Developing a laboratory session on wing aerodynamics

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INTRODUCTION

Aeronautical engineering has always been an attractive area of specialisation for many engineering students, mainly owing to its challenging and compelling nature. The University of Southampton has a long history of providing the Aeronautics and Astronautics Engineering course as one of their flagship courses. In the past few years, a continuous increase in the intake numbers of this course has led the Faculty of Engineering and the Environment to make significant investments in improving the student experience and retrofitting most of the modules involved in the course. This increase is reflected by the number of students enrolled as part of the 2nd year Aeronautics and Astronautics Engineering cohort: 95 students for the 2013-14 academic year, 112 students for the 2014-15 academic year and 124 students for the 2015-16 academic year. An integral part of this constant module update as a response to previous years' experience and feedback, occurring each academic year, is the design of laboratory sessions which are part of the summative assessments for the course and which complement the lectures and the self-assessed problem sheets. This paper describes the design of a new three-hour laboratory session on wing aerodynamics for the SESA2022 Aerodynamics module, a compulsory module for all second year aeronautical engineering students.

1 MODULES ALIGNEMENT

The SESA2022 Aerodynamic module (ECTS 7.5) is a Part 2 compulsory module that introduces fundamental concepts of aerodynamics such as inviscid flow, incompressible flow, compressible and viscous effects which are taught via 48 contact hours covering lectures, five formative tutorial sessions and four assessed laboratory sessions. The focus of the current paper is on the development of one of the laboratory sessions, the wing aerodynamics session, which also constitutes the largest contribution to the final module mark out of all laboratory sessions (10%). Fundamentally, the objectives of this experimental laboratory are measuring pressure distribution, lift and drag for 2D and 3D wing flows.

The ThermoFluids core module (ECTS 7.5) is the only pre-requisite for the SESA2022 Aerodynamics module since it introduces engineering students to thermodynamics and fluid mechanics principles. More importantly though, the Aerodynamics course is a pre-requisite for several advanced modules including Aerothermodynamics (ECTS 7.5), Wing Aerodynamics (ECTS 7.5), Race Car Aerodynamics (ECTS 7.5) and indirectly Hypersonic and High Temperature Gas Dynamics (ECTS 7.5). The core position of the SESA2022 Aerodynamics course in this overall module alignment, highlights both its theoretical and practical importance and showcases why the Wing Aerodynamics laboratory - which has the largest contribution to the final mark and is of interest here - is one of the main points of focus for the overall module development.

2 DEVELOPMENT OF THE LABORATORY SESSION

The main purpose of engineering laboratories is to provide students with an appreciation for the experimental method. During laboratories the students must have the opportunity to make phenomenological observations, critically assess them, ask relevant questions and validate theories [1]. The main development of the new laboratory session took place between 2012 and 2013 and has since run for three academic years. It included identifying the desired learning outcomes and aligning them with the module's aims and objectives (Table 1). The required scale of the setup was identified and an appropriate experimental facility was chosen (7 x 5 feet wind tunnel available in the Highfield campus). The new experimental setup, developed for the investigation of the aerodynamic performance of a wing, was designed and manufactured with the acknowledgement of the necessity of using experimental technologies for student laboratories and hence with the following design requirements [2]:

1. Ability to illustrate the difference in aerodynamic performance for finite and infinite span wings - fulfilled by designing a modular wing which spans the entire height of the wind tunnel, with the lower half easily removable
2. Allow for variable camber by the use of a flap – fulfilled by adding a plain flap which occupied a third of the total chord

3. Direct load measurements of lift, drag and pitch moment – fulfilled by using a six-axis sensor (forces and moments) mounted at the upper root of the wing. The sensor used is an ATI Delta SI-660-60 IP65
4. Direct pressure measurements across the upper and the lower surfaces of the wing by the use of suitably placed pressure taps – fulfilled by the use of 18 appropriately located pressure taps

Clear learning outcomes were established for the laboratory session so that an assessment procedure, capable of identifying the performance of the students, could be developed. This increased the effectiveness of the laboratory session and provided a basis for future improvements by focusing more resources on the more challenging learning objectives [3]. *Table 1* provides the aligned aims and objectives of the SESA2022 Aerodynamics module which are relevant to the experiment with the learning outcomes of the laboratory session.

