Flight Testing in a Simulation Based Environment

David W. Babka[1]
California Polytechnic University, San Luis Obispo, CA, 93405

---

[1] Undergraduate, Aerospace Engineering, 1 Grande Ave, San Luis Obispo CA 93407, AIAA Member 437959

Abstract

Over the past two decades performance flight testing of full scale aircraft has transferred some of the testing workload to simulation based systems. Flight testing full scale aircraft in the real world environment has always been expensive, especially now with the rise in aviation fuel costs. Additionally, new emerging technologies require extensive testing and doing so in the full scale environment is cost prohibitive. A cheaper alternative is to test systems in a simulation based environment. Not only can aircraft be simulated via a computer, but all the aircrafts systems can be modeled in the simulation. Furthermore, most of the aircraft systems, such as avionics and sensors, can be directly built into the simulation just as they would be on the actual aircraft. The purpose of this report is to review the progression of flight simulation technology, flight testing procedures, and conduct a series of flight tests to compare the data between the actual aircraft in flight with two simulators readily available to the general public. The two simulators considered are X-Plane 9 by Laminar Research and Flight Simulator X from Microsoft. Each simulator uses a different approach to creating the simulated environment. X-Plane uses an engineering process called "Blade Element Theory", while Microsoft Flight Simulator X uses the more traditional stability derivative method. In order to compare the accuracy of each of these simulations, three flight tests were conducted in each simulator and in the actual aircraft. A Cessna 172SP was the aircraft used in each of the tests. The three tests conducted were flight path stability, stall, and steady turns. Comparing the results, the simulations produced data very similar to that of the actual tests; however, the data did not suggest that either simulation was more accurate than the other. The only distinction between the two simulators that could be made was evident in their user interfaces and ease of operation. Overall, the results obtained in this paper illustrate the effectiveness of the modern flight simulator as an effective testing and design tool.

Acknowledgements

First, I would like to thank Dr. William Durgin for his guidance during the course of the project. Additionally, the flight tests in the actual aircraft could not have taken place if it were not for the efforts of Jeannine and Gary Sparks at the Pacific Aerocademy. The test aircraft, N172CY, was always in top condition and ready to complete the flight tests without any maintenance related issues.

Table of Contents

List of Figures

List of Tables

I. Introduction

AIRCRAFT flight testing is one of the most costly but essential steps in the design and manufacturing process. Before any aircraft, whether it be for the military or civilian markets, is ready for deployment, they must undergo a rigorous series of flight tests. Furthermore, flight testing programs are developed with the goal of revealing design flaws and providing necessary data for certification[1]. Before the age of computers, all flight tests were conducted on the prototype aircraft; consequently, design flaws which led to aircraft damage proved to be extremely expensive and would stop the design process until the prototype could be fixed and redesigned. The modern computer and the development of simulation based flight testing changed the design process completely.

Once computer technology caught up with the aerospace industry, the potential for aircraft design and testing became limitless. Aircraft developers were enabled to design, model, and test their aircraft in a safe and cost effective manner. Instead of having to repair a damaged airframe after a mishap in preliminary testing, the designer could simply make the design change in the computer model and re-fly the test. Additionally, simulation based testing helped reduce the cost of the testing process because simulators don't require fuel like their real world counterparts. The cost of fuel is one of the biggest limiting factors to flight testing. When a test program is developed, a specific amount of tests are planned in order to meet all the testing requirements and minimize the cost of the program. Because many designers outsource the flight testing process to a 3rd party, the testing agency incurs all additional expenses in the event a test requires repeating. Moreover, it would be more cost effective to test the aircraft model in a simulated environment first to reveal any design flaws beforehand.

With the ever rising price of oil, the use of simulation based flight testing is becoming more widely used as a primary means for testing. Both civilian and military programs have contributed to the development of the sophisticated simulators seen today. Most notably, Microsoft's flight simulation software, Microsoft ESP, was purchased by Lockheed Martin which used the technology to create a versatile simulation tool for preliminary testing. Lockheed's resulting software is called Prepar3D and has been packaged to sell to the commercial market. Figure 1 shows a rendering of the visual environment which Prepar3D creates[3]. A result from the development of high-tech simulators was the creation of medium fidelity consumer applications. The simulations that were developed for the consumer allowed the general public to experience the same simulation technologies used in commercial applications for recreational and educational purposes. The widespread use of the cheap, home-based flight simulators spawned a large community of flight simulator enthusiasts. Furthermore, the continued development of the home-based simulator has resulted in cheap and accurate simulation tools which have the potential to be used with a multitude of applications.

Figure 1. Lockheed Martin's commercial flight simulator: Prepar3D

The following paper explores the flight testing capabilities of home-based flight simulation models and environments. Primarily, the home-based simulator is designed for entertainment purposes; however, the educational applications are limitless. In order to demonstrate the capabilities of the home-based simulator, baseline tests were first conducted in an actual Cessna 172SP in the San Luis Obispo County area. The tests were then repeated in two different simulations and the data from all three tests were compared. Similar data sets would reveal the usefulness of the home-based simulators for educational and practical applications. In addition to investigating the usefulness of the home-based simulator, the overall project provided a great opportunity to learn flight testing protocols and flying techniques as well as an opportunity to develop data reduction scripts in MATLAB.

II. Literature Review

As the requirements for aerospace vehicles have become more advanced and exotic, the need for accurate, high-tech simulation software has increased accordingly. The new advanced aerospace systems are expensive to test full scale, thus developers must rely on scaled tests and simulations for preliminary testing. Finding design flaws at the early stages of design is vital in producing a product quickly and cost effectively.

In addition to being an invaluable tool to larger aerospace applications, less sophisticated simulation environments have extremely important applications for smaller, private designs and education opportunities. Home build aircraft designers can save themselves hours of troubleshooting and development costs by using cheap but effective simulations for their preliminary testing needs.

The following literature reviews will discuss simulation software which has been used for advanced aerospace concepts, as well as software that is currently being used presently. The first paper discusses the role of simulation in the development and flight testing of Highly Maneuverable Aircraft Technology (HiMAT) written by NASA engineers. Figure 2 illustrates the HiMAT concept via a three view drawing. Second, a paper was reviewed which discussed the use of open source, or free, software to simulate the testing of an autonomous unmanned aerial vehicle (UAV).

A. NASA HiMAT Vehicle Simulation

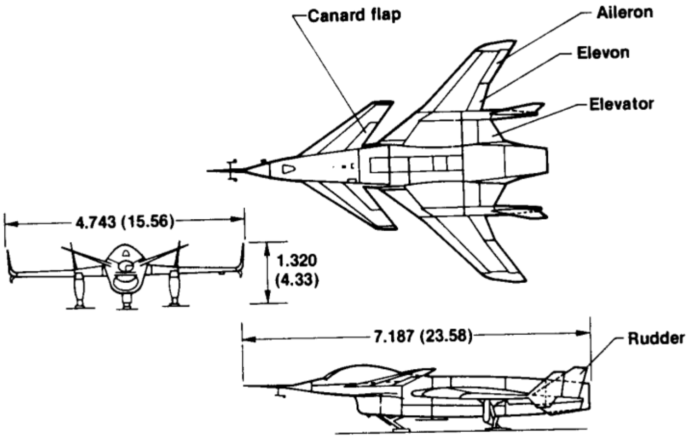


Figure 2. The HiMAT three-view reveals its special characteristics.

Beginning in the early 1980's, NASA began realizing the potential for the use of high fidelity simulation software. Full scale tests had become extremely expensive and in some cases impossible to perform. When studying the HiMAT vehicle concept, NASA engineers showed that flight simulation was *"the key to flight qualification of the HiMAT vehicle."*[1] The HiMAT vehicle concept was designed to demonstrate the maneuvering capabilities of an aircraft with reduced static stability and digital fly-by-wire controls. Because the HiMAT program planned for a *"limited amount of flights"* and had an *"unstable aircraft configuration"*, simulations were "*essential to the HiMAT program."* During the course of the HiMAT program many different simulation modules were developed. Some of the key components to note are the aerodynamics, primary and secondary control, propulsion, and uplink and downlink models. Each module closely simulates their actual real world counterparts and allowed the designers the chance to correct issues before actual tests were conducted. For instance, when simulating the downlink system, the designers were able to solve issues while still in the simulation.

Four different simulation versions were developed for the HiMAT vehicle: the Basic, Verification, computation and simulation of HiMAT (CASH), and Iron Bird. The Basic simulation was the most widely used because it allowed for *"relative ease of program modification"* and the use of the *"fewest number of computers"*. Ultimately, the basic simulation *"provided the principle tool for the final design"*. Figure 3 shows the actual Basic simulation block diagram used in the HiMAT program.

The next evolution to the simulation environment was the Verification simulator, which had the primary purpose of verifying the flight code and making sure the systems perform exactly as specified. Because most of the codes used in the simulation are those actually used on the aircraft, the must be verified in the simulator before being implanted practically.

The third type of simulation performed was the CASH simulation. CASH simulations were used primarily for system validation, flight planning, and pilot training and proved to be the best tool for testing flight software. Using ten different computers, the CASH system was highly complex yet more cost effective than using the actual HiMAT vehicle.

Last, the Iron Bird simulation systems were conducted. Iron bird simulations use the actual vehicle and were developed to perform full-system validations, limit-cycle tests, and failure mode and effects analysis. The actual data uplink and downlink systems were used to connect the vehicle to the simulation computers. Simulated sensor signals were sent to the actual vehicle which responded as if it were actually in flight. The tests proved to be invaluable in discovering critical time delays between the simulation signal implementation and the vehicle response. Those delays were important because the same delays would be evident when the actual vehicle was tested remotely in an actual environment. Because the Iron Bird system was expensive to operate, it was not extensively used for pilot training and flight planning.

