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AV-8B II+ DEVICE S2F176 FLIGHT MODEL DEVELOPMENT USING A PC-BASED SIMULATION ENVIRONMENT

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Abstract

The application of an off-the-shelf PC-based simulation environment was successfully demonstrated in the development of an updated aerodynamics model for the AV-8BII+ Italian Mission Simulator, Device S2F176. During this effort, the software was used to host the entire trainer flight model for evaluation, development, and testing. Aerodynamics model improvements were made across the entire flight envelope and validated using tools in the simulation environment. The use of a PC-Based environment for model development allowed for model to be modified then tested in both a batch mode as well as a piloted real time mode on the desktop, thus reducing time required for check out using trainer hardware. Prior to piloted evaluations, a fully compatible aerodynamics model was exported from the PC-based system and transmitted electronically for installation in the trainer. This paper provide details pertaining to the trainer development process using a PC-Based Simulation environment as well as several of the tasks performed during this work.

Introduction

The use of desktop real-time simulation environments is growing in popularity and has been to focus of much rhetoric in the simulation world. The main reason for this is the relative low-cost of the hardware and software required to operate these environments. With the rapid pace of the personal computer market, the price of high performance is dropping every day, thus making desktop simulation increasingly attractive. There has been much written about the design and development of such environments, but there has been little discussion of real-world applications of the tools in support of complex simulation development tasks. This paper focuses on the application of such a tool in direct support of the development of a military flight trainer.

Device S2F176, currently being developed by the US Naval Air Warfare Command Training Systems Division (NAWCTSD) and Indra DTD, in Madrid Spain, and will be the Italian Navy's AV-8B II Plus Mission Simulator (IMS). The flight model from the US Marine Corp Radar/Night Attack Weapon System Trainer (RNAWST), Device 2F150A, is the foundation for the Italian Device S2F176 and contained flight control, propulsion, and weight and balance models for the night-attack variant of the AV-8B.

The IMS Device is to be representative of the radar variant of a CUM 250 AV-8B, designated the AV-8BII+ (Figure 1). The AV-8B II+ possesses a different radome configuration than the night attack aircraft. A specification for acceptance of the trainer was defined based on the AV-8BII+ CUM 250 aircraft that the Italian Navy flies. For this reason as well as discrepancies cited in reference 1, the RNAWST aerodynamics model needed to be updated to meet trainer acceptance requirements. To perform this task, Indra DTD, contracted Bihrle Applied Research Inc. (BAR) to develop the aerodynamics model for the new trainer and provide flight-model test and evaluation support. BAR was tasked to improve the aerodynamic portion of the S2F176 flight model and validate the updated model. With the BAR facilities in Hampton, VA and the trainer development in Madrid, Spain, model development and testing was a logistical challenge. This challenge was made greater by a compressed schedule, and concurrent trainer hardware development. This situation made scheduling pilot time in the trainer for model development difficult.

The use of Bihrle Applied Research's PC-based simulation environment significantly reduced the number of engineering hours required in Spain with the trainer. This paper provides details pertaining to the use of D-Six simulation environment in each phase of the aerodynamics model's development.

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Nomenclature

Symbols

C_D	Drag coefficient (+aft parallel to free stream)
C_L	Lift Coefficient (+up normal to free stream)
C_m	Pitching moment coefficient (+nose up)
p	Roll Rate (deg/s)
q	Pitch Rate (deg/s)
r	Yaw Rate (degs/s)
α	Angle of attack (deg)
β	Angle of sideslip (deg)
θ	Pitch Angle (deg)

Acronyms

AFT	Automated Fidelity Test
BAR	Bihrle Applied Research Inc.
BAR	Bihrle Applied Research Inc.
DLL	Dynamic Link Library
DPS	Desktop Piloted Simulation
ESVD	Engineering Simulation Variable Display
HAGL	Height Above Ground Level (ft)
IMS	Italian Mission Simulator
JPI	Joint Program Inspection
MDA	McDonnell Douglas Aerospace Corporation
NASPAX	Naval Air Station Patuxent River
NAWCAD	Naval Air Warfare Center Aircraft Division
NAWCTSD	Naval Air Warfare Center Training Systems Division
NPE	Naval Preliminary Evaluation
OTW	Out the Window
RNAWST	Radar/Night Attack Weapons System Trainer
STOL	Short Take Off and Landing
TCR	Trainer Criteria Report
TTPRR	Trainer Test Procedure and Results Report
USMC	United States Marine Corps
USN	United State Navy
USNTPS	United States Navy Test Pilot School
VIFF	Vectoring in Forward Flight

PC-Based Simulation Environment

The fact that the aerodynamics model would be developed in the United States and tested in Spain required the use of BAR's six-degree-of-freedom simulation environment, D-Six. D-Six is a reconfigurable, PC-Based simulation tool that runs under Windows 95/98 and NT. The tool was designed to facilitate the development, validation, and deployment of simulation flight models, and has been used by BAR and its customers for a number of efforts supporting both the defense and civil aviation industry.