Table 1: Learning outcomes mapping

Fundamental aspects of aerodynamics applied to aircrafts (module aim and objective): 1. Critically assess the applicability of the fundamental assumptions concerning the flow’s nature (inviscid, incompressible and irrotational) in the current experimental environment and their role in the subsequent data analysis. (laboratory knowledge-based learning outcome) 2. Explain the consequences of three-dimensional aerodynamic effects on performance (laboratory knowledge-based learning outcome) 3. Explain the effects of camber on aerodynamic behavior and how the flaps relate to their implementation in modern wing designs (laboratory knowledge-based learning outcome) 4. Critically assess the technical limitations of the experimental setup in delivering the necessary data for analysis (laboratory application-based learning outcome) 5. Explain the differences noted between aerodynamic performances measured directly and derived by integrating pressure (laboratory knowledge-based learning outcome) 6. Demonstrate technical aspects related to the experimental setup: how to mount/dismount the wing safely, how to calibrate the setup and how the setup is controlled (laboratory skills-based learning outcome)
Potential flow and its applicability to predict the approximate behavior of aerofoils (module aim and objective): 1. Explain under which specific circumstances thin aerofoil theory is applicable and how it relates to the experimental results (laboratory application-based learning outcome) 2. Describe key design features of wind tunnels that allow for potential flow assumptions to be made and how they relate to the measurement uncertainty (laboratory skills-based learning outcome)

The pre-requisite skills for this laboratory session are learning outcomes for the boundary layer laboratory which is scheduled two weeks before the wing aerodynamics laboratory: the working principle of a manometer, the working principle of a pitot tube and the concept of boundary layers.

3 STRUCTURE OF THE LABORATORY SESSION

The allocated time-slot of three hours allows for ample discussions and observations and is a key condition in fulfilling the extensive number of learning outcomes. For each laboratory session, ten students are scheduled on average, which allows for all participants to move inside the wind tunnel for an in-situ, interactive lecture.

The session starts with a 15-minute briefing focused on the desired learning outcomes and the expected structure and content of the laboratory report. A 40-minute question-based discussion follows, starting from the general design requirements of wind tunnels considering the desired flow. The applicability of each assumption (e.g. inviscid, incompressible and irrotational flow) is discussed in depth, as well as how it relates to Bernoulli's equation and its limitations. The experimental setup is then described in detail, including the wing design, the pressure taps and multimanometer, as well as the function and mode of operation of a pitot tube. The students then have to identify the limitations of the current setup and how it could be improved to allow better illustration of the desired experimental observations.

The experimental procedure follows next and is divided in two sections, the finite and the infinite wing experiments. The wing performance is examined in each case for different angles of attack and flap angles, by taking direct load measurements (via a load sensor) and pressure readings (using a multimanometer). The students are specifically asked to record analogue pressure readings so that they can better understand the concept of pressure, which would be difficult to achieve with a digital instrument. The pressure readings help them to understand the pressure distribution across the wing and identify the pressure behavior in the pre-stall, stall and post-stall conditions. The whole procedure is designed to get as many students involved as possible, especially in hands-on tasks: assembly/disassembly of the wing, alignment and calibration. They are also asked to actively participate in the theoretical explanations and observations throughout the session. These revolve around the chord-wise uniformity of the flow for the full wing case (i.e. infinite wing) and the lack of chord-wise uniformity and the presence of attached or detached tip vortices for the half wing case (i.e. finite wing). The experiments and data collection last 90 minutes.