Moreover, all four simulation systems were highly effective in the design, development, and testing of the HiMAT test vehicle.

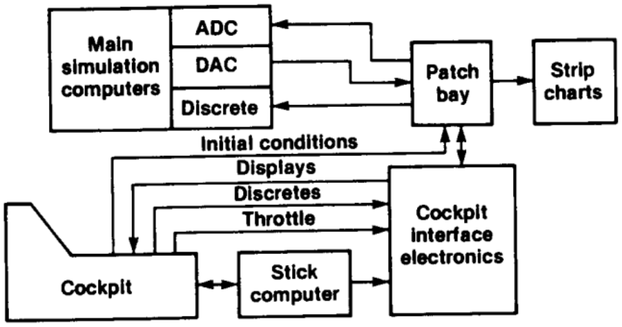


Figure 3. The Basic simulation was compact and simple.

B. Integration of Open Source Flight Simulation Software in Testing UAVs

As the use of small, unmanned aerial vehicles (UAVs) becomes more prevalent in military and commercial markets, the demand for low cost testing applications also increases. Building a dedicated and fully custom simulation model for a small UAV application is not only overkill but is also cost prohibitive[6]. Small UAVs are designed using simple flight models and a complicated simulation is not needed; thus, open-source (freeware) simulators and flight dynamics models are perfectly capable providing the correct amount of fidelity and cost effectiveness.

FlightGear, an open-source simulator, and JSBSim, an open-source flight dynamics model, are applications with unlimited possibilities. For instance, the Institute for Scientific Research (ISR), Inc. used FlightGear along with JSBSim to build a simulation environment for the testing of an Autonomous UAV (AUAV). Additionally MATLAB/Simulink was used in initial development and testing to simulate the AUAV’s autopilot. Figure 4 shows the FlightGear simulation environment and the MATLAB/Simulink autopilot control outputs.

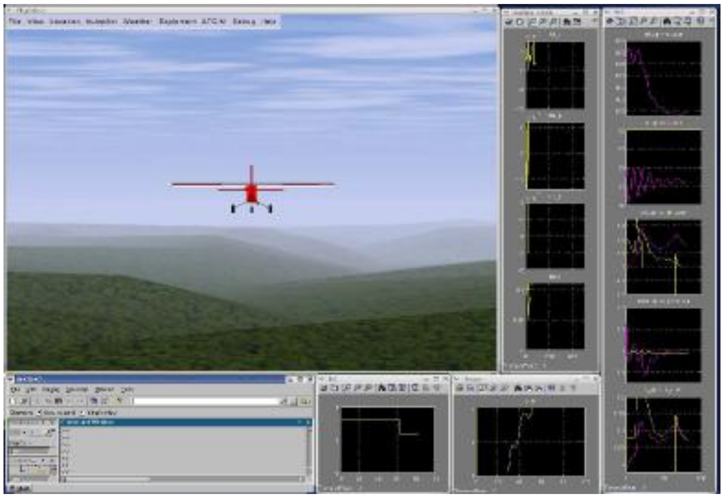


Figure 4. FlightGear/JSBSim and MATLAB/Simulink were used together to model the UAV's flight model and autopilot respectively[6].

The tests conducted by the ISR occurred in three stages. The first stage, or the development stage, used a MATLAB/Simulink bridge consisting of an S-Function that receives inputs from the autopilot and then transmits outputs to FlightGear. The S-Function bridge acts as the flight dynamics model and outputs values such as altitude, airspeed, pitch rate...etc[6]. The stage 1 test environment was a useful development tool; however, the development model proved only useful for short duration testing and did not provide a way to alter the desired testing conditions mid flight.

Stage 2, or regression testing, integrated the previously used MATLAB/Simulink autopilot with a C++ bridge that would pass data between MATLAB/Simulink and FlightGear. The regression test bridge was also linked to a text file which could set the desired test conditions at anytime during the test.

Additionally, scripts were used to drive the regression tests which then tested each capability of the autopilot.

The final stage, stage 3, integrated the actual autopilot hardware into the control loop. More specifically, instead of using a MATLAB/Simulink model of the automated control laws, the actual control hardware designed for the test vehicle was integrated into the simulation loop. Thus, every aspect, except the aircraft sensor board, was able to be thoroughly tested before spending the money and resources to test the aircraft in the field. Ultimately, the ISR was able to use readily available flight simulation software to limit their costs and effectively tests their vehicle and control system.

III. Methodology and Results

The following section describes safety considerations, testing procedure and illustrates the results of three flight tests. Each test was conducted in three different environments: the actual aircraft, Laminar Research's X-Plane environment, and in Microsoft's Flight Simulator X. The tests conducted in the real world environment were done so in a Cessna 172SP over the San Luis Obispo County area. Three tests were conducted, stall, steady turns, and flight path stability, and the data collected was used as baseline data points to compare with the results conducted in the two simulation environments. The objective of the data comparison was to determine which of the two simulation models was the most accurate. Additionally, the ease of use and cost of both the simulation tools were also compared.

Laminar Research's X-Plane is considered to be the most realistic simulator available to the public. Unlike most simulation engines, X-Plane does not rely on stability derivatives to define how an aircraft should fly; however, X-Plane uses actual flow calculations many times per second to figure out how the given aircraft flies in the simulated environment. Figure 5 shows a screenshot of how the aircraft interacts with the simulated environment in X-Plane. The engineering process used to calculate the simulated flow field is Blade Element Theory. Upon opening the X-Plane engine, the aircraft considered for flight has its surfaces divided up into many different elements. Then once the aircraft is in flight, X-Plane uses the finite elements created based upon the aircraft surfaces to determine the velocities acting at each element. Additionally, the downwash, prop wash and induced angle of attack are also calculated for each element. Force coefficient data are corrected for finite surface effects and then the forces and moments are summed on each element at a rate of over 15 times a second[4].

Figure 5. X-Plane performs multiple calculations per second to determine how the aircraft actually flies.

On the other side of the fence lies Microsoft's Flight Simulator X (FSX) which uses stability derivative and look up stables to predict how the aircraft in question might fly. Figure 6 shows the same Cessna model flying in the FSX environment. Aircraft stability coefficients are based upon the aircrafts geometry and each components interaction with each other during flight. Those coefficients can be estimated using equations or found using empirical sources such as the United States Airforce's (USAF) Digital DATCOM. Once the coefficients for the aircraft are found, they are compiled into a single file. Each one of the coefficients is available in that file for a number of angles of attack and mach numbers. Additionally, all aspects of the aircraft's geometry are placed in a separate file. The combination of the geometry and the coefficients files

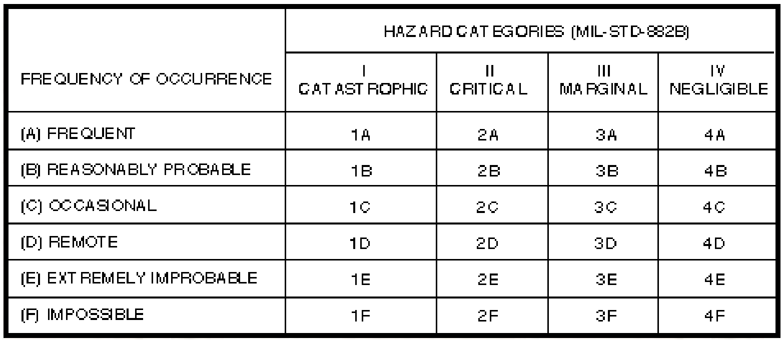
Figure 6. FSX uses stability derivatives to predict how the aircraft should fly.

makes up the basic flight model for the aircraft; thus, during flight FSX uses the stability derivatives for the given flight conditions to determine the proper aircraft reaction. Ultimately, an aircraft in FSX can be extremely accurate, but only if a sizeable amount of data is known for the aircraft in question[5].

Overall, both flight simulators have the potential to provide useful test data for a given aircraft. The following section investigates three tests previously mentioned and compares the results from both simulators to the data taken from the actual aircraft.

A. Safety

The first issue addressed before any flight testing was performed in the actual aircraft was safety. When the flight test practice was born, many test pilots were lost due to a lack of safety standards and regulations. In order to mitigate the risk involved with flight testing aircraft, safety protocols and regulations were implemented. A fallout of the new regulations introduced was the hazard category matrix shown in Figure 7 that come from Military Standard 882B (MIL-STD 882B). The matrix allows the test engineer to identify the hazards associated with the respective test. Additionally, the severity and the frequency of each hazard can be identified.



FREQUENCY OF OCCURRENCE	HAZARD CATEGORIES (MIL-STD-882B)			
	I CATASTROPHIC	II CRITICAL	III MARGINAL	IV NEGLIGIBLE
(A) FREQUENT	1A	2A	3A	4A
(B) REASONABLY PROBABLE	1B	2B	3B	4B
(C) OCCASIONAL	1C	2C	3C	4C
(D) REMOTE	1D	2D	3D	4D
(E) EXTREMELY IMPROBABLE	1E	2E	3E	4E
(F) IMPOSSIBLE	1F	2F	3F	4F

Figure 7. MIL-STD-882B Hazard matrix helps prevent accidents.

Table 1. Flight testing has some critical hazards.

	Hazard	**Category**
1	Engine Failure	II D
2	Spin	II B
3	Mid Air Collision	I D
4	Data Acquisition Failure	II C
5	Stall	III B

Table 1 shows the main hazards associated with flight testing and their respective categories. The first listed is total engine failure. Loss to the power plant of the aircraft leaves the aircraft in a critical situation. Some causes to engine failure include lack of oil, catastrophic cylinder detonation, magneto failure…etc. Engine failure is avoided by completing all preflight checks and ensuring the engine has undergone the required maintenance.

