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Analysis of Aircraft Actuator Failures within an Undergraduate Experiential Learning Laboratory

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ORIGINAL RESEARCH

Abstract

The design and implementation of an undergraduate laboratory is presented for the analysis of aircraft actuator failures through simulation. The laboratory was developed in the context of introducing aerospace engineering students to the practical implications of subsystem malfunctions on aircraft dynamics, performance, and control within the general framework of aircraft health management. However, the laboratory assignment can be a valuable addition to other courses in flight dynamics and controls. Advanced simulation tools are used to illustrate concepts and allow students to identify the dynamic fingerprint of aircraft actuator failures and investigate qualitatively their effects on system performance and handling qualities. The computational package relies on Matlab® and Simulink®. The typical aircraft aerodynamic control surfaces are targeted in the assignment: aileron, elevator, and rudder. They can be locked at trim or at a different deflection. The main objective of the lab consists in capturing the dynamic fingerprint of actuator failure as a necessary premise for the development of fault tolerant control laws and schemes for subsystem failure detection, identification, and evaluation. The students receive general guidelines on how to design and execute the simulation experiment; however, they are required to answer open-ended questions and encouraged to investigate and follow personal paths in reaching the objective of the assignment. The general design and implementation of the assignment employs active and experiential learning approaches and promotes student initiative and creativity. Instructor direct assessment and student formal feedback demonstrate that active and experiential learning methodologies using numerical simulation are received positively by students and prove to be effective in increasing student motivation and participation and generally enhancing the academic process.

Keywords: Aircraft Health Management, Active and Experiential Learning

Related ASEE Publications

[8] M. G. Perhinschi and D. Azzawi. “Undergraduate Experiential Learning Lab for Aircraft Parameter Identification,” *Computers in Education Journal*, vol. 5, no. 2, pp. 79–92, 2014.

[7] M. G. Perhinschi and F. Beamer. “Flight Simulation Environment for Undergraduate Education in Aircraft Health Management”,” *Computers in Education Journal*, vol. XXII, no. 3, pp. 50–62, 2012.

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1 Introduction

The design, manufacturing, and operation of modern complex technological products require an integrated interdisciplinary approach referred to as system engineering [1]. For an aircraft, a major component is represented by the aircraft health management (AHM), which is aimed at ensuring maximum safe operation within affordability constraints [2, 3]. AHM must be considered throughout the entire lifecycle of the system including design, production, operation, and maintenance. The importance of safety for the aerospace industry and research community is expected to continue to grow and, consequently, so does the responsibility of the higher education system to ensure proper workforce background in this area [4]. While system operation under nominal design conditions is addressed systematically, operation under abnormal conditions (ACs), when any subsystem malfunctions or encounters off-design situations, is much more difficult to handle, due to the immense diversity of possible scenarios, complexity, multi-dimensionality, and uncertainty.

Academic efforts at West Virginia University (WVU) have been focused on including elements into the aerospace engineering curriculum that are relevant to aircraft operation under abnormal flight conditions [5, 6]. Specifically, an undergraduate technical elective course is regularly offered addressing main concepts and important components of AHM [7, 8]. It represents a unique attempt in aerospace engineering undergraduate education from the point of view of both the content and its simulation support. As part of this course, a laboratory assignment is implemented focused on identifying the dynamic fingerprint of aircraft actuator failures and investigating qualitatively their effects on system performance and handling qualities.

The lab assignment is supported by an advanced simulation package [7] developed in Matlab® and Simulink® that allows user-friendly on-line interaction with students for setting up diverse scenarios including failures affecting major aircraft subsystems. Basic knowledge working with Matlab® and Simulink® is necessary for the students to be able to record and process simulation data.

Active and experiential learning approaches [9, 10] have been instrumental in designing and implementing the assignment due to their demonstrated capability for increasing the effectiveness of the learning process.

After this brief general introduction, the required student background in flight dynamics and experimental design concepts is summarized in section 2 and 3, respectively. The simulation tools used are briefly described in section 4. The assignment objectives and learning outcomes are outlined in section 5. Laboratory instructions, requirements, and output examples are presented in section 6. A brief discussion on the assessed educational impact and student perception is included in section 7, followed by conclusions in section 8.

2 Aircraft Dynamics under Actuator Failure Conditions

Students are expected to possess elementary knowledge of aerodynamics and flight dynamics basics, which are typically part of the background at the junior/senior level. They should be familiar with the geometry, role, and functionality of the aerodynamics control surfaces, as well as with the differential equations of motion reflecting the relationships between pilot inputs and the dynamic response of the aircraft [11, 12].