D-Six's primary design requirement was the application of a modular, object oriented structure that would enable a number of important functionalities. BAR has, in their support of the industry, been required to implement and operate a wide range of simulation projects, consequently, the need to make all simulation functions available to the range of simulation projects emphatically required the separation of model dependant and model independent functionality. This requirement dictated a simulation environment with a highly structured, object based form, capable of linking the required configuration drivers and libraries at start up or dynamically during the simulation sessions. To enable this level of simulation flexibility, D-Six uses a "project" idiom that maintains and loads all the model dependant code, library, and data files in a structure that relieves the user from the need to organize and direct these model elements. In the case of the AV-8B, the model dependant project consisted of the aerodynamic, weight and balance, thrust and flight control data tables, as well as all the model dependant code and logic needed to implement these data. The requisite project elements are dynamically linked to the model independent simulation environment as dynamic link libraries (DLL). The model independent components provide the user with modular simulation functions such as table interpolation and integration, as well as the interfaces required to control various simulation functions and extend the simulation's capabilities with "plug-in" modules. The model independent component interfaces do not rely on application specific information and can fall under the following categories; Graphics, Data Manipulation or Simulation Control.

Graphics

D-Six contains a graphical user interface (GUI) to perform a large majority of the interface with the user. The GUI is menu driven and provides the user with access to all of the simulation environment's key functions such as, the import of flight data, maneuver input programming, setting initial conditions, data plots and so on.

Also part of the GUI are engineering and run-time displays. The D-Six simulation environment provides the user with two different out-the-window displays that may be used during real-time and non-real-time simulation runs. In addition, D-Six provides several external views of a given aircraft geometry for flight path visualization, Figure 2. Simulation variables can be monitored during simulation session via data plotting windows or digital read out.

Data Manipulation

The data manipulation tools in D-Six include filtering, decimation, and wild-point extraction utilities for time-history data. These utilities facilitate the import of flight data for validation task and create an ideal interface for the import of simulation data for verification tasks when rehosting simulation models. The simulation environment also contains unique tools for manipulating large databases. This manipulation may be performed graphically or by the import of tabular data. To facilitate access to such a database, D-Six contains an efficient database function-table look-up algorithm that provides model dependent portions of a simulation with need database access.

D-Six also contains a powerful import/export tool, Aeroport, which allows a user to import or export databases and code to and from D-Six.

Simulation Control

Simulation control components of the D-Six include tools for setting initial conditions, run mode, and interfaces with hardware. Run model tools allow the user to operate a simulation in a real-time/pilot-in-the-loop mode using pilot interfaces ranging from game quality joysticks to flight hardware. A batch mode is also available that allows the simulation to be driven by predefined time-history data or a user defined input.

Flight Model Development Process

The development of a high-fidelity aerodynamics model for flight training is an iterative process that can be broken down into three phases. During Model Development, Phase I, engineers use available engineering models, wind-tunnel data, and/or flight data to determine a model structure. In the second Phase, Preliminary Evaluation, the model is implemented with other key components of the flight model, propulsion, control system etc. At this point evaluation can be performed in a batch mode with tools such as an automated fidelity tester (AFT). An AFT typically provides engineers with the flight model's response to a prescribed input that can be compared directly to defined criteria data. In addition to AFT evaluation, the flight model is interfaced with the trainer hardware and undergoes limit evaluation by engineers. In last phase, Trainer Validation, the flight model is implemented with the simulator hardware and flown by a qualified pilot. Maneuvers executed by the pilot during this phase are those that require considerable pilot attention and are flown in highly nonlinear regions of the flight envelope. Data from this phase are compared to criteria as specified in a criteria specification document. Pilot comments are also used during this phase to further develop and refine the model.

During the development of the device S2F176 aerodynamics model, the PC-Based simulation environment mentioned earlier was used in each phase of the process. Its use during the third phase of development saved time and money by providing pre-flight of piloted maneuvers prior to being transmitted to the trainer.

Phase I Model Development

As part of the model development phase, three aerodynamics models, the 2F150A aerodynamics model and two US Navy owned engineering models, were hosted in the simulation environment for evaluation. The 2F150A aerodynamics model was implemented into the simulation environment by incorporating the code into a new simulation DLL for use with in D-Six, Figure 3. This process allowed the same C code that is used in the trainer to be run in D-Six. Because of the use of identical code, confidence of correct implementation was high, as demonstrated in the aforementioned model verification.

