INTEGRATION OF COMPUTER SIMULATION FOR FLIGHT DYNAMICS AND CONTROL EDUCATION

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Abstract

This paper focuses on the integration of different flight simulation technologies of various levels of complexity within the aerospace engineering curriculum to support education in flight dynamics, controls, aerodynamics, and aircraft design. The computer simulation tools cover a wide range starting with simplified linear and non-linear models, continuing with PC-based simulation packages with high accuracy aerodynamic models and advanced graphics, and ending with a six degrees-of-freedom motion based flight simulator. These simulation technologies are used to perform sensitivity analyzes of aircraft performance and handling qualities with respect to specific design parameters. The methodologies are outlined in this paper and illustrated with simulation results. A detailed analysis has shown that the above simulation capabilities and the approach used for integration, especially the introduction of the motion based flight simulator, have a positive effect on the efficiency of the learning process.

Introduction

In recent years, flight test programs on full size aircraft have decreased in number due to their high costs. Research centers across the nation are looking into different and less expensive classes of technology demonstrators. Following this general trend, the Department of Mechanical and Aerospace Engineering (MAE) at West Virginia University (WVU) decided to replace previous capabilities in flight testing with more advanced capabilities in flight simulation.

The MAE faculty have implemented a plan for the establishment of flight simulation capabilities through the introduction of new relevant courses at the undergraduate and graduate level and the development of a flight simulation laboratory equipped with software and hardware covering several levels of complexity, from libraries of simulation routines to complex PC-based simulation packages and a 6 degrees-of-freedom (DOF) flight simulator.

These technologies accomplish their educational role in two primary ways. First, they provide illustration for the general architecture of a flight simulation model, operation, and integration of individual components. Second, they are used to generate flight data to analyze the effect on aircraft performance and handling qualities of various aircraft design parameters. Specifically, in using these simulation technologies, the students have the opportunity to take on all three major roles related to producing and analyzing flight test data: the pilot, the test engineer, and the handling qualities/performance engineer. This comprehensive perspective has shown to be a positive factor in enhancing the learning process and improving academic performance. In particular, the introduction of the motion based flight simulator has produced positive effects on student motivation, class attendance, and participation.

The purpose of this paper is to present the integration of computer simulation technologies of different levels of complexity to teach aircraft modeling and flight simulation at the undergraduate level, within a broader vision aimed at providing support and educational enhancement to several curriculum areas, such as flight dynamics, controls, aerodynamics, and aircraft design. The simulation technologies are briefly described in increasing order of their complexity along with sample assignments and relevant algorithms. The impact on the educational process of using the flight simulator is evaluated through a number of performance metrics. A final section summarizes the paper.

Low Complexity Simulation Tools

The students are first introduced to the application of the *Small-Disturbance* theory[1,2] for the derivation of aircraft transfer functions (TFs). A first assignment requires the use of Matlab and Simulink to build TF models for several aircraft in different classes. Three longitudinal TFs must be determined relating the elevator deflection to airspeed, angle of attack, and pitch attitude angle. Six TFs must be determined for the lateral-directional channel, relating the aileron deflection and the rudder deflection to the sideslip angle, roll rate, and roll attitude angle. Aerodynamic data available in textbooks[2] is used in the process. Simulating aircraft TF responses to standard inputs provides direct insights into vehicle dynamic characteristics. Additionally, the students are required to evaluate the roots of the characteristic equations and the modal parameters[1,2] as handling qualities evaluators (damping coefficient and natural frequency for the short period, phugoid, and dutch roll dynamic modes, as well as the time constants for the rolling and spiral dynamic modes). The simulations are performed using a set of standard pilot inputs (impulse, step, and doublet) with different magnitudes. The time histories obtained from models of aircraft of different classes are analyzed and compared to emphasize the correlation between dynamic response, the location of the roots, and the values of the modal parameters. The block diagram of this assignment is presented in Figure 1. An example of the Matlab interface to perform the assignment is shown in Figure 2.