Prior to performing the lab assignment, two to three lectures are dedicated to discussing the general types of malfunctions and damages affecting primary control actuators and their implications on producing aerodynamic control forces and moments. Special attention is given to the jammed control surface scenario, which is the target of the lab assignment.

The primary aerodynamic surfaces, elevator, aileron, and rudder, produce small changes in the lift, which have little contribution to the total lift of the aircraft. However, the moments produced by these small changes are significant and it is these moments that achieve the control of the aircraft. The elevator moves the airplane about its lateral axis, changing the aircraft pitch attitude. The aileron rolls the airplane about its longitudinal axis. The rudder yaws the airplane about its vertical axis. Multiple individual control surfaces are possible on each channel; however, only dual surfaces have been considered for the lab assignment. Note that the aircraft model implemented – a supersonic fighter – features dual vertical tail with left and right rudder.

The jammed control surface scenario assumes that, at a user prescribed moment, the control surface is locked at a certain deflection, current or imposed, and can no longer be moved. Formally, the deflection of an aerodynamic control surface δ_c subject to jamming at the current position can be modeled as:

$$\delta_c(t) = \left(\begin{array}{ll} \delta_c(t) \;\; provided\ by\ the\ pilot, & if\ t < t_f \\ \delta_c(t_f) & if\ t \geq t_f \end{array} \right. \tag{1}$$

where t_f is the moment of occurrence of the failure. If the surface is supposed to move to a user specified position δ_{cf} and stay there, then the deflection can be expressed as:

$$\delta_c(t) = \left(\begin{array}{cc} \delta_c(t) \;\; provided\ by\ the\ pilot, & if\ t < t_f \\ \delta_c(t_f) + \dfrac{1}{\tau s + 1}(\delta_{cf} - \delta_c(t_f)), & if\ t \geq t_f \end{array} \right. \tag{2}$$

where first order dynamics are assumed and the time constant τ must be specified by the user.

Whenever a primary aerodynamic control surface is deflected, a variation of lift $\triangle L$ is generated. The effect on drag is negligible. Depending on the location of the aerodynamic center of the control surface with respect to the center of gravity of the aircraft, moments about one, two, or all three axes of the aircraft body reference system of coordinates are produced. The $\triangle L$ generated at failure conditions will be different than the $\triangle L$ generated at nominal conditions, for the same pilot input. The corresponding moments will also be different. By assessing these differences, actuator failures can be detected and identified.

Elevator failure. Typically, elevators have two symmetric parts and are deflected collectively. Advanced automatic control systems allow for differential deflection as well as a means to increase control redundancy. When one of the elevators is jammed or damaged, the symmetry is perturbed and a coupling between the longitudinal and lateral channels occurs. Let us assume that the full deflection range of the elevator is $[\delta_{emin}, \;\; \delta_{emax}]$ and the achievable pitch rate range is $[q_{min}, \;\; q_{max}]$. The positive sign is assumed for the elevator deflected downwards and pitch rate nose-up. With this convention, positive elevator deflection produces negative pitch rate. If one elevator is jammed at $\delta_e = 0$, then the pitch rate range becomes $\left[\frac{q_{min}}{2}, \;\; \frac{q_{max}}{2}\right]$. However, if one elevator is jammed at $\delta_e = \delta_{emax}$ (corresponding to a deflection saturated downwards), then the pitch rate range is $\left[q_{min}, \;\; \frac{q_{min}+q_{max}}{2}\right]$. Because the two elevator surfaces are located on different sides of the plane of symmetry, at post failure conditions, roll rate will be induced whenever a longitudinal command is inputted. A nose-up longitudinal command will induce a roll to the right if the left elevator has failed and a roll to the left if the right elevator has failed. Opposite effects are obtained for a nose-down command. This characteristic can be used to distinguish between a left and right elevator failure.

Aileron failure. Let us assume that the full deflection range is $[-\delta_{amax}, \;\; \delta_{amax}]$ and the achievable roll rate range is $[-p_{max}, \;\; p_{max}]$. The positive sign is assumed for the right aileron deflected downwards and roll rate to the right of the pilot. With this convention, positive aileron deflection produces negative roll rate. If one aileron is jammed at $\delta_a = 0$, then the roll rate range is $\left[-\frac{p_{max}}{2}, \;\; \frac{p_{max}}{2}\right]$. However, if one aileron is jammed at $\delta_a = \delta_{amax}$, (corresponding to a right aileron deflection saturated downwards or a left aileron saturated upwards), then the roll rate range is $[-p_{max}, \;\; 0]$. Note that the effects of a left jammed aileron are very similar to the ones produced by the right aileron jammed at an opposite position.