4 LABORATORY SETUP

4.1 Description

The setup consists of the following components:

1. A 1.7 m chord carbon fibre skin with aluminium structure with a span of 0.3 m out of which the flap represents 0.1 m
2. A drive-sensor box for angle of attack and flap angle control consisting of two high torque stepper motors and an ATI Delta 6 axis sensor
3. A multimanometer connected to the wing's pressure taps which illustrates in a representative manner the pressure distribution across the wing
4. A control board which consists of a high power supply, two stepper drivers, a signal amplifier and a NI USB-6211 DAQ which samples the output of the sensor's amplifier
5. A computer running a control Matlab-based GUI

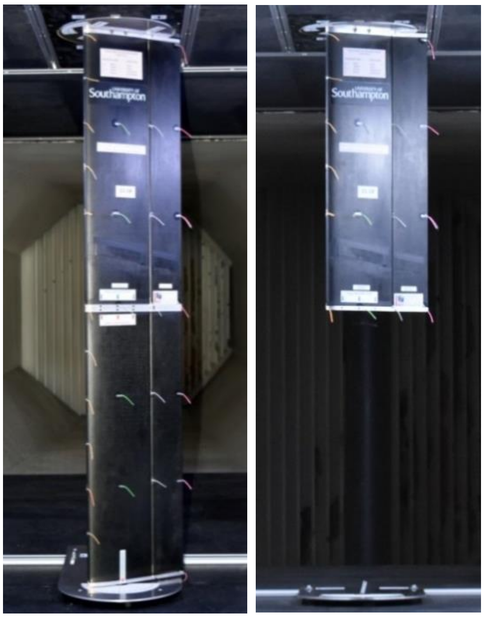

Fig. 1. The wing in full and half configurations

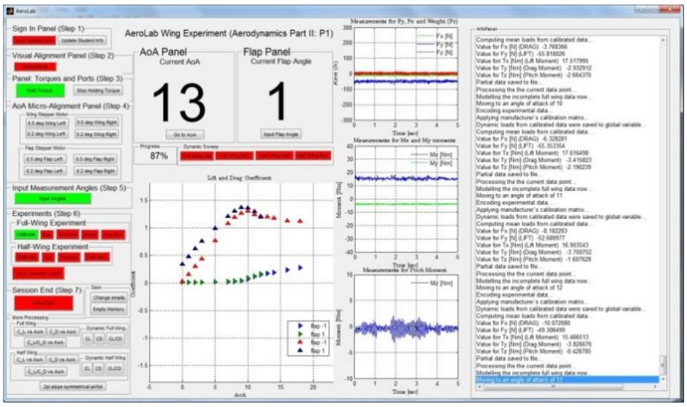

Fig. 2. Matlab control interface

Fig. 1 provides pictures of the final setup mounted in the wind tunnel in the two tested configurations; full wing to illustrate the performance of an infinite wing and finite wing to illustrate the impact of three-dimensional flow. Fig. 2 shows the Matlab GUI used for the control of the setup, data processing and plotting and laboratory session management.

4.2 Performance

A brief analysis of key data generated during the experiment is provided below.

Given the scale of the wing and the fact that the reference wind velocity is 20 m/s, measurements are carried at a moderate Reynolds number of 400,000. For each laboratory session, six angles of attack are strategically chosen along with one additional non-zero flap angle besides the zero flap angle case. This ensures that each group's set of data is different and that the flight envelope of the wing is fully exploited each academic year.

Fig. 3 and 4 provide the flight envelope of the experimental setup under finite wing (3D) configuration for different flap angles. The results closely corroborate the available literature on finite wings at similar Reynolds number. The experimentally determined results show a maximum coefficient of lift for the NACA0012 aerofoil of approximately 0.8 at a stall angle of approximately 13 degrees angle of attack [4][5][6]. In terms of the behaviour of the aerodynamic efficiency with varying flap angle, it can be observed that there is an efficiency penalty for negative angles of attack. The main reason for this is the use of 20 threads positioned on the in-view side of the wing to aid in the visualisation of aerodynamic behaviour. These threads have a negative impact on changing the overall surface roughness of the wing whose performance is sensitive to surface roughness variation at moderate Reynolds numbers [7]. Other key observations that the data illustrates is the fact that the stall angle steadily decreases with increasing flap angle and that the optimum angle of attack for maximising the aerodynamic efficiency decreases with increasing flap angle.