The Flight Dynamics and Control (FDC) Matlab/Simulink toolbox[3] is introduced next. A general view of the FDC toolbox is shown in Figure 3. The FDC simulation environment is used to perform a qualitative sensitivity analysis of the aircraft handling qualities. The polynomial aerodynamic model for a light propeller driven airplane is altered iteratively by changing the values of stability derivatives one at a time. Simulations with these modified values are performed and the time histories of relevant state variables are analyzed for assessing the effects of these changes on the modal parameters and implicitly on the dynamic response of the aircraft. At this level only qualitative assessments on these changes are performed.

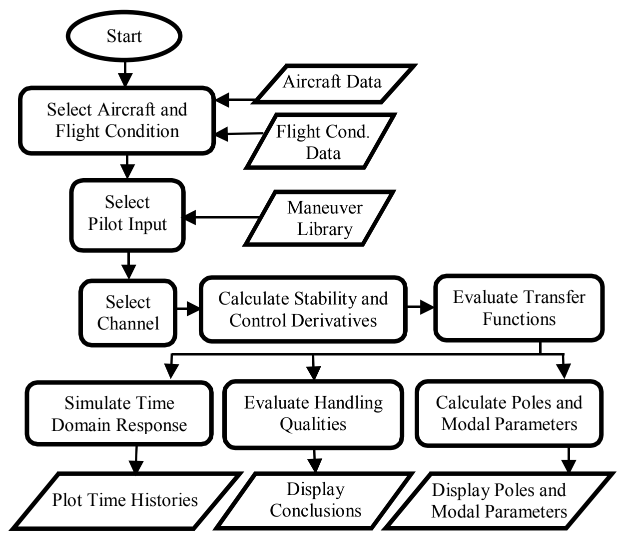

Figure 1. Handling Qualities Evaluation Using Transfer Functions.

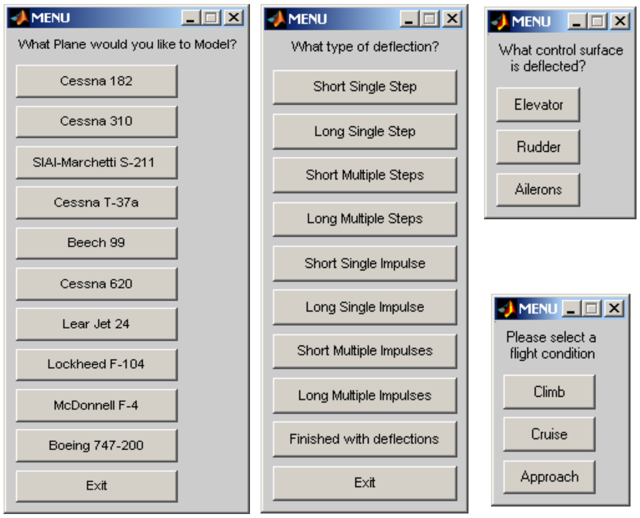

Figure 2. Matlab Interface for Handling Qualities Evaluation Using Transfer Functions.

Consider, for example, the derivative of the pitching moment with respect to the angle of attack, $C_{m\alpha}$. The effects of varying this parameter on the characteristics of the short period mode can be determined by analyzing the time history of the angle of attack in response to an elevator step input. Increasing $C_{m\alpha}$ will produce an increase of the natural frequency and a decrease of the damping with direct consequences on the longitudinal dynamic response and handling qualities of the aircraft. The changes in the stability derivatives are correlated with important aircraft design parameters, such as – in the case of $C_{m\alpha}$ - the horizontal-tail surface and its distance relative to the aircraft center of gravity.

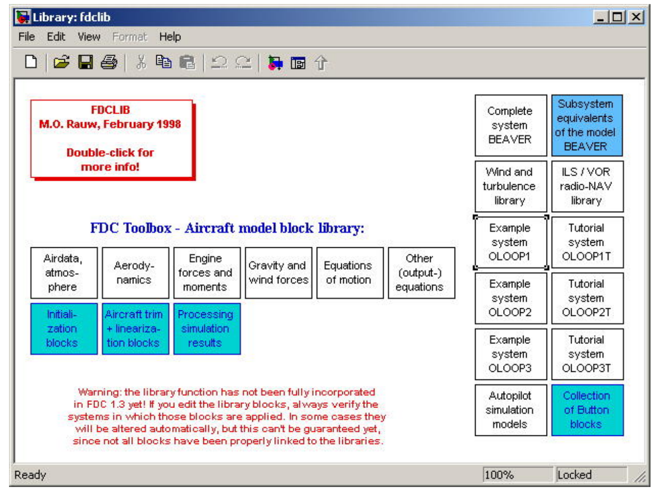

Figure 3. FDC Simulation Environment – Model Library.