Rudder failure. If the aircraft is equipped with a single rudder, and the rudder is jammed, then direct control is no longer possible on the directional channel, unless unconventional redundancy is available. If the jamming position is non-zero/non-neutral, then a yaw rate and a roll rate are induced without pilot input. Some compensation can be obtained using ailerons and differential throttle. If the aircraft is equipped with dual rudder and only one of them is jammed, then the overall effectiveness of the directional control is reduced by approximately 50%. The range of achievable yaw rates varies depending on the jamming position. Let's assume that the moment produced by the rudder is dependent linearly on the deflection angle δ_r and that the yaw rate depends linearly on the moment. For healthy symmetric surfaces, the full deflection range is $[-\delta_{rmax}, \ \ \delta_{rmax}]$ and the achievable yaw rate range is $[-r_{max}, \ \ r_{max}]$. If one rudder is jammed at $\delta_r = 0$, then the yaw rate range is $\left[-\frac{r_{max}}{2}, \ \ \frac{r_{max}}{2}\right]$. However, if one rudder is jammed at $\delta_r = \delta_{rmax}$, then the yaw rate range is $[-r_{max}, \ \ 0]$.

3 Basic Experimental Design Concepts

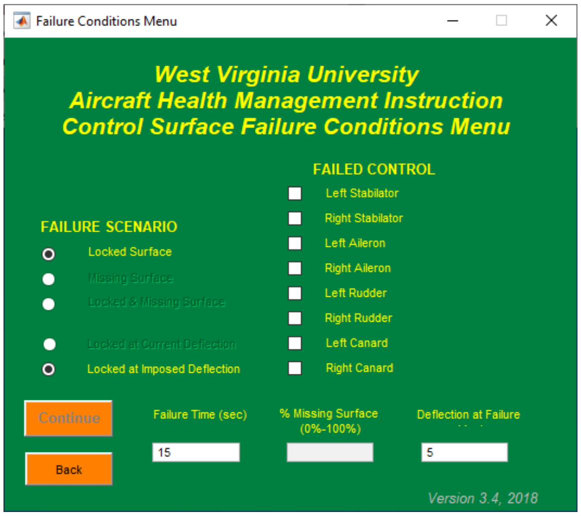
The laboratory assignment relies heavily on simulation tests performed on desktop computers and in a motion-based 6 degrees-of-freedom (DOF) flight simulator. These tests must be designed and organized carefully to maximize effectiveness within obvious time constraints. As part of the active and experiential learning strategy, the experimental design must be performed by the students. Whether or not they have already been significantly exposed to the concepts and practice of experimental design, a review is necessary, briefly discussing the following topics [13, 14]:

- main practical objectives of experiments and test for revealing cause/effect relationships;
- main phases of the experimental process starting with problem formulation and ending with verification of results;
- definition and significance of experimental design components such as factors, levels, and outcomes accompanied by examples on how to use them for flight simulation tests;
- full versus fractional factorial design;
- performing planned tests, data acquisition, and data sanity verification;
- statistical significance;
- correlation versus causality;
- verification and validation of results and conclusions.

4 Simulation Tools

Two simulation environments, desktop and motion-based, are used, sharing the same aircraft mathematical model developed in Matlab® and Simulink®. Cockpit and scenery visualization is provided by commercially available packages, FlightGear® and X-Plane®, respectively. Graphical user interface (GUI) menus allow for the interactive set-up of the simulation scenarios. As an example, the GUI for actuator failure simulation is presented in Figure 1.

The WVU AHM Instruction simulation environment [6, 7] is installed on desktop computers and represents the main tool for performing all the simulation tests. Its GUI is presented in Figure 2. The WVU motion-based flight simulator [5] , seen in Figure 3, is used to confirm the conclusions of the desktop simulation investigation and provide additional insight into the aircraft dynamic response through more extended sensorial immersion. Due to logistical constraints, only a limited subset of tests can be performed in the motion-based simulator.



