Flight Dynamics and Control Education Enhancement Using a Motion Based Flight Simulator

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I. Introduction

The Department of Mechanical and Aerospace Engineering (MAE) at West Virginia University (WVU) has been one of a few US academic institutions to offer an undergraduate course in flight testing. However, due to liability issues, safety concerns, increasing maintenance costs, as well as general financial constraints, it was decided to replace the capabilities in flight testing with capabilities in flight simulation. This decision followed the general trend in the past 10-15 years where the flight test programs on full size aircraft have decreased in number due to their high costs and associated risks and the research centers across the nation are looking into different and less expensive classes of “technology demonstrators”.

The MAE faculty have implemented a plan for the establishment of flight simulation capabilities through the introduction of new relevant courses 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.

The purpose of this paper is to present the integration of the 6 DOF flight simulator into the curriculum and the impact produced by the use of the simulator on the educational process in the area of flight dynamics and controls. The outline of the paper includes in section II a description of the main features and capabilities of the flight simulator followed in section III by an overview of the role and place within the curriculum of the MAE courses in flight simulation with emphasis on the use of the flight simulator as a central tool for academics and research. An assessment of the impact of the flight simulator on the educational process is presented in section IV. In section V, a typical assignment is presented to illustrate the use of the simulator in support of an undergraduate course in flight simulation.

II. MOTUS 600 6-DOF Flight Simulator

The WVU Motus 600 Flight Simulator (Figure 1) manufactured by Fidelity Flight Simulation, Inc., Pittsburgh, PA, offers a very realistic flight environment with extremely low operational and maintenance costs\(^1\). The system includes the following components:
• 6 DOF motion platform driven by electrical induction motors
• Laminar Research X-Plane2 flight simulation software
• LCD Mosaic Wall four-monitor external visual display
• Instructors operating station
• Computer and control cabinet

The motion platform provides adequate six-degrees-of-freedom translational and rotational motion cues. Electrical motors are used to drive the motion base (Figure 2) which represents a very versatile and inexpensive solution to this type of application. Motion drive algorithms convert the motion of the aircraft as resulting from the dynamic model into motion of the platform such that the perception of the pilot is optimized within the physical limitations of the ground based simulator. For example, constant linear accelerations that can only be sustained for a very limited time, are simulated by tilting the cockpit at an angular rate below the pilot’s perception threshold. Gravity is thus used to simulate the inertial force associated with constant linear acceleration.

X-Plane is a commercial comprehensive aircraft simulation package featuring high capabilities and flexibility in selecting the simulation scenario. It includes a huge 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 condition, and a wide variety of visibility, precipitation, and other weather parameters. Malfunctions of the aircraft systems can be simulated in the following categories: overall, instruments, equipment, engine, engine systems and flying surfaces. 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 3). 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.
The instructors operating station is located on a platform next to the cabin (Figure 1). The instructor has two visual displays for monitoring the simulation and perform simulation scenario set-ups/changes (Figure 4). All 5 computers can be controlled using the keyboard on the instructor’s desk. All functions of the motion base can be controlled through a separate Motion Control Box.

The large black aluminum cabinet next to the cabin houses all electrical and computing hardware. 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.

III. Integration of the Flight Simulator within the Curriculum

The plan for the establishment of flight simulation capabilities at WVU included the development of a flight simulation laboratory (Figure 5) and the introduction of two new courses:

- 1 undergraduate senior level course for the Aerospace Engineering (AE) and Dual Aerospace / Mechanical Engineering (AE/ME) students (Introduction to Flight Simulation);
- 1 graduate level course for MAE and Computer Science and Electrical Engineering (CSEE) graduate students with interest in flight controls/control theory (Flight Simulation).
The undergraduate course was offered for the first time in 2004 and is typically scheduled in the Fall semester. The graduate course is in preparation and will be offered soon. The undergraduate course in flight simulation takes on an important role within the AE curriculum (Figure 7) 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 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 Flight Dynamics and Control (FDC) Matlab/Simulink toolbox\(^3\) is first introduced; next, several simulation environments developed by MAE researchers\(^4,5\) are discussed and then the students are introduced to D-Six\(^6\), a very detailed flight simulation package (Figure 6) produced by Bihrlle Applied Research (BAR). Special emphasis is placed on the assessment of the aircraft handling qualities from flight simulations and sensitivity analysis of the handling qualities with respect to critical aerodynamic characteristics of the aircraft. A step forward to a higher level of complexity in flight simulation is made through the introduction of motion base flight simulators. At the end of this course, students are expected to be able to (learning outcomes):

- use the fundamental theorems of Mechanics to derive the 6DOF equations of motion for an aircraft;
- express and calculate the aerodynamic forces and moments using experimental and analytical methods and incorporate them in a simulation package;
- assess aircraft handling qualities through numerical simulations;
- identify the effects of geometric, inertial, aerodynamic, and thrust parameters on the handling qualities and the dynamic response of the aircraft;
- use the FDC toolbox and the D-Six simulation package;
- design an experiment, perform the test, and collect data using the WVU 6DOF flight simulator for aircraft handling qualities and dynamic performance analysis;
- process the data collected using the WVU 6DOF flight simulator and perform the aircraft handling qualities and dynamic performance analysis.

An important part of the undergraduate flight simulation course is dedicated to the WVU 6DOF motion base flight simulator, which 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. A typical assignment to illustrate the use of the simulator is presented in section V.