Advanced PC-Based Flight Simulators

MAE researchers have developed several flight simulation environments[4,5] over the years providing a customized yet flexible framework for analyzing a wide variety of research issues, such as control failure modeling, fault-tolerant control laws, neural augmentation, and real-time system identification. These packages are presented to the students and discussed within the course for illustrating the development and use of simulation tools for advanced aircraft control system design, as well as emphasizing methodologies of modeling and simulation of more sophisticated aspects, such as aerodynamic control surface failures and artificial neural networks. For graphic display and pilot interaction the dynamic model is interfaced with the *Aviator Visual Design Simulator* (AVDS) simulation package[6] as illustrated in Figure 4, or the Matlab *Virtual Reality Toolbox* (VRT) as presented in Figure 5.

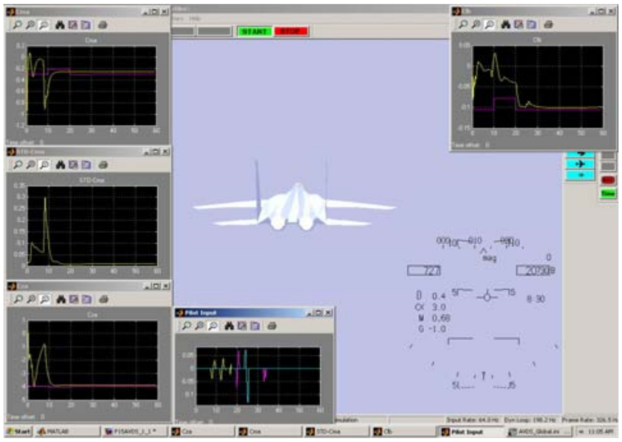

Figure 4. WVU Simulation Environment – AVDS Interface.

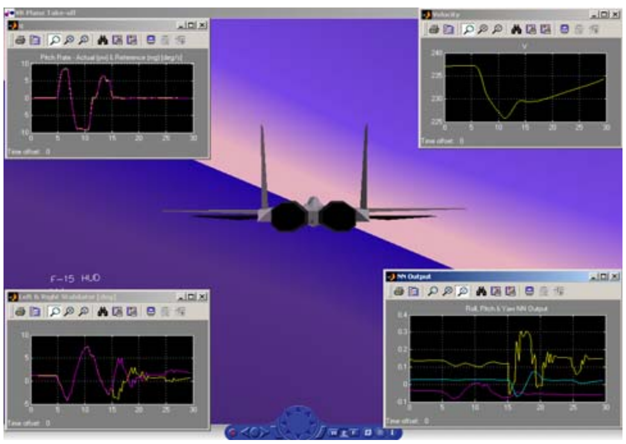

Figure 5. WVU Simulation Environment – Matlab VRT Interface.

Next, the students are introduced to D-Six[7]. D-Six - developed by Bihrle Applied Research - is an excellent tool for research and teaching in flight simulation, aircraft design, and aircraft dynamics and controls. D-Six combines in one package the real-time simulation with the simulation development and analysis tools. This PC/Windows-based simulation environment is very flexible and allows new or modified aircraft models to be easily implemented. D-Six features a tabular aerodynamic data structure with a user-friendly interface for visualization and editing. Several versatile options are available to provide input and to store, process, and display output (see Figure 6). The compatibility with Matlab and Simulink allows for additional data processing and analysis capabilities.