Next, the hazard of aircraft spin is labeled as critical and reasonably probable. When conducting low speed tests, especially related to stall, the aircraft is susceptible to spin. Spin occurs when the aircraft is stalled and enough yaw is introduced to rotate the plane about the spin axis[2]. Spin can be avoided by keeping the aircraft in coordinated flight or “stepping on the ball”. In the event of a spin the ailerons are moved to their neutral position and full opposite rudder is applied.

Perhaps one of the most dangerous and horrific hazards to pilots is the mid air collision which is a remote yet catastrophic failure. Mid air collisions can occur with a variety of objects and are usually caused by a lack of situational awareness (SA) by the pilot and poor flight planning. Objects other than aircraft, especially birds, can be avoided by choosing a testing altitude clear of bird traffic. Collisions with other aircraft can be avoided by choosing a non congested testing location, monitoring the frequencies of nearby approaches and airfields, and performing 90 degree clearing turns before every maneuver.

Data acquisition failure is labeled as a critical failure because the flight will have to be flown again thus doubling the cost of that particular test. A test flight may fail to acquire the necessary test data because the acquisition device failed or a piece of the equipment was forgotten or misused. In the case of the tests described in the following sections, the data was acquired using a video camera; thus, it was essential to ensure the cameras battery was charged and the memory storage device had sufficient space to record all the tests.

Last, stall is another prevalent hazard to flight test, especially when considering low speed testing. An aircraft by definition can stall at any airspeed and that is the reason why it is such a common hazard. The cause of stall mainly attributes to the angle of attack of the lifting surface reaching the critical angle of attack regardless of airspeed. Stall can be avoided by maintaining an awareness of the aircrafts airspeed and pitch attitudes; however in the event of a stall, the wings need to stay level and the turn coordinator centered. Ultimately, identifying the hazards associated with each flight test not only increased the safety of the test but also the efficiency of the test as well.

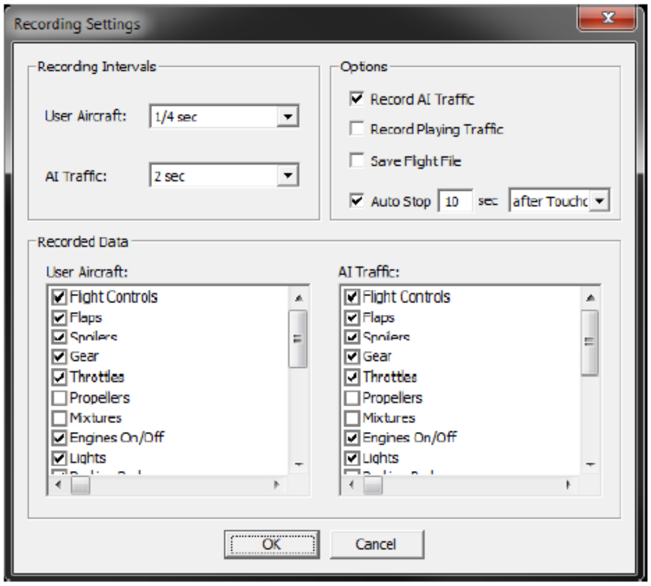
B. Data Acquisition

Each of the three test environments had their own data acquisition procedure and equipment. As noted in the safety section of the report, the data acquisition equipment needed to be fully functional and the instructions for use fully understood. Ensuring proper data collection ensured the integrity of the data and the time allotted for testing was used effectively.

The test setup for the flight tests performed in the actual aircraft was rather simple. A robust, aircraft specific, data collection unit was not available for use on the aircraft; thus, an HD video camera was used to record the instrument panel during flight. The camera used was a Go Pro® HD Hero which has the ability to record in 1080p resolution and is pictured in Figure 8. Since the frame rate acquisition was more important than resolution, the 720p resolution at 60 frames per second (fps) was used during the tests as opposed to a resolution of 1080p at 30 fps. Additionally, the mounting system shown in Figure 8 was used to attach the camera to the left section of the windscreen. The suction cup and tightening pins ensured the camera stayed in place during all aspects of the flight and an on camera stabilization allowed the camera to film the tests without shaking due to cabin vibrations. Overall the Go Pro® HD Hero proved to be a vital piece to the success of the flight tests.

Figure 8. The Go Pro® HD video camera was invaluable in acquiring the required test data.

The tests conducted in Microsoft's FSX used and open-source program called FS Recorder to record the flight data in real time. The primary purpose of FS Recorder is to record FSX aircraft data for the use of playing back flights for viewing purposes; however, FS Recorder also has to ability to convert the playback files to text files containing valuable aircraft data such as GPS coordinates, airspeeds, and altitude. The data contained in the text file is recorded 4 times a second during the course of the test[2] and is outputted to a file named by the user. Data acquisition in FSX using FS Recorder was initiated by first pausing the simulation and pressing alt on the keyboard to reveal the FSX menu on the top of the screen. Next, the FS Recorder tab was highlighted using the mouse and then the Record option is selected. Figure 9 shows a screenshot of the FS Recorder options window where aircraft flight data can be selected for recording along with the recording interval size. After the desired settings were selected, the simulation was unpaused and the test flight was flown to completion. Once the test was completed the simulation was again paused and then the alt key was again used to unhide the FSX menu. The FS Recorder tab was highlighted with the mouse and then the stop recording option was selected. Once the simulation stopped recording, a window opened enabling the recorded data to be saved to a specified filename and location. The final procedure in finalizing the raw data from FSX was to convert the .frc output file to a text file using the FRC Converter tool included with the FS Recorder program. A sample output file from FSX is available in the Appendix in Table 2. Ultimately, FS Recorder and its internal conversion program proved to be an effective data gathering tool for the tests ran in FSX.



Recording Settings

Recording Intervals
User Aircraft: 1/4 sec
AI Traffic: 2 sec

Options
☑ Record AI Traffic
☐ Record Playing Traffic
☐ Save Flight File
☑ Auto Stop 10 sec after Touchc

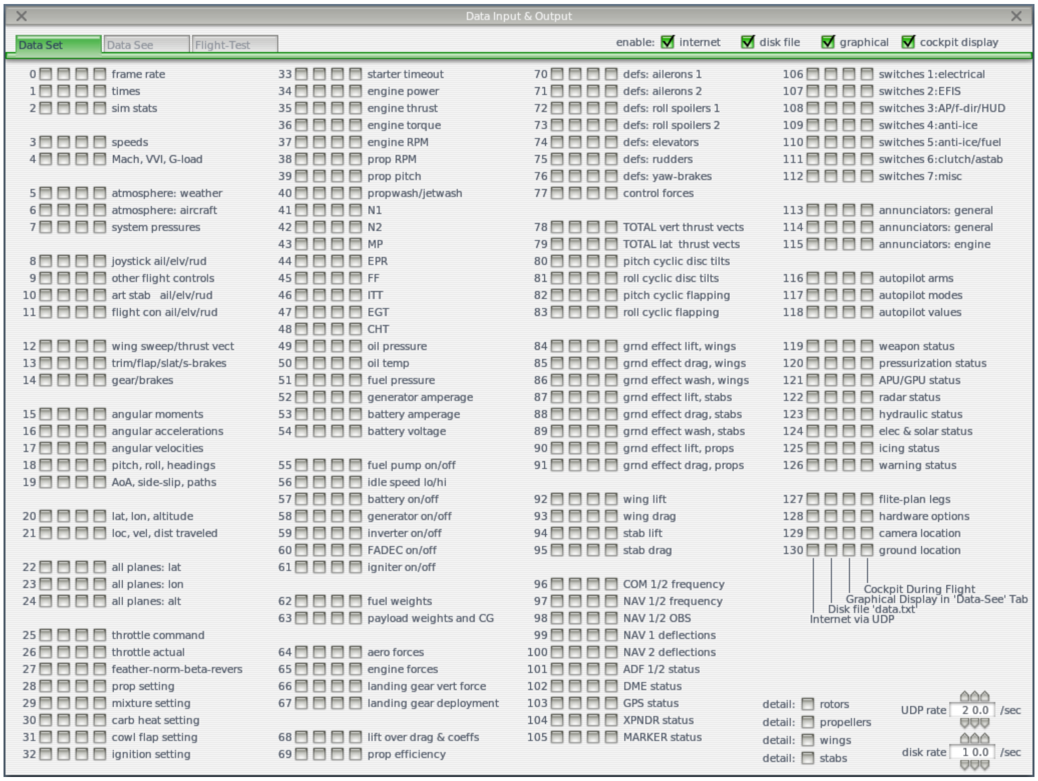
Recorded Data

User Aircraft:
☑ Flight Controls
☑ Flaps
☑ Spoilers
☑ Gear
☑ Throttles
☐ Propellers
☐ Mixtures
☑ Engines On/Off
☑ Lights

AI Traffic:
☑ Flight Controls
☑ Flaps
☑ Spoilers
☑ Gear
☑ Throttles
☐ Propellers
☐ Mixtures
☑ Engines On/Off
☑ Lights

Figure 9. FS Recorder allows for a multitude of aircraft

During the final tests conducted in X-Plane, X-Plane's internal data recording system was used to output the required test data. The data acquisition program is enabled from the main window during flight and X-Plane automatically records the selected data 10 times per second. The data is actively written to a generic data file in the main X-Plane folder. Much like in FSX the data recording in X-Plane is enabled from the menu located at the top of the simulation window. The menu was accessed by moving the mouse to the top of the simulation window. Next the settings menu was selected and then the data input and output tab was opened. Figure 10 shows X-Planes extensive data output selection window. Once the data required for the flight test is selected on data output selection screen, the window is closed and the window returns to the simulation. X-Plane was then recording data in real time and the test was then completed. After the test was finished the data output selection window was reopened the options previously selected were deselected and then the window was returned to the simulation. Table 3 in the Appendix shows an example of an output file from X-Plane. Once the aircraft was set up for the next flight test, the recording procedure was completed again for the next test. Each time a test was finished the flight test data was added to the main data file discussed earlier and each test was separated by a new header line in the main file. Just as FS Recorder for FSX, X-Plane's internal data recording proved invaluable to the data collection during the flight tests.