Failure Conditions Menu

West Virginia University
Aircraft Health Management Instruction
Control Surface Failure Conditions Menu

FAILURE SCENARIO
● Locked Surface
○ Missing Surface
○ Locked & Missing Surface
○ Locked at Current Deflection
● Locked at Imposed Deflection

FAILED CONTROL
☐ Left Stabilator
☐ Right Stabilator
☐ Left Aileron
☐ Right Aileron
☐ Left Rudder
☐ Right Rudder
☐ Left Canard
☐ Right Canard

Failure Time (sec): 15
% Missing Surface (0%-100%):
Deflection at Failure: 5

Figure 1. Set-up Interface for Aerodynamic Control Surface Failures

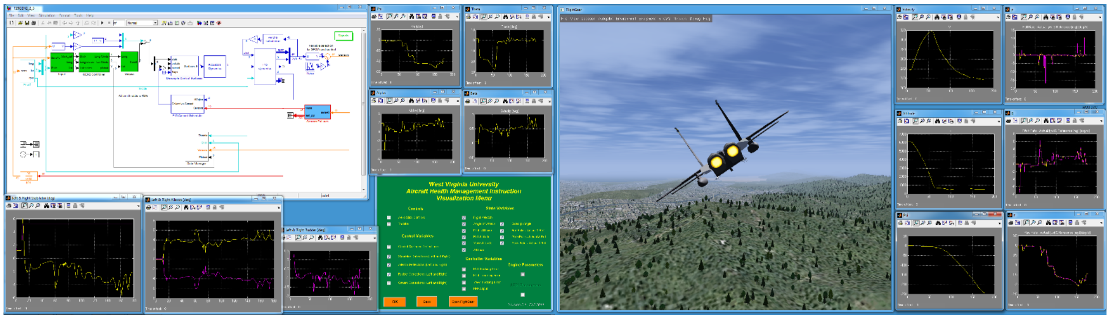


Figure 2. Dual Monitor Visual Interface Including FlightGear® and Simulink® Visualization

Figure 3. WVU Motion-based Flight Simulator: Instructor Console and Cabin Interior View (left); External View of Motion-based Cabin (right)

5 Laboratory Objectives and Learning Outcomes

The lab assignment and the supporting lecture segment have been designed aimed at the following main objectives:

- review of the most common failure conditions affecting aircraft aerodynamic control surfaces;
- analysis of dynamic effects on flight performance produced by actuator failures;
- assessment of dynamic signatures of actuator failures through simulation and tests using

desktop computer simulation and a motion-based 6 DOF flight simulator;

- introduction to experimental design concepts and implementation;introduction to the development of logical schemes for aircraft actuator failure detection, identification, and evaluation;

Upon completion of this lab assignment, the students are expected to achieve balanced levels of complexity and specificity within the cognitive domain according to Bloom's taxonomy [15]. They should be able to:

- describe the general dynamic effects of aircraft actuator failures;
- design and perform simulation tests on flight simulators, acquire and process pertinent data;
- analyze the dynamic signatures of actuator failures and identify their specificity related to the affected element, the type of failure, severity, and interaction with pilot maneuver;
- develop simplified detection, identification, and evaluation schemes for aircraft actuator failures;
- detect, identify, and evaluate actuator failures based on cockpit instruments and motion perception in the flight simulator.

The assignment design strategy relies on the establishment of mobilizing objectives with the possibility of simplifications applied by students based on their own investigation and identification of critical elements and optimum, most effective path to follow. This makes the laboratory hands-on experience more attractive and even entertaining. Student direct involvement in the decision process for organizing and performing the lab proves to be an effective tool for active and experiential learning. It stimulates student creativity and greatly intensifies their motivation and efficiency.

6 Laboratory Outline and Instructions

The lab assignment comprises two parts: an investigation based on desktop computer simulations followed by tests performed in the WVU 6-DOF motion-based flight simulator. Due to logistical constraints, only the desktop computer simulation part is extensive and complete. The tests in the motion-based flight simulator are expected to represent a summary of the previous ones allowing for confirming the main results in a more realistic environment including visual and motion cues.

The students are required to design and perform tests in the two simulation environments aimed at capturing and analyzing the dynamic effects of aircraft actuator failure. They are expected to identify the differences in the aircraft responses depending on the failed actuator and the severity of the failure, as a critical premise for developing failure detection, identification, and evaluation schemes. The WVU AHM Instruction simulation package [6, 7] should be used, specifically the model of a supersonic fighter aircraft. The following instructions and minimal requirements are provided to the students:

- The analysis must be performed for elevator, aileron, and rudder failures on both the left and right individual surfaces.
- A minimum of three different levels of severity must be considered depending on the position of the locked actuator: at current trim, at trim plus a small offset, and at trim plus a large offset. The actual values will be different for each channel and must be determined such that the control of the aircraft can be maintained in all situations.
- The main elements of the experiment, namely the factors, levels, and outcome (or response) variables must be clearly identified and justified.
- The experimental grid must be kept at a manageable level; however, a minimum of 3 levels must be considered for each factor.