D-Six is used within the *Flight Simulation* course for several purposes. First, it provides a detailed understanding of the architecture of a comprehensive simulation package. Second, it is used to exercise the development and customization of important simulation aspects such as data storage and transfer, cockpit instrument display, simulation scenario events (system failures, warning messages, changes of variables). For example, an assignment consists of the implementation of visual and audio cockpit warnings for abnormal flight conditions such as low altitude and large angle of attack. An other assignment requires the design and implementation of cockpit instruments such as speed indicators or altimeters.

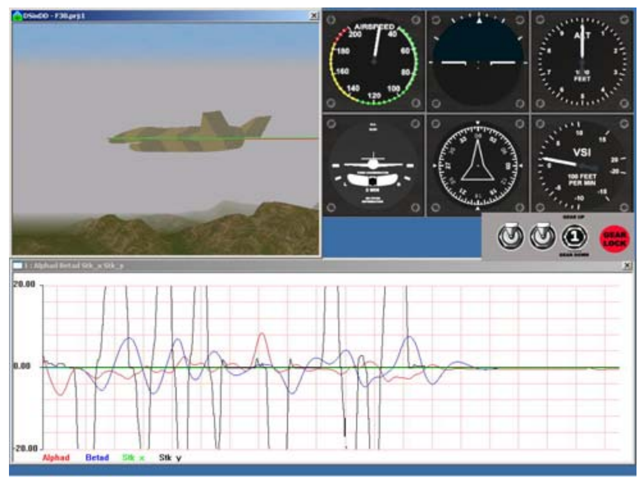

Figure 6. Interface of the D-Six Simulation Environment.

Finally, D-Six provides an excellent environment for the design of flight tests, data collection, processing, and analysis. In fact, D-Six is used to perform a detailed sensitivity analysis of the main modal handling qualities parameters with respect to stability derivative.

A general experimental approach is used similar to the one described in the previous section. The recorded data is transferred from D-Six to Matlab and processed within this environment to determine the values of the handling qualities parameters. A typical assignment requires that the sensitivity of the natural frequency ω_{nSP} and damping ratio ζ_{SP} of the longitudinal short period (SP) motion mode be analyzed with respect to the 6 most important stability derivatives. These coefficients include the derivatives of the aerodynamic longitudinal moment and vertical force with respect to pitch rate, angle of attack, and its rate of variation. The time history of the angle of attack in response to an elevator step input can be used to determine first the overshoot (OS) and the time necessary to reach the first response peak (T_p) as illustrated in Figure 7. Next, the modal parameters can be obtained using the following approximate equations[2]:

$$\zeta_{SP} = \sqrt{\frac{\ln^2 OS}{\pi^2 + \ln^2 OS}} \qquad (1)$$

$$\omega_{nSP} = \frac{\pi}{T_p \sqrt{1-\zeta_{SP}^2}} \qquad (2)$$

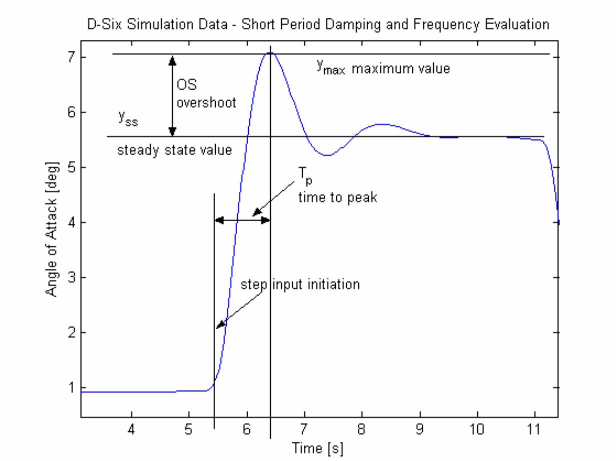

Figure 7. Determination of the Short Period Modal Characteristics.

MOTUS 600 6 - DOF Flight Simulator

The WVU Motus 600 Flight Simulator[8] (Figure 8) manufactured by Fidelity Flight Simulation, Inc., Pittsburgh, PA includes the following components:

- 6 DOF motion platform driven by electrical induction motors
- Laminar Research X-Plane[9] flight simulation software
- LCD four-monitor external visual display
- Instructors operating station
- Computer and control cabinet

The motion platform provides 6-degrees-of-freedom translational and rotational motion cues. Electrical motors are used to drive the motion base, which represents a very versatile and inexpensive solution to this type of application.