Fig. 5 and 6 provide the flight envelope of the experimental setup under infinite wing (2D) configuration for different flap angles. The results determined experimentally closely corroborate the literature available on 2D studies of NACA0012 aerofoil at moderate Reynolds numbers. The experimentally determined results for the current case give a maximum coefficient of lift of 1.2 measured at a stall angle of 11 degrees angle of attack [5][8]. As in the finite wing case, the difference in surface roughness due to the 30 threads attached to the in-view side of the wing increases the overall drag for negative angles of attack that in turn reduces the overall aerodynamic efficiency. Other key observations that the data illustrates is the fact that the stall angle decreases with increasing flap angle and that the angle of attack at which the aerodynamic efficiency is maximised, decreases with increasing flap angle. The stall region is also clearly illustrated by the plotting technique used. Furthermore, comparing across the 3D and the 2D cases, the overall reduction in both lift performance and aerodynamic performance due to three dimensional aerodynamic effects (such as wing tip vortices) is clearly illustrated by the experimental data.

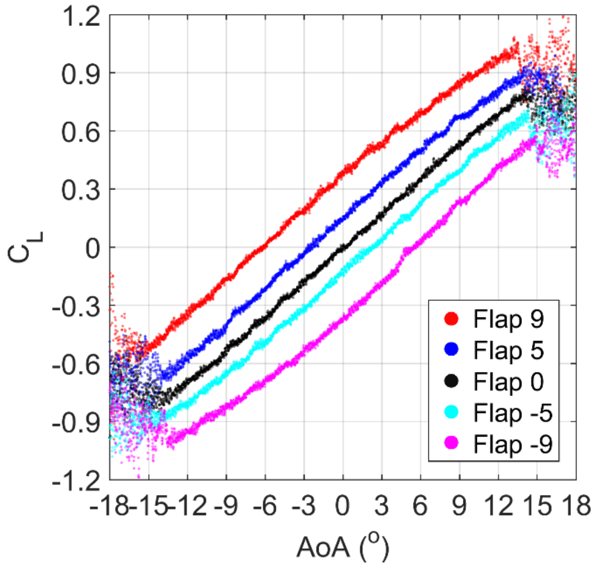

Fig 3: Lift coefficient envelope for the finite wing (3D) configuration with different flap angles

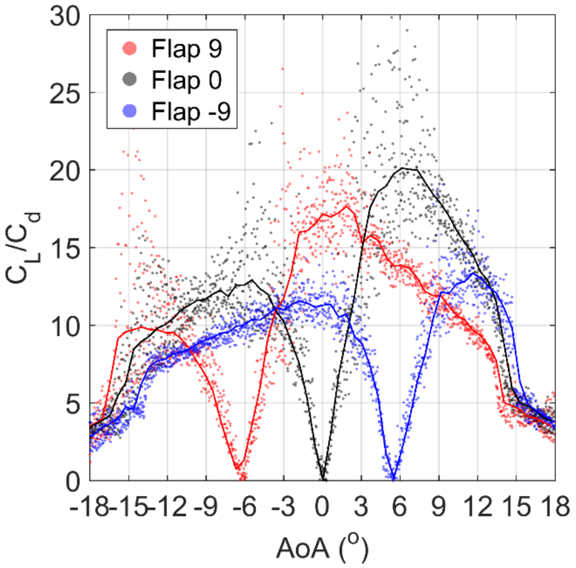

Fig 4: Aerodynamic performance envelope of the finite wing (3D) configuration with different flap angles

