in Aeroelastic Analyses at Northrop,” Tech. rep., Hawthorned: MSC Software, 1978.

[19]MSC Software, “Aeroelastic Analysis User’s Guide,” Tech. rep., MSC Software, 2001.