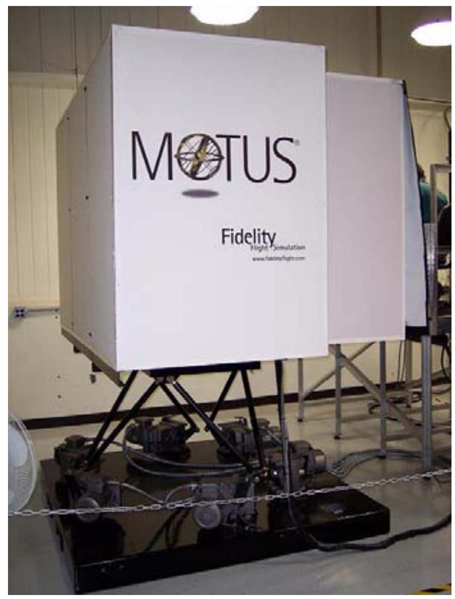

Figure 8. The WVU 6 – DOF Flight Flight Simulator Cabin.

X-Plane is a commercial comprehensive aircraft simulation package featuring high capabilities and flexibility in selecting the simulation scenario. It includes an extensive database of aircraft, airports, and scenery around the world. Weather conditions can be selected prior and during the simulation to include cloud layers, wind and turbulence, temperature, runway conditions, and a wide variety of visibility, precipitation, and other weather parameters. Different aircraft malfunctions can be simulated including instrumental errors, engine shutdowns, and surface actuator failures. Finally, new aircraft models can be introduced into the database using the aerodynamic capabilities of X-Plane.

The 2-seat cockpit accommodates dual controls and instrument clusters (Figure 9). Visual information in the cockpit is provided by a total of 6 LCD visual displays. Two visual displays host the instruments clusters and four others provide the external visual cues.

Five computers are used to operate the WVU Flight Simulator. Computer #1 drives the left 45° visual display. Computer #2 drives the left and right forward visual displays. Computer #3 drives the right 45° visual display. Computer #4 is the "Server" computer and runs the core flight simulation software and the pilots' instruments. All simulation data to be used for analysis is stored on this computer. Computer #5 is the instructor's operating station.

Figure 9. Visual Displays, Controls, and Instrument Clusters.

The WVU 6DOF motion base flight simulator supports the undergraduate flight simulation course in two primary ways. It provides first hand illustration to the general architecture of a flight simulator, operation, and the integration of different components. More important, it provides the capability to collect data to be used for the application of various techniques for the determination of aircraft dynamic characteristics (modal characteristics) that play a major role in the assessment of aircraft performance and handling qualities and in the development of simulation models.

When using the 6 DOF WVU Flight Simulator, the students are expected to take on the roles of the flight test engineer, the pilot, and the handling qualities engineer. Thus, they are required to carefully plan the flight test scenario. The variables to be written on the hard disk must be selected within the output menu of X-Plane. The right shape, magnitude, and duration of the pilot input must be determined and executed. A typical assignment requires to design a flight simulator experiment for collecting and processing data, and compute the modal parameters for the lateral-directional motion of an aircraft (the time constant of the Roll mode[1,2] and the natural frequency and damping of the Dutch Roll mode[1,2]).

Based on linear analysis of the aircraft dynamics, the Roll mode can be modeled by a first order transfer function and it describes a fast, non-oscillatory dynamic response. It is best excited using aileron inputs and it has, typically, the most important effect on the roll rate response of the aircraft. The time constant for a first order system is the interval necessary for the output to reach 63% of the steady state in response to a step input. To determine the time constant of the roll mode an aileron step input is required and the time history of the roll rate. The contribution of the Roll mode to the time history of the roll rate *p* is expressed as:

$$p(t) = p_{ss}\left(1 - e^{t/\tau_R}\right) \qquad (3)$$

where p_{ss} is the steady state value of the roll rate and τ_R is the time constant of the Roll mode. The approach is illustrated in Figure 10.