enable: ☑ internet ☑ disk file ☑ graphical ☑ cockpit display

0 ☐ ☐ ☐ ☐ frame rate
1 ☐ ☐ ☐ ☐ times
2 ☐ ☐ ☐ ☐ sim stats
3 ☐ ☐ ☐ ☐ speeds
4 ☐ ☐ ☐ ☐ Mach, VVI, G-load
5 ☐ ☐ ☐ ☐ atmosphere: weather
6 ☐ ☐ ☐ ☐ atmosphere: aircraft
7 ☐ ☐ ☐ ☐ system pressures
8 ☐ ☐ ☐ ☐ joystick ail/elv/rud
9 ☐ ☐ ☐ ☐ other flight controls
10 ☐ ☐ ☐ ☐ art stab ail/elv/rud
11 ☐ ☐ ☐ ☐ flight con ail/elv/rud
12 ☐ ☐ ☐ ☐ wing sweep/thrust vect
13 ☐ ☐ ☐ ☐ trim/flap/slat/s-brakes
14 ☐ ☐ ☐ ☐ gear/brakes
15 ☐ ☐ ☐ ☐ angular moments
16 ☐ ☐ ☐ ☐ angular accelerations
17 ☐ ☐ ☐ ☐ angular velocities
18 ☐ ☐ ☐ ☐ pitch, roll, headings
19 ☐ ☐ ☐ ☐ AoA, side-slip, paths
20 ☐ ☐ ☐ ☐ lat, lon, altitude
21 ☐ ☐ ☐ ☐ loc, vel, dist traveled
22 ☐ ☐ ☐ ☐ all planes: lat
23 ☐ ☐ ☐ ☐ all planes: lon
24 ☐ ☐ ☐ ☐ all planes: alt
25 ☐ ☐ ☐ ☐ throttle command
26 ☐ ☐ ☐ ☐ throttle actual
27 ☐ ☐ ☐ ☐ feather-norm-beta-revers
28 ☐ ☐ ☐ ☐ prop setting
29 ☐ ☐ ☐ ☐ mixture setting
30 ☐ ☐ ☐ ☐ carb heat setting
31 ☐ ☐ ☐ ☐ cowl flap setting
32 ☐ ☐ ☐ ☐ ignition setting
33 ☐ ☐ ☐ ☐ starter timeout
34 ☐ ☐ ☐ ☐ engine power
35 ☐ ☐ ☐ ☐ engine thrust
36 ☐ ☐ ☐ ☐ engine torque
37 ☐ ☐ ☐ ☐ engine RPM
38 ☐ ☐ ☐ ☐ prop RPM
39 ☐ ☐ ☐ ☐ prop pitch
40 ☐ ☐ ☐ ☐ propwash/jetwash
41 ☐ ☐ ☐ ☐ N1
42 ☐ ☐ ☐ ☐ N2
43 ☐ ☐ ☐ ☐ MP
44 ☐ ☐ ☐ ☐ EPR
45 ☐ ☐ ☐ ☐ FF
46 ☐ ☐ ☐ ☐ ITT
47 ☐ ☐ ☐ ☐ EGT
48 ☐ ☐ ☐ ☐ CHT
49 ☐ ☐ ☐ ☐ oil pressure
50 ☐ ☐ ☐ ☐ oil temp
51 ☐ ☐ ☐ ☐ fuel pressure
52 ☐ ☐ ☐ ☐ generator amperage
53 ☐ ☐ ☐ ☐ battery amperage
54 ☐ ☐ ☐ ☐ battery voltage
55 ☐ ☐ ☐ ☐ fuel pump on/off
56 ☐ ☐ ☐ ☐ idle speed lo/hi
57 ☐ ☐ ☐ ☐ battery on/off
58 ☐ ☐ ☐ ☐ generator on/off
59 ☐ ☐ ☐ ☐ inverter on/off
60 ☐ ☐ ☐ ☐ FADEC on/off
61 ☐ ☐ ☐ ☐ igniter on/off
62 ☐ ☐ ☐ ☐ fuel weights
63 ☐ ☐ ☐ ☐ payload weights and CG
64 ☐ ☐ ☐ ☐ aero forces
65 ☐ ☐ ☐ ☐ engine forces
66 ☐ ☐ ☐ ☐ landing gear vert force
67 ☐ ☐ ☐ ☐ landing gear deployment
68 ☐ ☐ ☐ ☐ lift over drag & coeffs
69 ☐ ☐ ☐ ☐ prop efficiency
70 ☐ ☐ ☐ ☐ defs: ailerons 1
71 ☐ ☐ ☐ ☐ defs: ailerons 2
72 ☐ ☐ ☐ ☐ defs: roll spoilers 1
73 ☐ ☐ ☐ ☐ defs: roll spoilers 2
74 ☐ ☐ ☐ ☐ defs: elevators
75 ☐ ☐ ☐ ☐ defs: rudders
76 ☐ ☐ ☐ ☐ defs: yaw-brakes
77 ☐ ☐ ☐ ☐ control forces
78 ☐ ☐ ☐ ☐ TOTAL vert thrust vects
79 ☐ ☐ ☐ ☐ TOTAL lat thrust vects
80 ☐ ☐ ☐ ☐ pitch cyclic disc tilts
81 ☐ ☐ ☐ ☐ roll cyclic disc tilts
82 ☐ ☐ ☐ ☐ pitch cyclic flapping
83 ☐ ☐ ☐ ☐ roll cyclic flapping
84 ☐ ☐ ☐ ☐ grnd effect lift, wings
85 ☐ ☐ ☐ ☐ grnd effect drag, wings
86 ☐ ☐ ☐ ☐ grnd effect wash, wings
87 ☐ ☐ ☐ ☐ grnd effect lift, stabs
88 ☐ ☐ ☐ ☐ grnd effect drag, stabs
89 ☐ ☐ ☐ ☐ grnd effect wash, stabs
90 ☐ ☐ ☐ ☐ grnd effect lift, props
91 ☐ ☐ ☐ ☐ grnd effect drag, props
92 ☐ ☐ ☐ ☐ wing lift
93 ☐ ☐ ☐ ☐ wing drag
94 ☐ ☐ ☐ ☐ stab lift
95 ☐ ☐ ☐ ☐ stab drag
96 ☐ ☐ ☐ ☐ COM 1/2 frequency
97 ☐ ☐ ☐ ☐ NAV 1/2 frequency
98 ☐ ☐ ☐ ☐ NAV 1/2 OBS
99 ☐ ☐ ☐ ☐ NAV 1 deflections
100 ☐ ☐ ☐ ☐ NAV 2 deflections
101 ☐ ☐ ☐ ☐ ADF 1/2 status
102 ☐ ☐ ☐ ☐ DME status
103 ☐ ☐ ☐ ☐ GPS status
104 ☐ ☐ ☐ ☐ XPNDR status
105 ☐ ☐ ☐ ☐ MARKER status
106 ☐ ☐ ☐ ☐ switches 1:electrical
107 ☐ ☐ ☐ ☐ switches 2:EFIS
108 ☐ ☐ ☐ ☐ switches 3:AP/f-dir/HUD
109 ☐ ☐ ☐ ☐ switches 4:anti-ice
110 ☐ ☐ ☐ ☐ switches 5:anti-ice/fuel
111 ☐ ☐ ☐ ☐ switches 6:clutch/astab
112 ☐ ☐ ☐ ☐ switches 7:misc
113 ☐ ☐ ☐ ☐ annunciators: general
114 ☐ ☐ ☐ ☐ annunciators: general
115 ☐ ☐ ☐ ☐ annunciators: engine
116 ☐ ☐ ☐ ☐ autopilot arms
117 ☐ ☐ ☐ ☐ autopilot modes
118 ☐ ☐ ☐ ☐ autopilot values
119 ☐ ☐ ☐ ☐ weapon status
120 ☐ ☐ ☐ ☐ pressurization status
121 ☐ ☐ ☐ ☐ APU/GPU status
122 ☐ ☐ ☐ ☐ radar status
123 ☐ ☐ ☐ ☐ hydraulic status
124 ☐ ☐ ☐ ☐ elec & solar status
125 ☐ ☐ ☐ ☐ icing status
126 ☐ ☐ ☐ ☐ warning status
127 ☐ ☐ ☐ ☐ flite-plan legs
128 ☐ ☐ ☐ ☐ hardware options
129 ☐ ☐ ☐ ☐ camera location
130 ☐ ☐ ☐ ☐ ground location

Cockpit During Flight
Graphical Display in 'Data-See' Tab
Disk file 'data.txt'
Internet via UDP

detail: ☐ rotors
detail: ☐ propellers
detail: ☐ wings
detail: ☐ stabs

UDP rate 2 0.0 /sec
disk rate 1 0.0 /sec

Figure 10. X-Plane boasts an extensive data recording capability.