IV. Impact on the Educational Process

To assess the impact on the educational process of using the WVU flight simulator 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. It should be noted that the low values of the evaluation parameters recorded in Fall 2004 may be due in part to the fact that the course was then offered for the first time. The values of the evaluation parameters over a period of three years are summarized in Table 1 and illustrated in Figure 8.

<table>
<thead>
<tr>
<th>Eval. Par. : Year</th>
<th>Enrollment</th>
<th>Retention</th>
<th>Average Grade</th>
<th>Average Passing Grade</th>
<th>Attendance</th>
</tr>
</thead>
<tbody>
<tr>
<td>2004</td>
<td>9</td>
<td>0.78</td>
<td>76</td>
<td>91</td>
<td>0.92</td>
</tr>
<tr>
<td>2005</td>
<td>17</td>
<td>0.82</td>
<td>80</td>
<td>92</td>
<td>0.91</td>
</tr>
<tr>
<td>2006</td>
<td>29</td>
<td>0.97</td>
<td>88</td>
<td>91</td>
<td>0.95</td>
</tr>
</tbody>
</table>

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

![Normalized Values](image)

*Figure 8. 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

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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.

V. Analysis of Lateral-Directional Handling Qualities Based on Flight Simulator Data

A typical assignment consists of designing a flight simulator experiment to collect data, process the data, and compute significant parameters such as the time constant of the Roll mode\(^7,8\) and the natural frequency and damping of the Dutch Roll mode\(^7,8\) that can be used to analyze the aircraft handling qualities and dynamic performance. 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. They must plan carefully 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 set of flight simulator data to be used for lateral-directional handling qualities analysis is shown in Figure 9.

![Flight Simulator Data - Lateral-Directional Handling Qualities Evaluation](image)

**Figure 9. Data Collected from the WVU Flight Simulator to Determine Lateral-Directional Modal Characteristics**

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:

\[
p(t) = p_{ss}\left(1 - e^{-t/\tau}\right)
\]  

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

The Dutch Roll mode is 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 $\beta$ is expressed as:

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

where $\omega_{n\text{DR}}$ is the “undamped” or “natural” Dutch Roll frequency, $\omega_{d\text{DR}}$ is the “damped” Dutch Roll frequency, $\zeta_\text{DR}$ is the Dutch Roll damping coefficient, $A$ is the amplitude, and $\mu$ is the phase angle. The values of both $A$ and $\mu$ depend on the initial conditions. The relationship between the “damped” and “undamped” frequencies is given by:

$$
\omega_d = \omega_n \sqrt{1 - \zeta^2}
$$

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 2 one can define:

$$
DA_1 = |\beta_1| + |\beta_2| = Ae^{-\zeta_\text{DR} \omega_\text{DR} t_1} \sin\left(\omega_\text{DR} t_1 + \mu\right) \left[1 + e^{-\zeta_\text{DR} \omega_\text{DR} \frac{T_R}{2}}\right]
$$

Similarly, $DA_2$ can be modeled using:

$$
DA_2 = |\beta_2| + |\beta_3| = Ae^{-\zeta_\text{DR} \omega_\text{DR} t_2} \sin\left(\omega_\text{DR} t_2 + \mu\right) \left[1 + e^{-\zeta_\text{DR} \omega_\text{DR} \frac{T_R}{2}}\right]
$$

From expressions for $DA_1$ and $DA_2$, their ratio can be found using:

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\[ \frac{DA_2}{DA_1} = \frac{Ae^{-\zeta_{dDR} \omega_{dDR} t_2} \sin(\omega_{dDR} t_2 + \mu) \left[ 1 + e^{-\zeta_{dDR} \omega_{dDR} \frac{T_p}{2}} \right]}{Ae^{-\zeta_{dDR} \omega_{dDR} t_1} \sin(\omega_{dDR} t_1 + \mu) \left[ 1 + e^{-\zeta_{dDR} \omega_{dDR} \frac{T_p}{2}} \right]} = e^{-\zeta_{dDR} \omega_{dDR} \frac{T_p}{2}} \] (5)

However, it is clear that more accurate values for this ratio can be found by evaluating their average using the relationship:

\[ TPR = \left( \frac{DA_2}{DA_1} + \frac{DA_3}{DA_2} + \frac{DA_4}{DA_3} + \ldots + \frac{DA_{N+1}}{DA_N} \right)^{1/N} \] (6)

From the expression for \( TPR \), the associated logarithmic decrement can be evaluated using:

\[ \delta = \ln(TPR) = -\zeta_{dDR} \omega_{dDR} \left( \frac{\pi}{\omega_{dDR}} \right) \] (7)

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

\[ \zeta_{dDR} = \frac{\ln(TPR)}{\sqrt{\pi^2 + \ln^2(TPR)}} \] (8)

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

\[ \omega_{nDR} = \frac{2\pi}{T_p \sqrt{1 - \zeta_{dDR}^2}} \] (9)

VI. Conclusions

A 6-DOF motion base flight simulator has recently been acquired by the MAE department at WVU as part of its strategic plans for enhancing academic and research capabilities in the area of flight dynamics, simulation, and control.

The flight simulator was integrated within the MAE curriculum to support the undergraduate course *Introduction to Flight Simulation*. The simulator is used to illustrate the general architecture and operation of a flight simulator and provide simulation data to practice the use of flight tests for aircraft performance and handling qualities evaluation.

The use of the flight simulator had a positive impact on the academic process increasing enrollment, retention, and the class average grade for the undergraduate course *Introduction to Flight Simulation*.

References


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