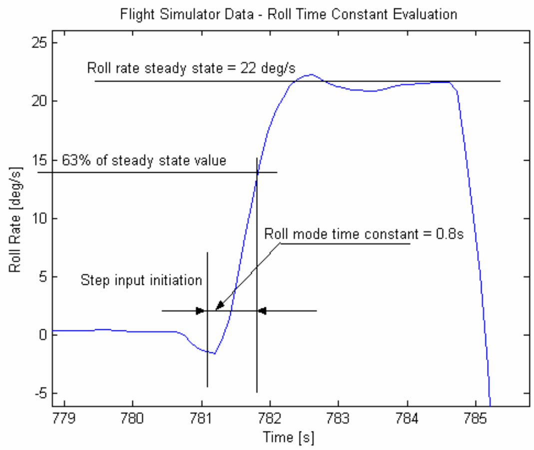

Figure 10. Determination of the Roll Mode Time Constant.

The Dutch Roll mode can be modeled by a second order transfer function and it describes an oscillatory dynamic response. It is best excited using rudder inputs and it has, typically, the most important effect on the sideslip angle response of the aircraft. The contribution of the Dutch Roll mode to the time history of the sideslip angle β is expressed as:

$$\beta(t) = Ae^{-\zeta_{DR}\omega_{nDR}t}\sin\left(\omega_{dDR}t + \mu\right) \qquad (4)$$

where ω_{nDR} is the "undamped" or "natural" Dutch Roll frequency, ω_{dDR} is the "damped" Dutch Roll frequency, ζ_{DR} is the Dutch Roll damping coefficient, A is the amplitude, and μ is the phase angle. The values of both A and μ depend on the initial conditions. The relationship between the "damped" and "undamped" frequencies is given by:

$$\omega_d = \omega_n\sqrt{1-\zeta^2} \qquad (5)$$

Consider t_1 and t_2 the values of the time associated with successive 'peak' and 'valley' of the sideslip angle (one half cycle apart from each other as shown in Figure 11). Using equation 4 to express DA_1 and DA_2, one can determine the *transient peak ratio* (TPR) to be equal to:

$$TPR = \frac{DA_2}{DA_1} = e^{-\zeta_{DR}\omega_{nDR}T_P/2} \qquad (6)$$

More accurate values for *TPR* can be found by evaluating the average over several consecutive peak pairs. From the expression for *TPR*, the associated logarithmic decrement can be evaluated using:

$$\delta = \ln(TPR) = -\zeta_{DR}\omega_{nDR}\left(\frac{\pi}{\omega_{dDR}}\right) \qquad (7)$$

Finally, the damping of the Dutch Roll mode can be obtained using:

$$\zeta_{DR} = \frac{\left|\ln(TPR)\right|}{\sqrt{\pi^2 + \ln^2(TPR)}} \qquad (8)$$

and the natural frequency of the Dutch Roll mode can be obtained using:

$$\omega_{nDR} = \frac{2\pi}{T_p\sqrt{1-\zeta_{DR}^2}} \qquad (9)$$

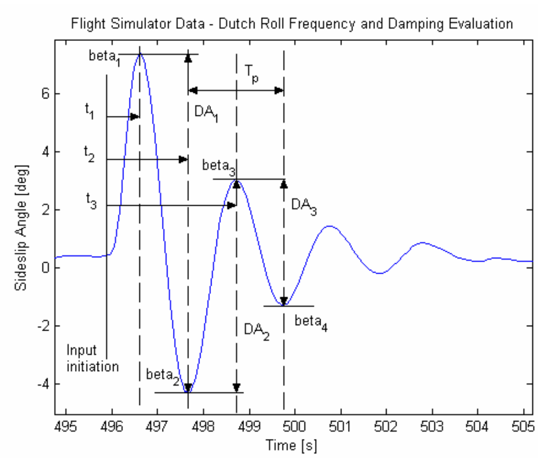

Figure 11. Parameters of the Peak-to-Valley Method to Determine the Dutch Roll Modal Characteristics.

A typical set of flight simulator data to be used for lateral-directional handling qualities analysis is shown in Figure 12.