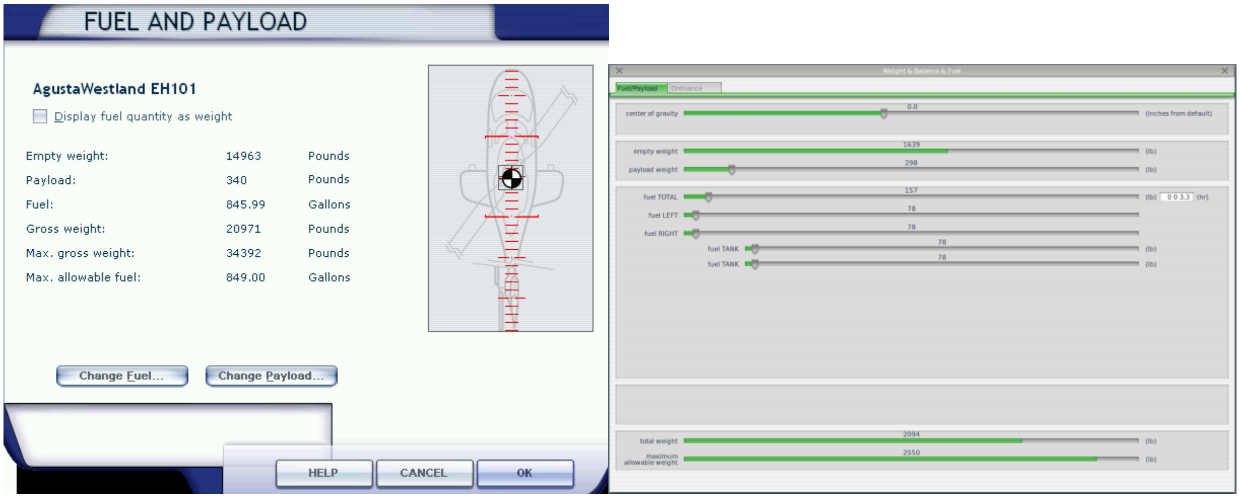
C. Test Procedure – Stalls

In addition to identifying the hazards associated with each flight test, detailed procedures for each test were written to further ensure the safety and effectiveness of each test. The first order of business before any of the flight tests were conducted in the actual aircraft was to make the go/no go decision based on the weather. If the weather was rendered conditions that were out of the aircrafts or the pilot's capabilities, the test was moved to a later date. On the condition that the weather was acceptable, the test was given a go. Next, the weather data was recorded from the Automatic Terminal Information Service (ATIS) for later use in the simulation based environment and data reduction. The proceeding weather checks were used on all three test days. In addition to the weather data, fuel weights were also recorded to ensure the tests in the simulators used the correct weight and balance.

Once the standard preflight inspections and the aircraft and weather data were recorded, the aircraft was ready to begin the first test. After departing San Luis Obispo Regional Airport (KSBP), the aircraft was turned toward the coast and a steady climb to 3000 feet MSL was initiated. The first test that was completed was the power on stall test. First the aircraft was trimmed for steady level flight at 3000 feet and after stabilization the video camera was turned to record. Then, reducing the RPM to 1700, the aircraft was slowed to approximately 70 KIAS. After reaching 70 KIAS, full power was applied as well as strong back pressure on the flight yoke. As the aircraft climbed, elevator was used to slow the aircraft and an approximate rate of 1 knot per second. A deceleration rate of 1 knot per second helped keep the aircraft controllable and highlighted the break once stall occurred. Additionally, right rudder was applied to keep the aircraft coordinated throughout the test. Once the aircraft stalled, the nose was pushed down to regain the kinetic energy lost during the maneuver[2]. For the sake of safety, the video camera was not dealt with (turned off) until the aircraft showed a safe airspeed and attitude. The test was then repeated for the power on situation using the procedure just mentioned.

Next, the aircraft underwent power off stall testing. First, the aircraft was trimmed again at or around 3000 feet for steady level flight and the camera was switched to record. The rpm setting was then reduced to 1500 and when appropriate 10, then 20, and finally 30 degrees of flap deflection were added to stabilize the aircraft in "slow flight" or the landing configuration. Once the aircraft was stable in slow flight, elevator deflections along with the coordinating right rudder were used to slow the aircraft to stall. After the aircraft experienced the stall, the nose was pushed down, full power was applied, and the flaps were raised to 20 degrees. Then, once the aircraft settled into a safe condition the camera was turned off and the aircraft was set up for the second power off test.

During the testing conducted in the simulators, the same procedure as noted above was used for both the power on and power off tests; however, the procedure for data acquisition was based on the simulator being used as described in the previous section. Additionally, the simulated aircraft was also set up with the same weight and balance as the test aircraft. Figure 11 shows the weight and balance interface available in FSX and X-Plane from the left to right respectively. Similar menus were also available to set the weather conditions specific to that of the day when the test was conducted in the actual aircraft, including wind, visibility, and barometric pressure.



AgustaWestland EH101

☐ Display fuel quantity as weight

Empty weight:	14963	Pounds
Payload:	340	Pounds
Fuel:	845.99	Gallons
Gross weight:	20971	Pounds
Max. gross weight:	34392	Pounds
Max. allowable fuel:	849.00	Gallons

center of gravity	0.0	(inches from default)
empty weight	1639	(lb)
payload weight	298	(lb)
fuel TOTAL	157	(lb) 0 0 3.3 (hr)
fuel LEFT	78	
fuel RIGHT	78	
fuel TANK	78	(lb)
fuel TANK	78	(lb)
total weight	2094	(lb)
maximum allowable weight	2550	(lb)

Figure 11. FSX and X-Plane have the ability to customize the weight and balance of the aircraft.

D. Test Procedure – Steady Turn

Just as with the Stall test from the previous section, the first steps of the steady turn tests was to make the go/no go decision, properly preflight the aircraft, and record the necessary fuel and weather data. Once in the air, the aircraft was flown again to an altitude of 3000 feet MSL and to an area free of traffic. The steady turn test proved to have the simplest procedure out of the three tests. First the throttle was set to roughly 2100 rpm and the aircraft was then allowed to accelerate and stabilize, while the aircraft's altitude was held constant. After the airspeed stabilized, the control force was trimmed off the yoke using the trim wheel. Then, once the aircraft was in steady, level, trimmed flight, the camera was switched to record and the aircraft was banked to an angle of 30 degrees. During the turn bank angle and altitude were held constant. Since the aircraft was operating on the front side of the power curve, the velocity should stabilize at a lower value than just before the start of the turn. The maneuver was flown until the airspeed was stabilized at the constant bank angle, altitude and load factor. Then the aircraft was rolled wings level and the camera was set to standby. The above procedure was then completed again for engine RPMs of 2200 and 2300.

E. Test Procedure – Flight Path Stability

The final test conducted involved investigating the flight path stability of the aircraft, more specifically the approach stability. An aircraft is stable on approach if the pitch for speed and throttle for rate of climb relationship remains intact. The first steps, as in the previous tests, were to check the weather for safe flying conditions, record the fuel weights and properly preflight the aircraft. Next, the aircraft was flown again to an altitude of 3000 feet and trimmed for steady level flight. Two variations of the test were performed, the first was conducted in the clean configuration and the second used 20 degrees of flaps. Other than the aircraft configuration, the difference in the variations was the approach speed and rpm setting. The clean configuration approach speed was flown at 1500 RPM and 75 KIAS and the flap down test was conducted at 1700 RPM and 70 KIAS. Once the aircraft was established at either approach condition, the camera was switched to record and then the airspeed was decreased using pitch control only 5 KIAS. The test concluded when the aircraft descended through 2500 feet MSL and the camera was switched to standby. Then the aircraft was returned to its initial condition of steady level flight at 3000 feet MSL. After returning to the initial flight condition, the aircraft was again set up for the approach speed associated with the clean or dirty configuration. Next, the camera was turned again to record and the aircraft was pitched to increase its approach speed by 5 KIAS. Again, the test concluded when passing through 2500 feet MSL and the camera was switched to standby[2].

F. Results – Stall

After the procedure for each test was fully understood, the tests were then performed. The first tests conducted involved stalling the aircraft in the power on and power off configurations. Using the procedure noted in section IIIC of the report, the stall tests were completed in all three environments. Figure 12 shows the results of the power on stall test. The chart in the left portion of the figure illustrates the change in altitude during the test. It is important to note that both charts in the figure were plotted against a normalized axis to better compare the three different data sets. The 0 point on the charts represents the test start and 1 represents the test end. All the plots included in the remainder of the report are configured in the same manner.

The first interesting point to note is the decrease in altitude during the beginning of the test. A loss in altitude at that particular time indicates that while the aircraft was slowed by reducing throttle, care was not taken to hold altitude. Nevertheless, both the test performed in FSX and X-Plane show trends consistent with the real test data. However, both simulation data sets show a stall velocity 4 to 10 knots higher than the actual test data. Additionally, the altitude data suggests that the FSX model had a higher climb rate during the test than the other two. One explanation for the higher climb rate may have been that the engine model in FSX was different or the mixture setting, which effects engine performance, was also different.

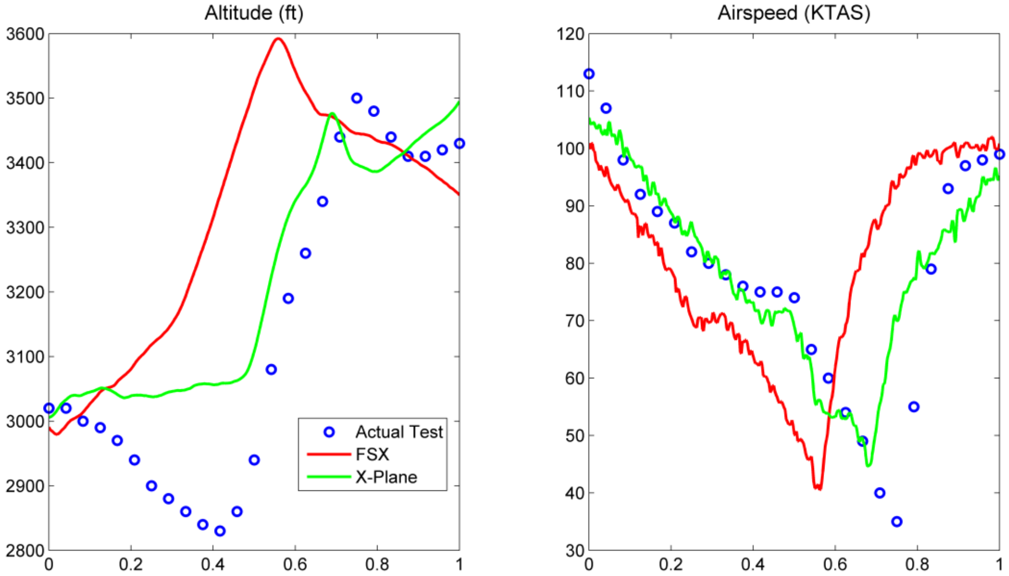


Figure 12. Power on stall test results

Once the power on test was completed, a power off test was also completed per the requirements and procedures located in section IIIC of the report. Figure 13 illustrates the power off stall results with the chart on the left showing altitude, while the chart on the right shows airspeed. As expected for a power off stall, the altitude trend is for the most part constant and then after stall a steep drop in altitude occurred. When conducting a stall, the FAA requires the pilot to be able to perform the maneuvers without having lost more than 100 ft in altitude; however, the stall tests were exaggerated to gain a larger range of data.