- The investigation must be conducted such that all information necessary for detecting, isolating, and evaluating the failure can be obtained. A logical scheme for this purpose must be proposed.
- A reduced number of most relevant tests must be selected to be performed in the motion-based flight simulator.
- All tests must be performed rigorously as designed. Data recording, labeling, and storage for later use must be performed in a well organized manner.
- A flexible Matlab® script must be built for plotting relevant parameters for analysis and comparison. All graphical and technical aspects of the plots, such as axes labels, title, units, legends, readability, etc. should be properly addressed.
- Safety measures and rules must be carefully followed when using the motion-based flight simulator.

The mathematical model of the aircraft is the same for both simulation environments. Up to 3-4 hours are typically scheduled for the desktop computer simulation part. For the motion-based simulator tests, a 20-minute session is dedicated to nominal flight conditions and a 30-minute session, including 10 minutes for each channel is dedicated to failure testing.

The analysis of the dynamic effects of aircraft actuator failures should provide answers to the following questions to be included in the lab report:

1. What are the main effects of the failures investigated on the dynamic response of the aircraft? In other words, what are the parameters/variables affected, when, and how are they affected?
2. What are the differences between the failures affecting different actuators?
3. What is the difference between a failure occurring on the left and right surface in a pair?
4. What is the effect of increasing the severity of the failure?
5. What must one do to be able to detect a failure, identify the failed element, and assess the severity? In other words: What are the parameters that need to be looked at? What is the logic of the process? Are there any specific maneuvers or special conditions needed?
6. What are the differences between the perception of failure dynamic fingerprint in the desktop computer simulation tests and in the motion-based simulator tests?

Laboratory reports are expected to included detailed discussion and comparative analysis supported by relevant plots. Example time histories of relevant states illustrating the effects of different actuator failures on the respective angular rates are presented in Figure 4for elevator failures, in Figure 5 for aileron failures, and in Figure 6for rudder failures.

After the lab, students are required to take a graded quiz/test consisting of three parts. Part I has a homework format and the students are required to produce a detailed plan for a 7-minute test in the motion-based flight simulator during which they would be exposed to an actuator failure affecting an undisclosed control surface starting at an unknown moment. A logical scheme to detect, isolate, and evaluate the failure must be formulated at this time. Part II consists of the 7-minute test in the flight simulator, during which the students have to announce the moment of failure occurrence, identify which of the six control surfaces is affected, and specify qualitatively the level of severity. Finally, Part III represents a take-home post-test analysis, in which the students are required to explain the test based on recorded data and discuss what was done correctly or incorrectly, if their logical scheme was successful or not and why, and what could or should have been done differently.

A detailed professionally written lab report is required and counts 11% towards the total course grade, while the 3-part quiz counts 7%.