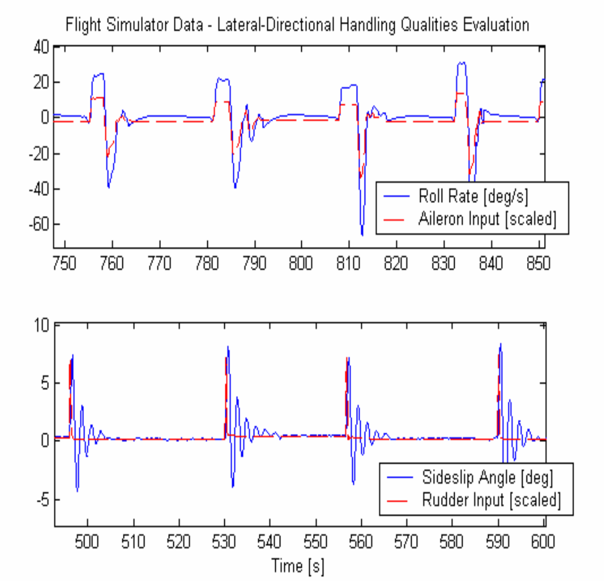

Figure 12. Data Collected from the WVU Flight Simulator to Determine Lateral-Directional Modal Characteristics.

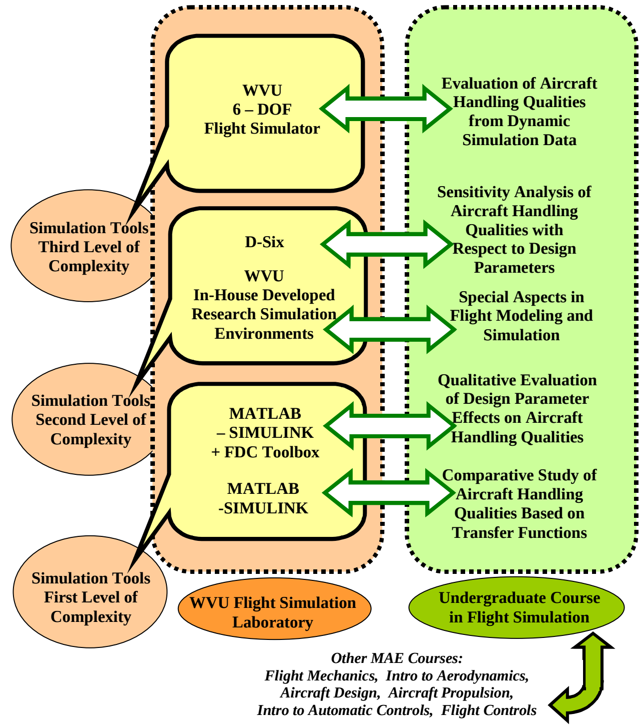

Figure 13. Integration of Several Levels of Simulation Technologies for Flight Dynamics and Controls Education.

Impact on the Educational Process

The undergraduate course in flight simulation was designed to give aerospace engineering students the fundamental concepts of flight simulations and provide them with the necessary basic skills for implementing aircraft mathematical models within a modern flight simulator. In addition, the students are exposed to recent trends in the aviation industry for the hardware and software components of flight simulators. The objectives of the course are reached through integration of several levels of flight simulation technologies and assignments of progressive complexity as illustrated in Figure 13. The undergraduate course in flight simulation takes on an important role within the aerospace engineering curriculum since it can feed to/from critical concepts in a wide range of other courses such as *Flight Mechanics*, *Introduction to Aerodynamics*, *Aircraft Design*, *Aircraft Propulsion*, *Introduction to Automatic Controls*, and *Flight Controls*.

The WVU 6DOF motion base flight simulator has an important role within the curriculum. The undergraduate course in flight simulation was offered for the first time in 2004 and is typically scheduled in the Fall semester. The flight simulator was first used in Fall 2006. The simulator supports the course in two primary ways. It provides the capability to collect data to be used for the application of various techniques for the determination of aircraft dynamic characteristics (modal characteristics) that play a major role in the assessment of aircraft performance and handling qualities and in the development of simulation models. It also provides first hand illustration to the general architecture of a flight simulator, operation, and the integration of constituent components.

