Flight Control System Design: Learning Enhancement Through Motion Based Flight Simulation

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Abstract*: In these modern times of flight automation, students of aerospace engineering need to learn the importance of flight control system design and stability. However few have any experience of the operation and dynamic performance of these systems. It is difficult for students to connect design procedures used in computer based design exercises with the practical behaviour of a system in flight. Experiential laboratory exercises have been designed using a motion based flight simulator to assist students in learning the impact of their design decisions by experiencing their control system responses 'in-flight'. This paper discusses the curricular aspects of flight control system design and the design of a simulation based experiential learning laboratory. It presents the outcomes of a questionnaire based learning assessment that shows substantial learning improvements are achieved. Student feedback indicates students draw great learning benefits through exposure to practical operation of flight control interfaces and consequent motion-based flight responses.*

Introduction

The School of Aerospace, Mechanical and Mechatronic Engineering (SAMME) at the University of Sydney operates its Variable Stability Flight Simulator (VSFS) (Figures 1 and 2) as an instrument for providing experiential learning in flight mechanics. The topic of flight mechanics covers analysis and design principles associated with aircraft flight stability, handling qualities assessment and control system design. The intention is that by experiencing these phenomena 'in-flight', students can better understand the roles of various aerodynamic and control design parameters and can develop *good design practice* in the generation of the final aeronautical product. The use of the VSFS for the improvement of learning in aircraft handling qualities has proven to be very successful (Gibbens, Medagoda and Dumble, 2009). This paper addresses the extension of its application to the teaching of flight control system analysis and design, and the assessment of its impact in terms of learning outcomes.

Figure 1: Variable Stability Flight Simulator

Historically, flight simulation commenced as a means for pilot training. It is only recently that they have been used for engineering training in an academic environment. Many of these developments address the teaching of handling qualities (Tomczyk, 2008, Hsiao, et.al. 2000, White & Padfield, 2006). Some have been developed to address the teaching of flight control systems (Twigg & Johnson, 2003, Fennell & Hemmens, 2000, Cotting et. al. 2007), though most do not involve motion. For those that do there is little detailed information on how they have been implemented in coursework, how effective they are in learning improvement, or how this has been assessed. In control systems engineering teaching, it is well known that there is a critical teaching gap between theory and practice. In fact a common complaint from

Figure 2: VSFS Cockpit Learning Environment

employers of control engineers is that students need more laboratory and hands-on experience. Kheir, Astrom et. al. (1996) outline the importance of practical experience in learning control systems engineering. They primarily address control engineering in mechatronics, manufacturing, process and electrical engineering applications, though the issues are generic to all disciplines. They particularly stress the pedagogical benefits of experimentation, logic and sequencing training, CAD and the use of simulation as a means of making experimentation more accessible and affordable. Experiential learning through simulated practical exercises appears to be a key element in future engineering education.

In the aeronautical context, this can be provided by flight simulation facilities that are intended by their nature to provide realistic experience. In this case the intention is to utilise flight simulation as a means of demonstrating the effectiveness of autopilot systems and particularly to allow students to implement and fly their own designs and to compare them to 'control' autopilot designs. Inherent in this strategy is the goal for the student to experience the stability and performance of these various solutions by observation of the subsequent aircraft responses. It is the transient responses that are of most importance in this regard. These can be observed by the student through observations of flight instruments like the Air Speed Indicator (ASI), Vertical Speed Indicator (VSI) and Altimeter (ALT), for speed and climb rate, Direction Gyroscope (DG) and Attitude Indicator (AI) for heading direction and bank and pitch angles, and via the visual cues of an image of the outside world available through projected or collimated displays. However, as is the case in flight training and engineering training for handling qualities, it is the vestibular feedback afforded by simulator motion that gives the student the most immediate appreciation of the dynamic responses, in this case, of the control system. It is this factor that exemplifies this current work in providing true experiential learning of control system responses, allowing students to connect good and bad design practices with their consequential transient dynamics and stability properties.

In this paper we present an outline of simulation based experiential learning laboratory exercises introduced into coursework at the School of Aerospace, Mechanical and Mechatronic Engineering at the University of Sydney in 2009, and an assessment of the learning benefits that they afford students. The course AERO4560 Flight Mechanics 2 is a final year unit of study in Aerospace Engineering and builds upon previously developed skills in flight stability and handling qualities (Gibbens, Medagoda and Dumble, 2009). Students study the response of an aircraft to control inputs, the response of the aircraft to stochastic inputs (wind gusts), and develop flight control systems to manage the flight path and to reject the effects of wind gusts on the aircraft's flight. The final component of the course is a major project involving the design of stability augmentation and autopilot control systems. The simulator laboratory is then used to demonstrate the effects of well-designed, badly-designed and (if available), their own design of control solutions. As part of the exercise, the students are guided through a structured sequence of test points in which they fly the aircraft and engage the various controllers through the same control interfaces used by pilots. In this way they experience the transient performance characteristics of the closed-loop aircraft response and can connect these with their observations of their own controller performance from their analysis and design stages. This exercise has the secondary benefit of familiarising engineering students with the equipment and processes used by operational pilots, thus they learn by first-hand experience the roles and functionality of the various cockpit instruments and avionics systems.