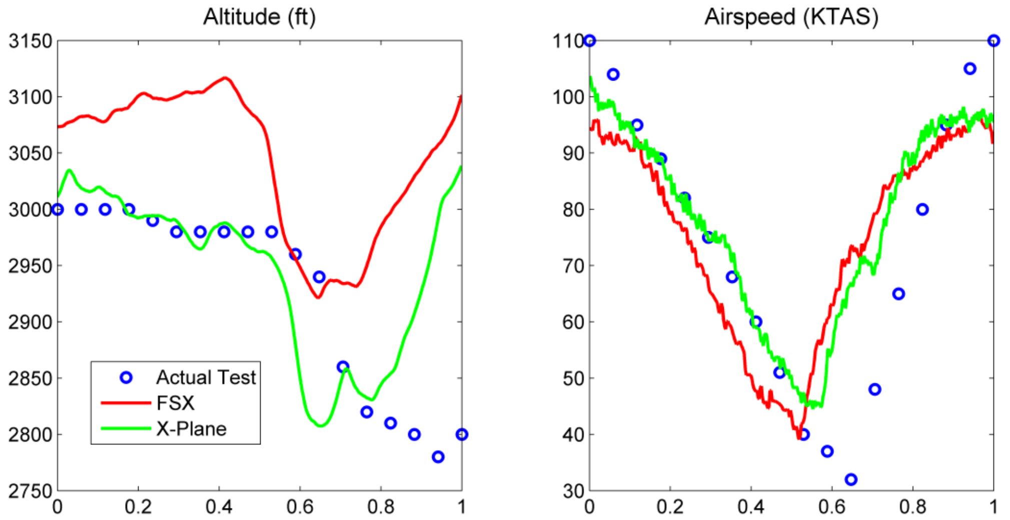


Figure 13. Power off stall test results

As with the power on stall data, FSX and X-Plane show trends consistent with the actual test data. The difference in altitude evident from the FSX data occurred because the test was initiated at a higher altitude; however, the FSX data still shows roughly the same amount of altitude loss. Additionally, both sets of simulation airspeed data show a slightly smaller stall speed. Overall, the both data sets for the power on and power off stall tests present data which is very similar to that of the real thing.

G. Results – Steady Turn

The second test conducted involved three subtests of steady level flight at engine RPMs of 2100, 2200, and 2300. Each test was conducted using the procedure outlined in section IIID of the report. The purpose of the steady turn test was to look into the accuracy of the engine model and thus the airspeeds at which the aircraft would settle during the constant load factor turn. Figure 14 illustrates the results of the three different turn tests. The airspeed and altitude trends during each test are shown in charts a-c and d-f respectively.

First, it is interesting to note that the turn tests resulted in a much more sporadic data set between the three test mediums. Looking at the test data from the test conducted with the 2100 engine RPM setting, the initial airspeeds show a large spread between initial settling airspeeds in FSX, X-Plane, and the real thing. Additionally, the altitude trends are also different for all three sources. According to theory, as load factor increases, the airspeed should decrease if a constant altitude is held during the turn. Holding the turn at a constant altitude proved to be a more difficult task than expected in the real aircraft. Nonetheless, when the altitude was held constant for a brief period of time, the correct trend of decreasing airspeed was seen in both the FSX and actual aircraft tests. The X-Plane data showed a constant airspeed trend as the load factor was increased and the altitude was held constant.

The data from the test conducted at an engine RPM of 2200 yielded some different results than the test at 2100 RPM. First, the initial airspeed stabilization is more consistent across the three test mediums. Also, the X-Plane data shows an increase in velocity as the altitude is held relatively constant during the turn and is not consistent with theory and the other two data sets. The data from the actual aircraft test doesn’t show a decrease and eventual settling of the airspeed because the altitude was not held constant during the test. The same trend is evident for the data taken from FSX.

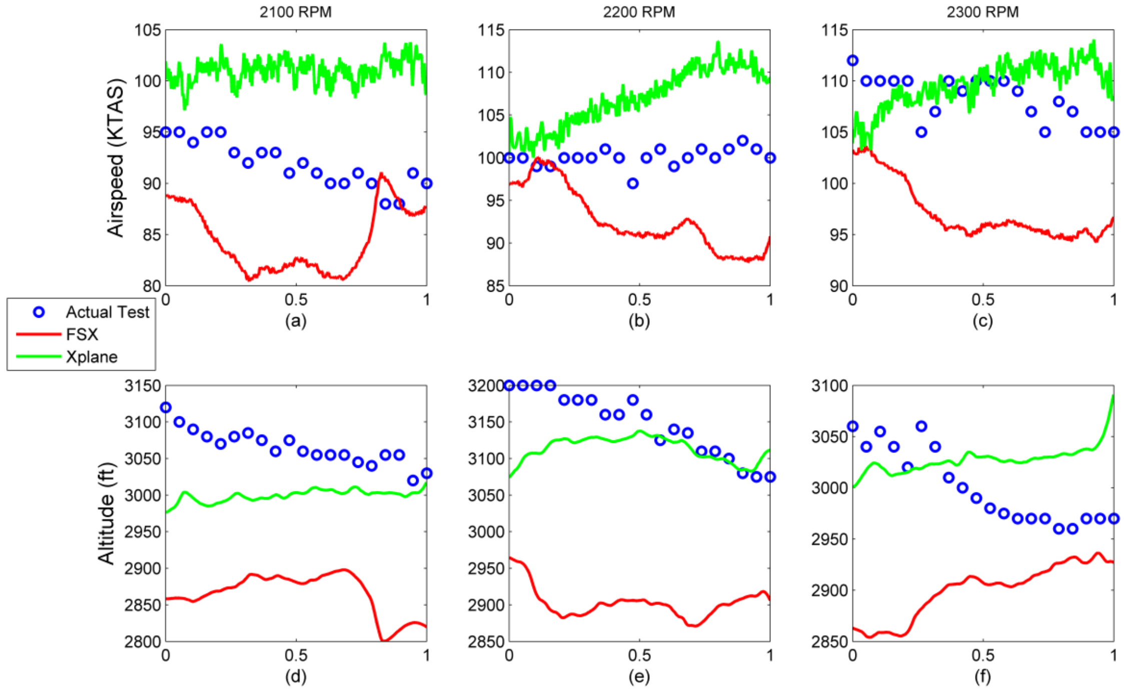


Figure 14. Steady turn test results

Last, the turn test conducted at 2300 RPM showed more of the same results described previously. The inconsistency in data can be attributed to the lack adhering to the flight test procedure. The starting altitudes were not all the same and altitude was not maintained during the tests. Overall the test data recorded did not produce the trends expected and could not be used to compare the accuracy of the simulators with great confidence; however, the X-Plane trends shown did raise the question concerning the increase in airspeed at a constant load factor greater than one. A possible explanation for the X-Plane results may be that the equations used in blade element theory do not model the coupling of the vertical and directional forces well enough to show the expected trend on such a low power aircraft.

H. Results – Flight Path Stability

The final tests conducted to compare the three test mediums evaluated the Cessna 172 in the approach condition, both with flaps down and up. For each approach configuration two separate data sets were compiled, one for an approach speed of 5 knots above and one for 5 knots below the selected initial speed. The tests with the flaps down and flaps up were conducted with an initial approach speed of 70 and 75 knots respectively.

The objective of the flight path stability tests was to ensure the aircrafts descent rate did not change significantly with a change in flight path angle. Despite some minor coupling, the effects of change in pitch and throttle are considered to be separate. More commonly know to pilots as pitch for speed and throttle for rate of climb, the aircraft should increase speed with a decrease in flight path angle and increase rate of climb with a an increase in throttle[2].

Figure 15 shows the test results from the flight path stability test in the flaps down configuration. The altitude during the test maneuver is tracked in the plot on the left and the velocity is shown on the right. Additionally on each chart there are two sets of data for each testing medium, one for the test 5 knots below and the other for the test conducted 5 knots above the initial speed of 70 knots. The velocity data shows that it was much more difficult to hold airspeed in the simulations than in the actual aircraft. Most likely the issue that causes trouble with holding airspeed in the simulator is that the pilot flying the simulation does not feel any of the accelerations acting on the aircraft. Thus, the pilot's adjustments are often late or too large. Nonetheless, the altitude data shows good results in that there was not a significant change in the slope of the descent line during the test for the two descent speeds. As a result, FSX and X-Plane show similar and correct low speed stability characteristics as the actual aircraft.