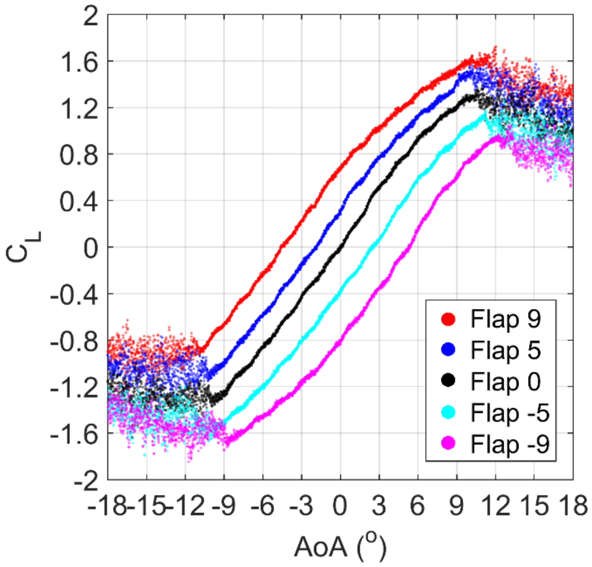

Fig 5: Lift coefficient envelope for the infinite wing (2D) configuration with different flap angles

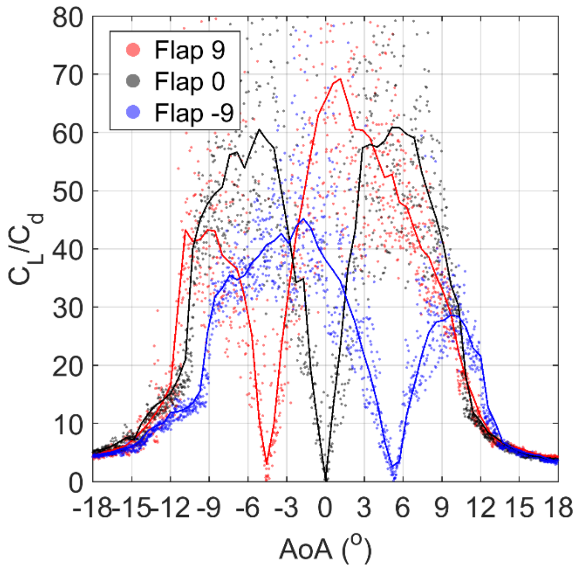

Fig 6: Aerodynamic performance envelope of the infinite wing (2D) configuration with different flap angles

The quality of the data generated during the laboratory session has been improved consistently throughout the past three academic years by adding new and improved calibration sequences which enhance the repeatability of the current experimental methodology. As it can be observed in Fig 3,4,5 and 6, the data generated during the laboratory session is capable of illustrating the intended learning outcomes.

5 LEARNING OUTCOMES FULFILMENT

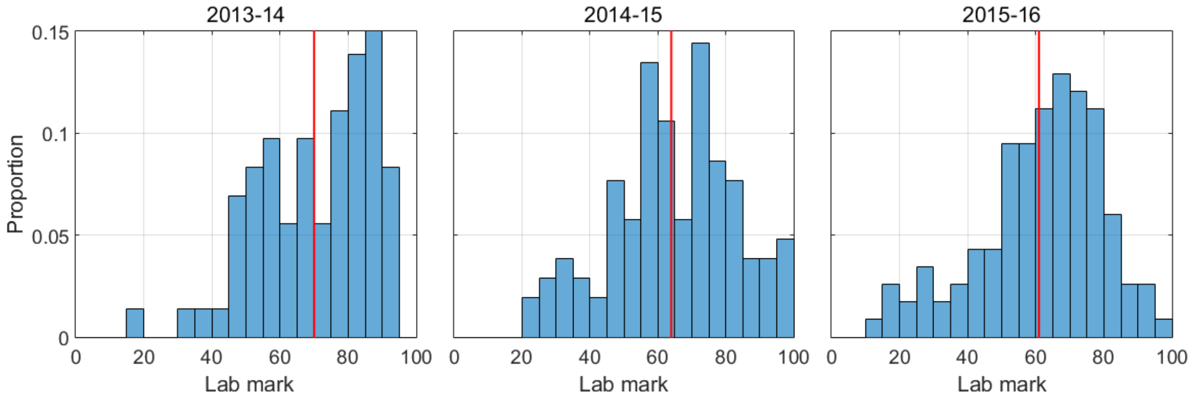

Fig 7: Proportion of students to achieve a certain mark for the laboratory session during the past three academic years. The solid red line shows the mean score.