Experiential Learning

In 2009 the major project statement involved the development of longitudinal control systems for the management of the dynamics and flight path in the vertical plane of a turboprop training aircraft. This aircraft model is chosen due to its agility, thus making the dynamics of the aircraft and control systems very observable for students. The goal is to modify the natural pitch characteristics and to control the vertical speed (climb rate) and altitude behaviour of the aircraft with a vertical speed autopilot, and to manage the airspeed with an auto-throttle. The students design control loops and then analyse the performance of the controllers and the effects of wind gusts using CAD tools (MATLAB).

The experiential learning exercise involves a session in the flight simulator in which students fly the aircraft and engage the autopilot and auto-throttle in order to study the transient behaviour and hence stability of the control solutions obtained. Two standard control solutions are provided, one 'good' controller and one ‘bad’ controller. These are used to highlight the ramifications of good and bad control design practice on the stability of the closed-loop aircraft behaviour. They are provided with design information that students can use to connect the flight results with particular features or flaws in design practice. If students have their own solutions available, they can be embedded in the simulator and flown so that students can reflect upon their design process after observation of the flight results (relative to the behaviour of the good and bad solutions).

The simulation session procedure is outlined in a guideline document provided to students in advance so they can familiarise themselves with the procedure as well as the equipment. The session involves a number of scenarios involving the independent operations of the vertical speed autopilot and the auto-throttle, as well as their operation in conjunction. Table 1 details these scenarios and their purposes. The session involves running through this sequence of scenarios four times:

1. At the design condition 150Kn at 500ft, with well-designed controllers,
2. At the design condition 150Kn at 500ft, with badly-designed controllers,
3. At the off-design condition 90Kn at 500ft, with well-designed controllers,
4. At the off-design condition 90Kn at 500ft, badly-designed controllers.

giving a total of 24 test points.

Test Point	Scenario	Purpose
1	Open Loop.	To establish steady flight condition and feel for the aircraft response to the pilot.
2	Vertical Speed mode and Auto-throttle engagement – steady state.	To establish nominal autopilot performance and to hold a steady flight condition.
3	Vertical Speed mode engagement, climb at 1000 ft/min (without Auto-throttle) – no airspeed management.	To observe the transient performance of the vertical speed autopilot. To observe cross-coupling with the airspeed response. Airspeed will not be maintained.
4	Vertical Speed mode engagement with Auto-throttle, climb at 1000 ft/min – constant airspeed climb.	To observe the transient performance of the vertical speed autopilot and auto-throttle. To observe cross-coupling with the airspeed response. Airspeed will be maintained at nominal airspeed after transient response settles.
5	Vertical Speed mode engagement (0 ft/min) with Auto-throttle – level flight acceleration, increase airspeed by 30Kn.	To observe that with the vertical speed autopilot engaged, the airspeed is managed with auto-throttle. Observe performance of the vertical speed autopilot in maintaining level flight as airspeed changes. Observe airspeed transient response. Observe cross-coupling.
6	Auto-throttle engagement (without Vertical Speed autopilot)– level flight acceleration, increase airspeed by 30Kn.	To observe that with no vertical speed autopilot engaged, the auto-throttle will not manage airspeed due to the aircraft’s natural flight stability.

Table 1: Flight simulation scenarios

The control solutions are designed specifically for the dynamics that the aircraft exhibits at a given flight condition – in this case 150Kn airspeed at 500 ft altitude. One of the major issues with control design is the robustness of controllers to variations in the operating point. Thus the performance of each of the controllers is demonstrated at an off-design condition (in this case 90Kn airspeed at the same altitude) to highlight the robustness (or lack thereof) of the design solutions. This is observed by the student through the inadequacy of the transient behaviour of the controllers, by feeling the motion and via the behaviour of the flight instruments.

For each scenario, students are given instructions in the guidelines in how to operate the equipment (also delivered verbally by the instructor during the sessions). An example sequence is given below for Scenario 4. The instructions pertain to the operation of the control system through the Autopilot Mode Control Panel (MCP) interface shown in Figure 3. They then observe the subsequent transient response through vestibular feedback from the motion, through visual feedback from the outside world display, and through the highlighted instrument readings on the instrument panel shown in Figure 4. The effect of the auto-throttle is also sensed through audio feedback of engine RPM.