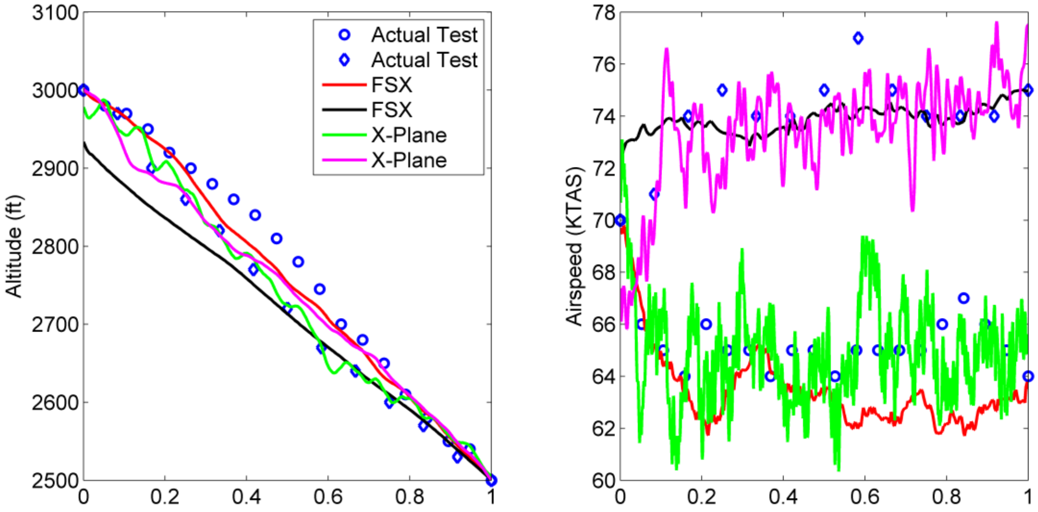


Figure 15. Flight path stability test with flaps deployed

The second flight path stability test that was conducted without the use of flaps is presented in Figure 16. As with the test with flaps, the data presented in Figure 16 suggests the same trends are present for the altitude data. The only peculiar set of data is evident in the X-Plane data denoted by the magenta data set. Most likely the increase in descent rate shown can be attributed to pilot error and not a change in the aircrafts flight stability. Furthermore, the airspeed also shows again that airspeed is much harder to hold in the simulation. Between the two simulations, the data suggests airspeed was more easily held in the FSX environment.

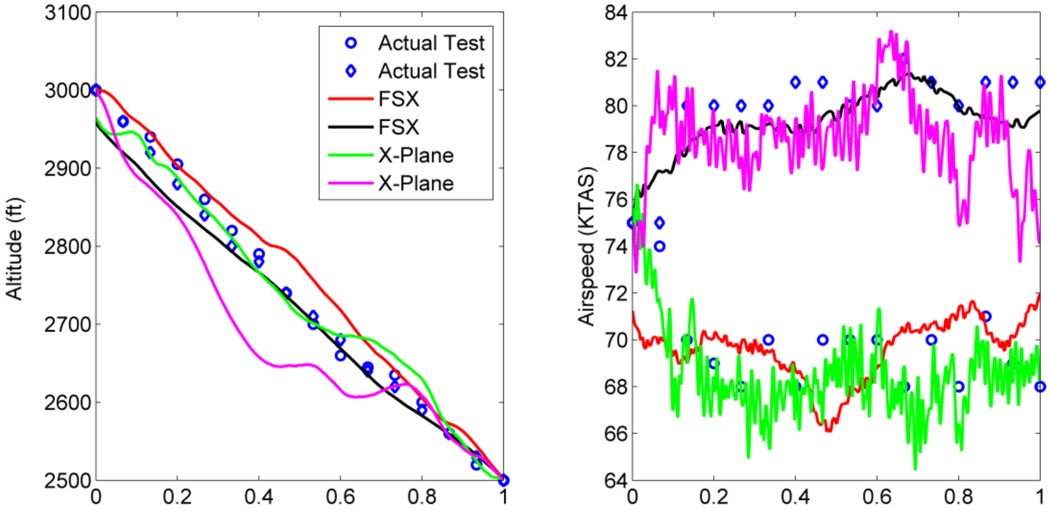


Figure 16. Flight path stability test without flaps

I. Flight Simulator GPS Data

The final set of data that was analyzed from the simulator tests was the GPS latitude and longitude coordinate outputs. Figures 17 and 18 in the Appendix show the GPS tracks of all the tests performed in FSX and X-Plane respectively. The output data from the simulators was then converted to a Google Earth compatible file which was then uploaded to Google Earth for viewing. Overall the GPS data from both FSX and X-Plane was accurate and could prove useful for further analysis of a multitude of simulation based tests.

IV. Conclusion

In summary, the project as a whole was successful in completing its main objectives of comparing the capabilities of two different types of flight simulation engines and investigating the ins and outs of flight test in general. Ultimately the data presented did not show with any certainty that FSX or X-Plane was any more accurate than the other; however, the data did show that both simulators have extremely accurate models when compared to the actual aircraft. Despite a few inconsistencies because of pilot error, the test data from both simulations was remarkably similar to that of the actual aircraft. Furthermore, the data sets may have been more aligned had the tests in all three cases been flown with more precision. Flight testing with high accuracy takes years of training and meticulous mission planning, which ultimately is the cause for the high cost of the process. Through the use of flight simulation, unlimited amounts of flight testing can be completed with unlimited possibilities and high accuracy for a low cost.

The next step in validating the two simulations presented in this report would be to conduct higher precision flight testing. Those tests could be done by using an autopilot to help take some of the workload off the test pilot. Ultimately, the tests would become more accurate and more convincing conclusions could be made on the strengths and weakness of each simulation. With regards to the output data presented in the results section, FSX and X-Plane proved to have very similar results; however, the two simulators differed with regards to user interface and ease of use. X-Plane has a much larger and complex user interface than FSX, which allows for a more customizable experience. Additionally, X-Plane’s ability to test virtually any aircraft configuration without the use of stability coefficients is an enormous selling point. However, the FSX model and overall flight qualities, if a robust set of stability derivatives are available, are superior to those in X-Plane. In closing, both FSX and X-Plane have limitless potential for flight testing in the commercial and educational arenas.