Fig. 7 shows the distribution of marks obtained during the laboratory sessions over the past three academic years (2013-14, 2014-15 and 2015-16). These results are also summarised in Table 2, which shows the percentage of students falling within each grade bracket giving some indication to the proportion of students who successfully achieved the learning outcomes of the session. In the first two years the marks were reliant on the result of a pressure integration task which led to a clear division between high and low scores. Throughout the three academic years, due to the validation and repeatability of the experimental data measured, the marking scheme has shifted from a qualitative-based assessment to a quantitative-based assessment; the requirement for accuracy from the student's work has increased as the setup has matured and proved itself reliable. In effect, this has produced a normalized distribution of the marks achieved by the students. This has reduced the number of high marks that in previous years was disproportionate with the module exam, and the average has converged to approximately 61%. It was also observed that on average, the total number of students that fulfilled all or mostly all learning outcomes were a majority with 69.2% for 2013-14, 59.6% for 2014-15 and 59.4% for 2015-16 respectively, which is an encouraging statistic.

Table 2: Percentage of students falling within each grade boundary over the past three years

Mark	2013-14	2014-15	2015-16	
70+	53.9%	43.3%	35.3%	All L.O. fulfilled
60-69	15.3%	16.3%	24.1%	Most L.O. fulfilled
50-59	18.1%	19.2%	19.0%	Moderate number of L.O. fulfilled
40-49	8.3%	9.6%	8.6%	Some L.O. fulfilled
-40	4.2%	11.5%	12.9%	Mostly no L.O. fulfilled

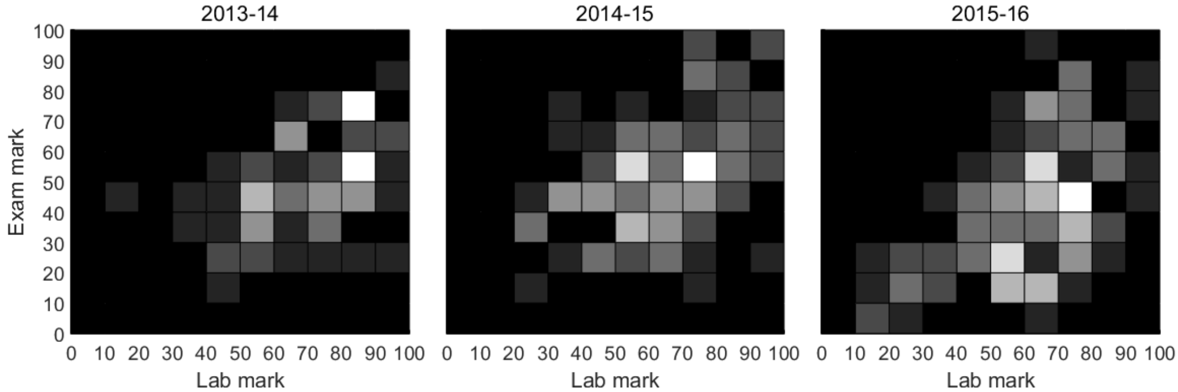

Fig 8: Comparison between laboratory marks and final exam marks obtained over the past three academic years. Lighter colour indicates a larger percentage of students. [9]

Fig. 8 compares the laboratory marks to the final exam marks obtained over the past three years. Lighter coloured areas indicate a larger proportion of students, while darker areas represent a smaller proportion. A similar weak positive correlation is observed between the two data sets for each of the three years, indicating that to some extent students who perform well in the laboratory session do better in the final exam. This result seems reasonable as although the laboratory learning outcomes do focus on a number of fundamental aerodynamics concepts important for the exam, they do not constitute the entirety of the syllabus. The average weighted exam marks for this module are 47.3% for 2013-14, 51.1% for 2014-15 and 49.6% for 2015-16 which are considerably lower than the average laboratory marks. This provides a better perspective for the fact that the correlation is more positive between high laboratory marks (60%+) and considerably lower exam marks (30%+).