Scenario 4: Closed Loop – Vertical Speed mode engagement with Auto-throttle – constant airspeed climb

1. Set 1000 ft/min in the V/S command window using the thumbwheel.
2. Sim will be started. Engage the vertical speed autopilot by lifting the 'DISENGAGE' bar, pressing an autopilot button (L will suffice) and then press the V/S button.
3. Engage Auto-throttle as quickly as possible as too much airspeed loss will be difficult to recover. Engage the auto-throttle by lifting the 'A/T ARM' toggle switch and by pressing the 'SPD' button on the MCP panel. Observe the airspeed to settle at 150Kn.
4. The aircraft will enter a climb. Check for any enduring steady-state error in Indicated Airspeed (IAS) or Vertical Speed (V/S). Take note of the transient behaviour of the V/S needle in reaching 1000ft/min – speed of response, amount of overshoot.
5. Observe the airspeed response – the aircraft will initially lose speed as the thrust increases but it will recover to 150Kn. Note rate of speed loss and amount of overshoot as it reaches the target IAS.
6. Sim will be put on hold (re-set initial condition). Disengage the autopilot by lowering the 'DISENGAGE' bar and switching off the 'A/T ARM' toggle (down).

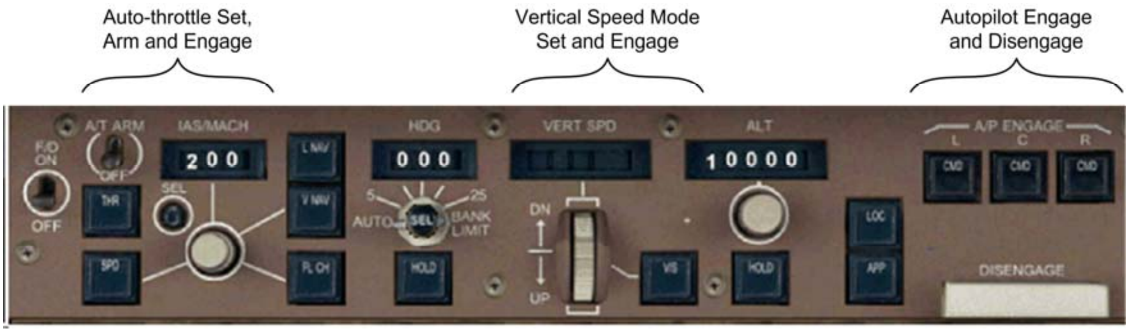

Figure 3: Autopilot Mode Control Panel (MCP)

Figure 4: Typical instrument panel showing ASI, AI, VSI, ALT and DG instruments

Appraisal of learning effectiveness

Students participated in the laboratory exercise near the conclusion of the design assignment and just prior to the examination period. They were surveyed before and after the simulation exercise to assess its direct impact on student knowledge and understanding of concepts. The surveys are therefore a good gauge of their knowledge improvement represented by the practical exercise and the effect it will have on their final result. Questionnaires were completed that include a section of student self-assessment, a section of assessor based questions, and a section of written responses relating to the students' responses to the lab exercise and the facility. These allow a variety of assessments to be made. Firstly, the correctness of student understanding from the assessor perspective, secondly, the effectiveness of the exercise from the student perspective, and to collect impressions and suggestions regarding the simulation experience. Students are not *directly* assessed towards their course results in the lab exercise. The lab exercise is performed solely for the purpose of improving student learning of key concepts. The learning outcomes are instead intended to improve student performance in examinations and other assessments. Survey assessments are performed only for the purpose of analysing the effectiveness of the teaching system in terms of student learning outcomes.

- **Student self analysis** – Students are requested to rate their understanding of key concepts on a scale of 1-5 where 1: Very poor, 2: Poor, 3: Average, 4: Good, 5: Excellent. Improvement is analysed by comparing the average before and after levels, and the difference. Percentage improvement is judged by comparing the increment relative to the scale of 5 (e.g. 1.1/5=22%).
- **Assessor analysis** – the assessor analysis segment of the questionnaire involves six-part multiple choice responses to a set of 18 questions that target specific knowledge concepts. Correctness is analysed before and after students undertake the laboratory session. The results are collected into categories and presented for each knowledge category. They are shown on a scale showing the percentage of students giving the correct response.

Learning Outcomes

Overall learning outcomes: Both student self analysis and assessor appraised result show that the laboratory exercises improve student understanding in key concept areas significantly;

- **Student self analysis** – Analyses of responses shown in Figure 5 indicate that students consider they achieved significant overall improvement (~14-38% for the various key concepts, average 22%) in understanding from the simulation exercise.
- **Assessor analysis** – Important outcomes from the assessor analysis are that the students are on average improving their knowledge in these concept areas by 13%. Figure 6 shows improvements for individual concepts range from 4% to 21%.