The use of the WVU 6-DOF Flight Simulator has a significant impact on the educational process. To assess this impact, the following evaluation parameters were defined:

- total enrollment at the beginning of the class
- retention rate computed as the ratio between the number of students receiving a passing grade and the total enrollment
- average grade including failing grades and grades of students who withdrew (on a scale of 100)
- average passing grade not including failing grades and grades of students who withdrew (on a scale of 100)
- attendance computed as the ratio between the sum of hours class was attended by each student and the number of hours offered times the number of students. Note that partial attendance records were available and only students who received a passing grade were considered in computing this parameter.

These evaluation parameters were computed every time the undergraduate course *Introduction to Flight Simulation* was offered (Fall semester 2004, 2005, and 2006). The WVU flight simulator was used only in Fall 2006. No other changes were made to the content of the course or policies. The values of the evaluation parameters over a period of three years are summarized in Table 1 and illustrated in Figure 14.

Table 1. Evaluation Parameters for Academic Impact of the WVU Flight Simulator.

Year → Evaluation Paramaters ↓	2004	2005	2006
Enrollment	9	17	29
Retention	0.78	0.82	0.97
Average Grade	76	80	88
Average Passing Grade	91	92	91
Attendance	0.92	0.91	0.95

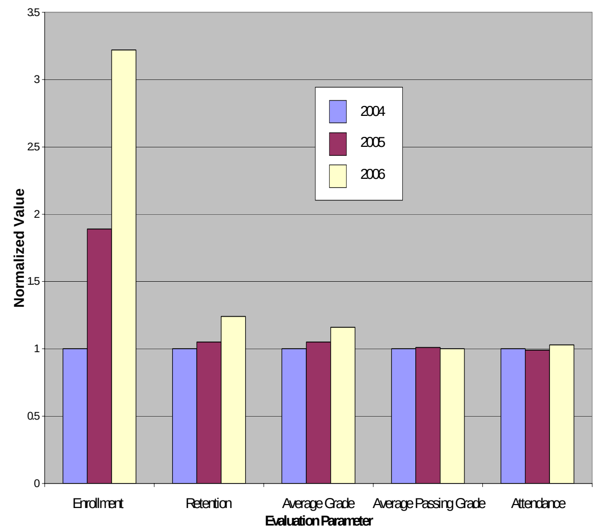

Figure 14. The Impact of Using the Flight Simulation on the Educational Process.

All the evaluation parameters for academic impact show a significant increase in 2006 except for the average passing grade which remains constant. This increase can be attributed to the introduction of the flight simulator and is explained by the increase in student interest and enthusiasm due not only to the excitement of using this tool but, more importantly, due to the new perspective it provides on the material taught and the changes on the dynamics of the class.

Conclusions

Extensive flight simulation capabilities have been developed at WVU with a comprehensive perspective to enhance the aerospace engineering curriculum and support learning in flight dynamics, controls, aerodynamics, and aircraft design.

A flight simulation laboratory was equipped with advanced simulation tools of increasing levels of complexity ranging from simple linear dynamic models, to simulation packages with accurate aerodynamic models and complex interfaces for control and data processing, and up to a motion based 6-DOF flight simulator.

The approach for the integration of computer flight simulation technologies had an important impact on the academic process. In particular, the introduction of the 6-DOF flight simulator produced a significant increase of the enrollment, retention, and the class average grade for the simulation course.

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Biographical Information

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Marcello R. Napolitano is currently a Professor with the Department of Mechanical and Aerospace Engineering at West Virginia University. He teaches courses in the area of Flight Dynamics, Flight Controls, Flight Simulation, and Automatic Controls. He received a MS degree in Aerospace Engineering from the University of Naples, Italy in 1985 and a PhD degree in Aerospace Engineering from Oklahoma State University in 1989. His research areas of interest include: application of neural networks to flight control systems, fault-tolerant flight control systems with flight testing on scale models, aircraft parameter estimation from flight data, system requirements for fault tolerant flight control systems, formation control laws for UAVs, and autonomous aerial refueling for UAVs.