6 STUDENT FEEDBACK

The main goal for the development of this laboratory session was to help students gain a better understanding of the course material and get a visual experience of the physical phenomena involved. Concepts such as pressure, stall, and flow separation are fundamental in aerodynamics but also notoriously difficult to grasp theoretically, so our primary focus was to design the session in such a way that the students could get a better insight into these notions but without severely detracting from the complexity of the underlying physics**.**

In order to assess the effectiveness of the laboratory's structure and deliverables, a survey was circulated among the students belonging to the previous three academic years. From the total replies received, 15% belonged to students that took the course in the first year (2013-14), 24 % in the second (2014-15), and 61% in the third (2015-16), showing a clear increase in response rates for later years. To provide further perspective on the student diversity, the gender breakdown is also provided: 13% female/ 87% male for 2013-14 cohort, 9% female/ 91% male for 2014-2015 cohort and 9% female/ 91% male for 2015-16 cohort. No further analysis in relation to gender is included in this paper. The survey, which was conducted between 5th – 15th of May 2016, was designed according to the University of Southampton standards, and was approved by the University's Ethics Committee (category C Research – ID 20369). It comprised of 8 questions of which 7 were multiple choice and one was a general comment on the laboratory. The questions focused on the helpfulness of the session in understanding the course material, how clear the learning outcomes were stated, the overall degree of difficulty and clarity of the laboratory session, the general assistance and feedback provided and the potential effect of the session on their interest in the subject. Here, we will focus on the first four points, which were the most relevant to our study. Earlier studies, also using feedback from students, have shown that problem-based learning and hands-on experiences in aerospace education increase the effectiveness of the courses according to the students [10], while the development of wind-tunnel experimental sessions [11][12] and use of visualisation techniques [11] are crucial for better understanding of the flow physics. The experimental experience further enables the students to perform better in design and construction courses [12].

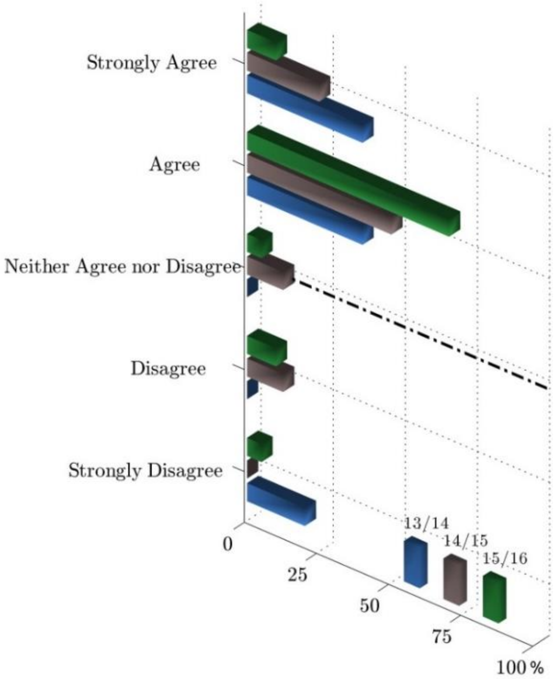

Fig 9: Student Feedback to question*:* Was the laboratory session *helpful* in understanding the course material?

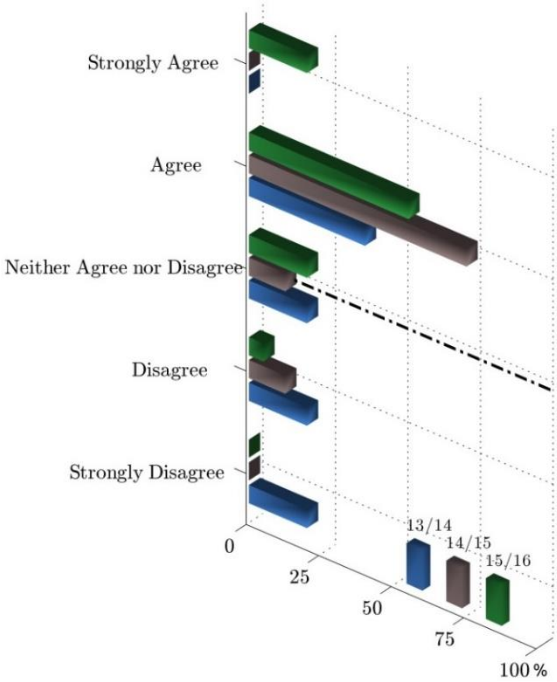

Fig 10: Student Feedback to question: Were the main learning points *clearly* stated?