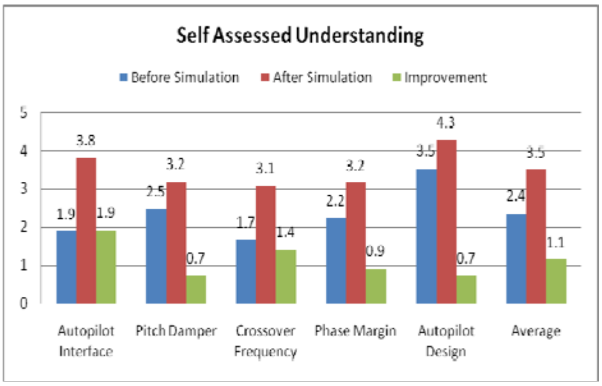

Figure 5: Student self-assessment levels

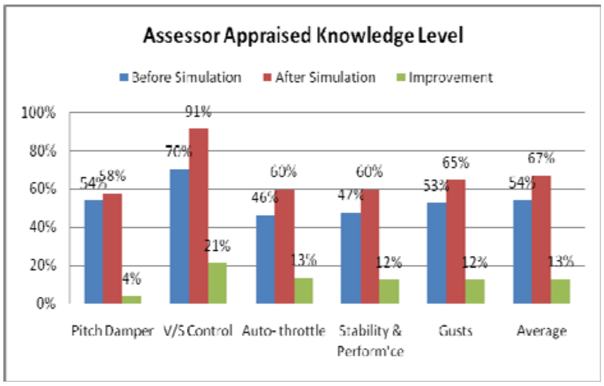

Figure 6: Assessor appraised knowledge levels

Demographic outcomes: In (Gibbens, Medagoda and Dumble, 2009) it was found that significant advantages were gained by students with little or no piloting experience in the learning of the connection between aerodynamics and aircraft handling qualities, relative to those with flight experience. This was not unexpected as one of the main goals was to reach those that had not had the benefit of experience. Figure 7 shows that in this case both groups have shown improved knowledge from the simulation experience, though the difference between them is not great. In fact it is the group with flight experience that has benefited slightly more. It is hypothesised in this case that this may be due to the coverage of material that is beyond the prior experience of both groups. The pilots among the group are not instrument rated and therefore have little prior experience of automatic control systems in-flight. They would, however, be expected to have a more natural aptitude for these systems and should be expected to pick up these concepts more quickly. The experienced pilots make the same level of improvement in most areas, but from a higher base level. A breakdown of the key concept areas shows that the key gains for the experienced pilots are in the areas of auto-throttle operation and sensitivity of the control system operation to gusts, areas they might be expected to pick up easily.

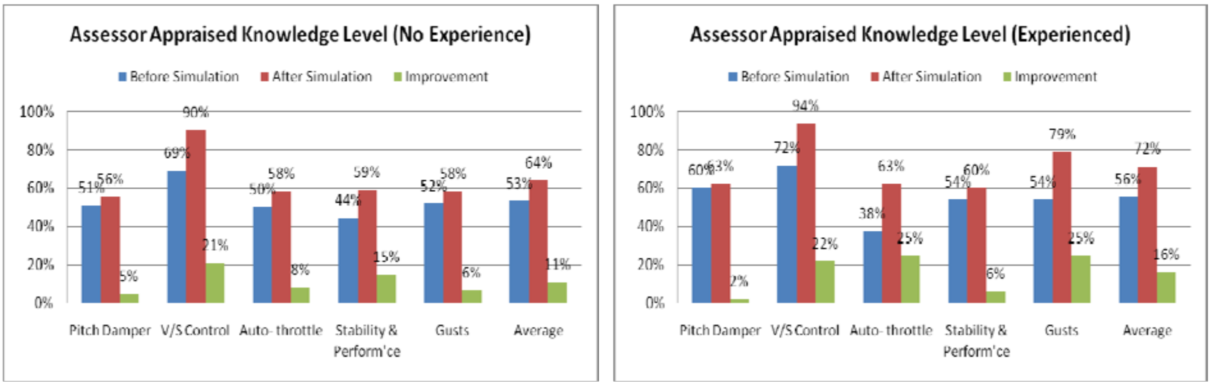

Figure 7: Knowledge levels for students with and without piloting experience.

Conclusions

The flight simulation system and learning exercises presented herein have been specifically designed to address a pressing need for experiential learning in avionics and flight control system design. This is an area in which students would not usually be exposed to the real physical outcomes of their design efforts due the expense and inaccessibility of testing avionics systems in-flight. Such experience would normally be obtained on-the-job in industry and so injecting experiential learning into tertiary education will prepare students better for industry placement. These initiatives are a novel implementation of experiential teaching techniques in a highly specific area of training. They have been shown to provide significant learning benefits by before and after knowledge analysis.

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