V. Appendix

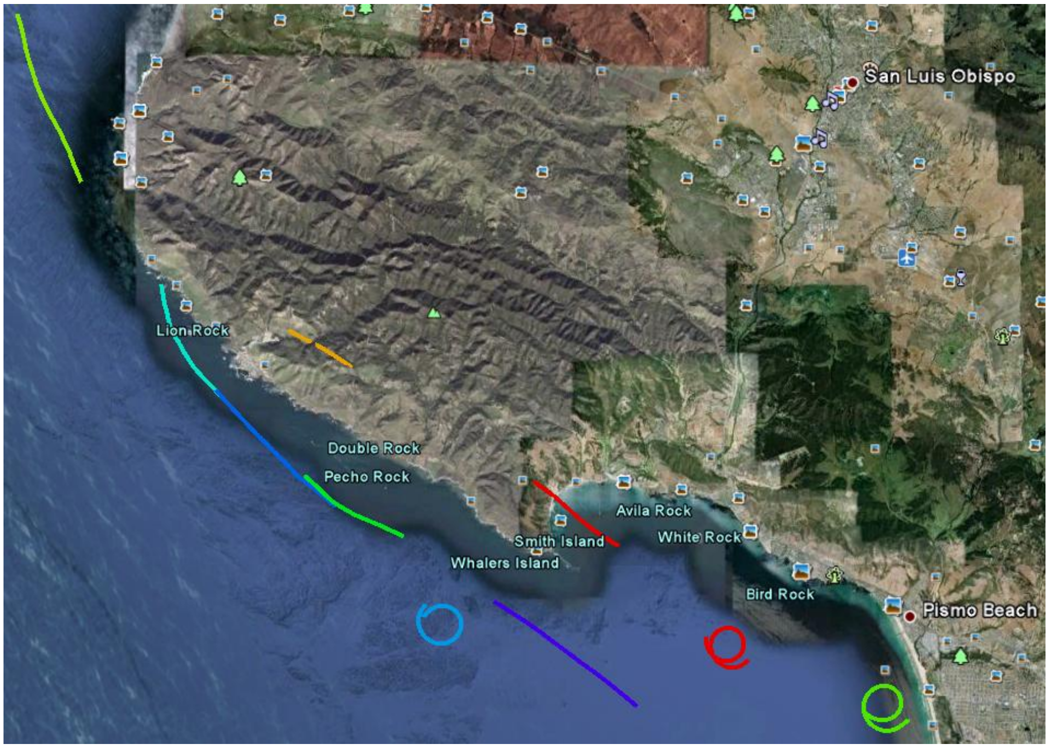


Figure 17. X-Plane GPS track data

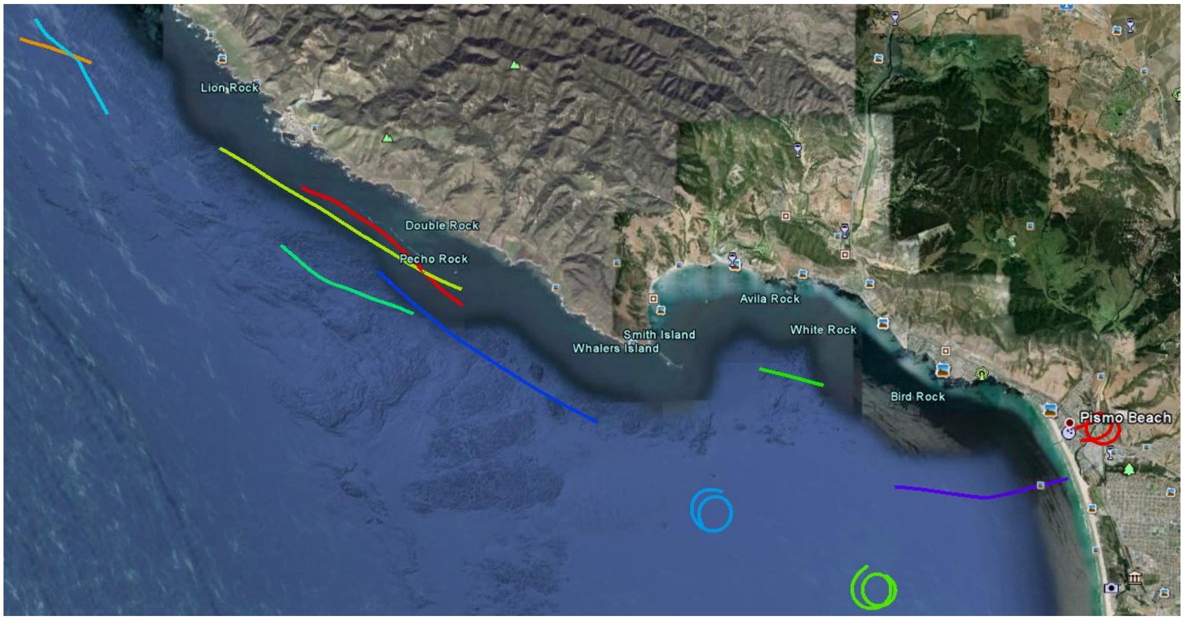
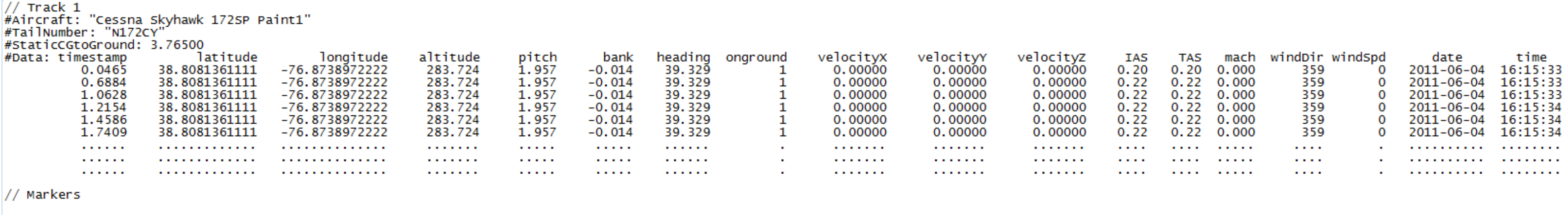


Figure 18. FSX GPS track data

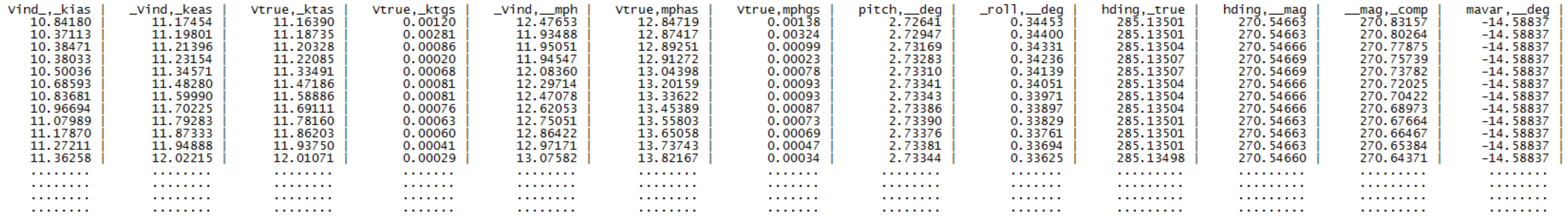
Table 2. FSX data output sample



```
// Track 1
#Aircraft: "Cessna Skyhawk 172SP Paint1"
#TailNumber: "N172CY"
#StaticCGtoGround: 3.76500
#Data: timestamp       latitude       longitude   altitude   pitch    bank  heading  onground  velocityX  velocityY  velocityZ   IAS   TAS   mach  windDir  windSpd        date      time
          0.0465  38.8081361111  -76.8738972222    283.724   1.957  -0.014   39.329         1    0.00000    0.00000    0.00000  0.20  0.20  0.000      359        0  2011-06-04  16:15:33
          0.6884  38.8081361111  -76.8738972222    283.724   1.957  -0.014   39.329         1    0.00000    0.00000    0.00000  0.22  0.22  0.000      359        0  2011-06-04  16:15:33
          1.0628  38.8081361111  -76.8738972222    283.724   1.957  -0.014   39.329         1    0.00000    0.00000    0.00000  0.22  0.22  0.000      359        0  2011-06-04  16:15:33
          1.2154  38.8081361111  -76.8738972222    283.724   1.957  -0.014   39.329         1    0.00000    0.00000    0.00000  0.22  0.22  0.000      359        0  2011-06-04  16:15:34
          1.4586  38.8081361111  -76.8738972222    283.724   1.957  -0.014   39.329         1    0.00000    0.00000    0.00000  0.22  0.22  0.000      359        0  2011-06-04  16:15:34
          1.7409  38.8081361111  -76.8738972222    283.724   1.957  -0.014   39.329         1    0.00000    0.00000    0.00000  0.22  0.22  0.000      359        0  2011-06-04  16:15:34
          ......  .............  ..............    .......   .....   .....   ......         .    .......    .......    .......  ....  ....  .....     ....        .  ..........  ........
          ......  .............  ..............    .......   .....   .....   ......         .    .......    .......    .......  ....  ....  .....     ....        .  ..........  ........
          ......  .............  ..............    .......   .....   .....   ......         .    .......    .......    .......  ....  ....  .....     ....        .  ..........  ........

// Markers
```

Table 3. X-Plane data output sample



```
 Vind_,_kias | _Vind,_keas | Vtrue,_ktas | Vtrue,_ktgs | _Vind,__mph | Vtrue,mphas | Vtrue,mphgs | pitch,__deg | _roll,__deg | hding,_true | hding,__mag | __mag,_comp | mavar,__deg |
    10.84180 |    11.17454 |    11.16390 |     0.00120 |    12.47653 |    12.84719 |     0.00138 |     2.72641 |     0.34453 |   285.13501 |   270.54663 |   270.83157 |   -14.58837 |
    10.37113 |    11.19801 |    11.18735 |     0.00281 |    11.93488 |    12.87417 |     0.00324 |     2.72947 |     0.34400 |   285.13501 |   270.54663 |   270.80264 |   -14.58837 |
    10.38471 |    11.21396 |    11.20328 |     0.00086 |    11.95051 |    12.89251 |     0.00099 |     2.73169 |     0.34331 |   285.13504 |   270.54666 |   270.77875 |   -14.58837 |
    10.38033 |    11.23154 |    11.22085 |     0.00020 |    11.94547 |    12.91272 |     0.00023 |     2.73283 |     0.34236 |   285.13507 |   270.54669 |   270.75739 |   -14.58837 |
    10.50036 |    11.34571 |    11.33491 |     0.00068 |    12.08360 |    13.04398 |     0.00078 |     2.73310 |     0.34139 |   285.13507 |   270.54669 |   270.73782 |   -14.58837 |
    10.68593 |    11.48280 |    11.47186 |     0.00081 |    12.29714 |    13.20159 |     0.00093 |     2.73341 |     0.34051 |   285.13504 |   270.54666 |   270.72025 |   -14.58837 |
    10.83681 |    11.59990 |    11.58886 |     0.00081 |    12.47078 |    13.33622 |     0.00093 |     2.73343 |     0.33971 |   285.13504 |   270.54666 |   270.70422 |   -14.58837 |
    10.96694 |    11.70225 |    11.69111 |     0.00076 |    12.62053 |    13.45389 |     0.00087 |     2.73386 |     0.33897 |   285.13504 |   270.54666 |   270.68973 |   -14.58837 |
    11.07989 |    11.79283 |    11.78160 |     0.00063 |    12.75051 |    13.55803 |     0.00073 |     2.73390 |     0.33829 |   285.13501 |   270.54663 |   270.67664 |   -14.58837 |
    11.17870 |    11.87333 |    11.86203 |     0.00060 |    12.86422 |    13.65058 |     0.00069 |     2.73376 |     0.33761 |   285.13501 |   270.54663 |   270.66467 |   -14.58837 |
    11.27211 |    11.94888 |    11.93750 |     0.00041 |    12.97171 |    13.73743 |     0.00047 |     2.73381 |     0.33694 |   285.13501 |   270.54663 |   270.65384 |   -14.58837 |
    11.36258 |    12.02215 |    12.01071 |     0.00029 |    13.07582 |    13.82167 |     0.00034 |     2.73344 |     0.33625 |   285.13498 |   270.54660 |   270.64371 |   -14.58837 |
    ........      ........      ........      .......       ........      ........      .......       ........      .......      .........     .........     .........      ........
    ........      ........      ........      .......       ........      ........      .......       ........      .......      .........     .........     .........      ........
    ........      ........      ........      .......       ........      ........      .......       ........      .......      .........     .........     .........      ........
    ........      ........      ........      .......       ........      ........      .......       ........      .......      .........     .........     .........      ........
```

References

[1] Evans, M. B., and Schilling, L.J., "The Role of Simulation in the Development and Flight Test of the HiMAT Vehicle," NASA TM-84912, 1984.

[2] Kimberlin, R.D., *Flight Testing of Fixed-Wing Aircraft*, AIAA, Virginia, 2003, Chaps 4,15,21.

[3] Lockheed Martin., "Prepar3D Product Information and Overview," URL: http://www.prepar3d.com/products/prepar3d-client/#productinfo [cited 7 May 2011].

[4] Laminar Research., "X-Plane Instructions Manual,"[Appendix A: How X-Plane Works].

[5] Microsoft., "Microsoft's Flight Simulator X Flight Model Overview," URL: http://msdn.microsoft.com/en-us/library/cc526961.aspx [cited 7 May 2011].

[6] Sorton, E. F., and Hammaker, S., "Simulated Flight Testing of an Autonomous Unmanned Aerial Vehicle Using FlightGear," AIAA 2005-7083.