Results showed that over 86% of the students found the session helpful in better understanding the course material and for 93.5% of them, the learning outcomes were clearly stated during the session (Fig. 9, 10). Even though the relative percentage of replies for the first two years is low to make definite statements, there seems to be an improving trend over the three years regarding the clarity of the learning points. This is encouraging since the structure of the laboratory session evolved over the three-year period with the aim of improving the clarity and enhancing student understanding.

Similar encouraging trends can also be observed in Fig. 11 regarding the overall clarity of the laboratory session, which was regarded as mostly positive by 83% of the students. This question referred to the entire laboratory session including handouts, experiments, explanations and discussions. In terms of how the students rated the difficulty of the session, Fig. 12 shows that 94% rated it as above average with almost a third of them rating it as very difficult. This last result, together with the positive response of the majority of the students regarding the helpfulness of the session in understanding the course material, supports the core of our efforts, which was to help students get a physical understanding of some fundamental but difficult and challenging concepts of aerodynamics without oversimplifying the underlying physics.

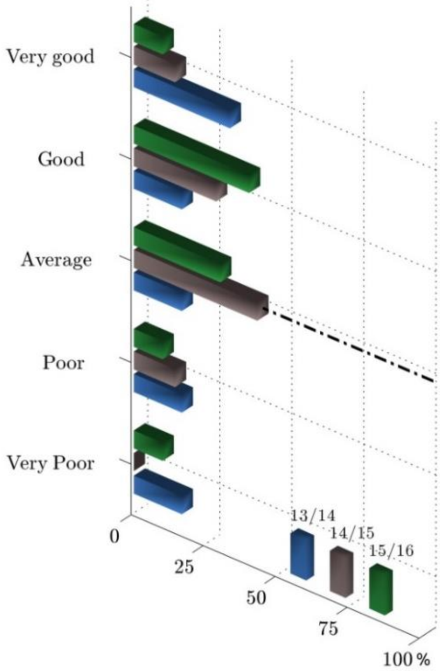

Fig 11: Student Feedback to question: How would you rate the overall *clarity* of the laboratory session?

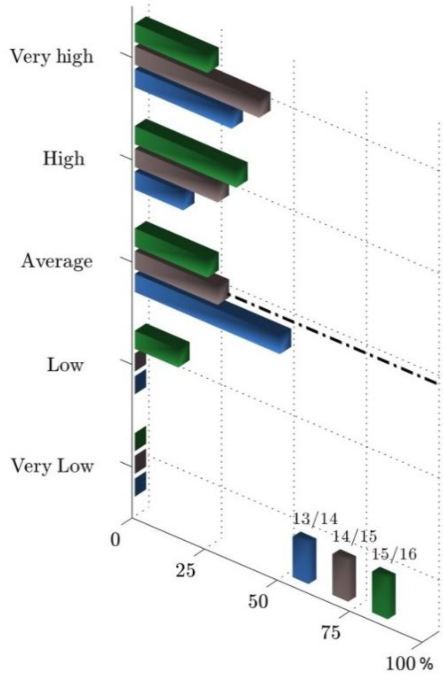

Fig 12: Student Feedback to question How would you rate the overall *difficulty* of the laboratory session?

7 SUMMARY AND ACKNOWLEDGMENTS

This paper has described the design and development of a wing aerodynamics laboratory along with discussing and analysing the desired learning outcomes and their degree of fulfilment which can be expected given its adequacy for a second year undergraduate degree laboratory. The analysis considers the qualitative results of student's experience and the quantitative results of the summative assessments. This provides a comprehensive view on the overall performance of the laboratory session and guides towards further improvements.

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