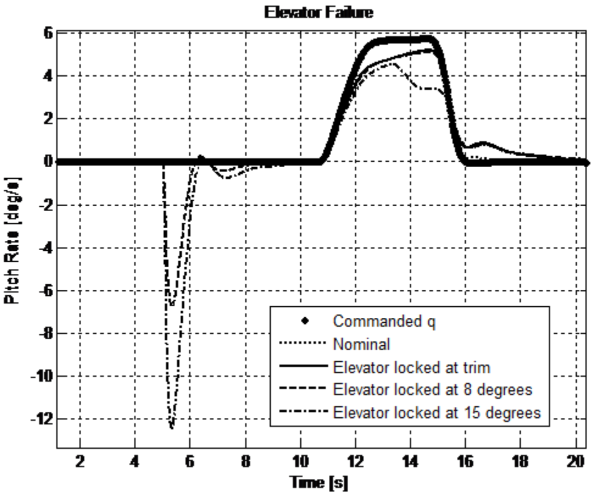


Figure 4. Effects of Elevator Failures on Pitch Rate

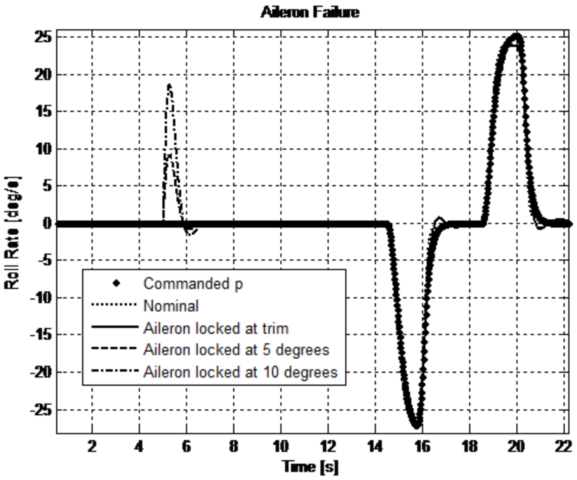


Figure 5. Effects of Aileron Failures on Roll Rate

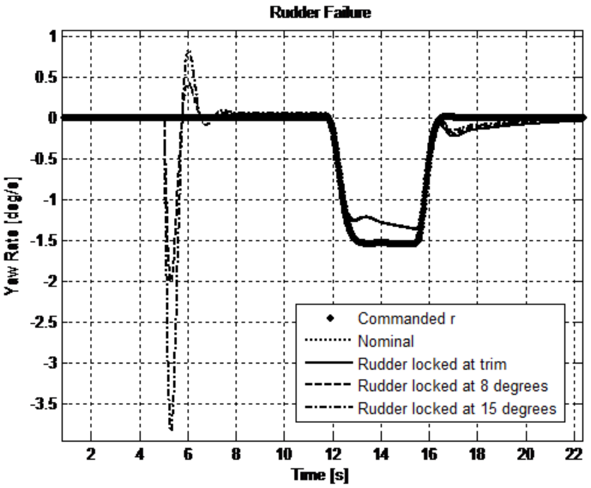


Figure 6. Effects of Rudder Failures on Yaw Rate

7 Academic Impact and Student Feedback

A 10-question multiple-choice quiz was administered before and after the lab to assess its impact in two consecutive semesters with a total enrollment of 35 students. All questions were equally weighted and have been addressed during both the lecture and the lab. Two example questions and their alternative answers are presented next with the correct answers marked in italics.

Example question #1: *Consider that the aircraft is initially in a steady-state, horizontal, and symmetric flight. At a certain moment, the left elevator is locked at trim. Without any pilot input, the occurrence of the failure can… (circle one).*

- ***a)*** *easily be detected mainly due to the significant pitch rate produced without any other rotation.*
- ***b)*** *easily be detected mainly due to the significant roll rate produced without any other rotation.*
- ***c)*** *easily be detected mainly due to the significant pitch rate produced coupled with roll rate.*
- ***d)*** *easily be detected mainly due to the significant pitch rate produced coupled with yaw rate.*
- ***e)*** *not be easily detected.*

Example question #2: *Consider that the aircraft is initially in a steady-state, horizontal, and symmetric flight. At a certain moment, the left aileron deflects downwards at the maximum possible deflection and remains locked there. The pilot control authority on the lateral (roll) channel is mainly affected as follows: the pilot …(circle one).*

- ***a)*** *will continue to be able to command and achieve roughly the same range of roll rates because the right aileron can still be moved over the entire deflection range.*
- ***b)*** *will be able to command and achieve roughly half of the range of roll rates in both directions, because only one control surface is now available.*
- ***c)*** *can no longer achieve roll rates to the right.*
- ***d)*** *can no longer achieve roll rates to the left.*
- ***e)*** *can no longer achieve any commanded roll rates.*

An average 35% improvement of quiz scores has been recorded after the lab. Three questions that after lecture remained unanswered at a rate of 74%, achieved an average improvement up to 82%. Table 1 summarizes these outcomes.

Table 1. Summary of Lab Effectiveness Reflected by Quiz Scores

	Before Lab	After Lab	Relative Improvement
Total Average Score	67.9%	91.8%	35.1%
3 Lowest-Score Question Avg.	17.1%	82.0%	480%

While the questions included in the Student Evaluation of Instruction were somewhat modified over the years, the average score for the entire course over the past 4 years was 4.77/5. The average of scores addressing student motivation, interest, critical thinking, and thought-provoking level was 4.92/5.00.

8 Conclusion

An experiential learning laboratory based on simulation for aircraft dynamics under subsystem failure conditions has been successfully designed and taught at WVU.

The academic use of flight simulation tools in conjunction with an open-ended, hands-on assignment has been demonstrated to increase significantly student participation, motivation, and performance.

The implementation of active and experiential learning methodologies based on flight simulation facilitates student initiative and creativity.

Concept understanding, relating cause and effect, and connecting theory and practice in the context of flight dynamics can be more efficiently achieved through this type of laboratory assignments.

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