The two Navy engineering models were transmitted as data tables and functional data mechanization documentation, consequently, further coding was required. The math model documentation was used to create C code to implement the models in the simulation environment as a DLL. The aerodynamics data were converted to the D-Six native format using BAR's Aeroport database conversion tool. Like the 2F150A model, the engineering models were incorporated into a simulation project and verified with check cases.

With the implementation of the models complete, engineers had the ability to exercise each model, examine the output and perform comparisons of each model's output. This ability was important in the design of the model update.

The assessment of the three models was performed through a series of batch runs to extract flight model output given a prescribed input, Figure 4. The prescribed inputs were independent of time, but exercised all aerodynamic model functionality for the fixed state inputs. The output from the simulation batch runs consisted of six aerodynamic coefficients. The fact that identical input values were provided to each model allowed for the direct comparison of the output of the simulation runs for each model. Many similarities were found among the data sets, but differences were also revealed in regions of the engineering databases that had been updated in recent years, as seen in Figure 5. Other differences found in the models were in effects that were not modeled in the engineering models, for example store effects on the aerodynamics. The engineering model contained detailed aerodynamics data for a limited number of fixed store loadings whereas the trainer model accounted for most every store loading available on the aircraft through use of a drag index accounting method.

By the end of the preliminary assessment, the project engineers had a strong working knowledge of the three models' structure and content. Based on the work performed, it was determined that applying adjustments to the 2F150A aerodynamics model would be extremely difficult and result in a model that was constructed of many incremental pieces. The engineering models assessed in this phase were very similar in structure and more conducive to modification than was the 2F150A model. In addition, data content of the two models was also similar, but, as mentioned above, lacked important functionality contained in the 2F150A model. As a result, an aerodynamics model structure was chosen that closely resembled the engineering model, but incorporated the extensive functionality of the 2F150A aerodynamics model. This lead to the creation of a fourth aerodynamics model containing data from each of the three sources. This new model was implemented as the baseline S2F176 aerodynamics model.

Phase II Preliminary Evaluation

Preliminary evaluation of the S2F176 aerodynamics model was performed using both the PC-Based simulation environment and trainer software tools. In order to fully evaluate the aerodynamics model the remainder of the trainer flight model was hosted in the simulation environment. The simulation structure of D-Six enabled BAR engineers to host the exact trainer C code defining the propulsion, weight and balance, landing gear, and flight controls models without code modification. Model independent code from the trainer that implemented equations of motion and integration algorithms was not hosted and D-Six native algorithms were uses. A limited amount of code was written to provide default simulation settings that are set using hardware in the trainer and to provide trainer code interface with D-Six tools and variable structure (Figure 6). This interface allowed engineers to define store loadings and other weight and balance information, flap and gear lever positions, as well as other pilot input.

Using batch run data from the device S2F176 to overdrive the simulation, the flight model, as implemented in D-Six with the 2F150A aerodynamics model, was verified to be hosted correctly. With the verification complete, BAR engineers possessed, on the desk top, a fully operational flight model that was identical to the flight model installed in a trainer several thousand miles away.

Soon after the complete flight model rehost, the 2F150A aerodynamics model was replaced with the new device S2F176 aerodynamics model. This model was then flown by BAR engineers in real-time on the desk-top. The purpose of this preliminary flight evaluation was to perform a continuity check of the new aerodynamics model, ensuring that transitions between various parts of the database were continuous.

The next part of the preliminary evaluation involved comparing simulation model output to trainer criteria data or truth data. These comparisons were performed using three methods the Auto Fidelity Tests (AFT), Direct Simulation Overdrive (DSO), and Desktop Piloted Simulation (DPS). AFT was used to evaluate simulation response and performance for simple maneuvers requiring little piloted input, like accelerations, level stall, doublets etc. DSO runs were used to drive the simulation with flight data or simulated pilot input. This technique was used in the absence of appropriate AFT tests. The DPS were used to execute and evaluate maneuvers that are difficult to program with the AFT or require particular pilot attention such as STOL model flight, high-angle-of-attack maneuvering etc.

Evaluation Using Automated Fidelity Testing

To perform tests using the AFT in Spain, the new aerodynamics model needed to be transmitted to Indra. Since the new model was hosted in D-Six using the same code structure and format used in the trainer, porting the aerodynamics model code to the trainer was transparent. Because a decision was made to use existing table-look-up algorithms in the trainer, the aerodynamics data needed to be converted from the D-

Six database format to the trainer format. This was done using a BAR database conversion utility named Aeroport. Using this utility, BAR engineers were able to import a D-Six database and export device S2F176 compatible database code. To aid in the verification of database conversions, trainer data-look-up code was hosted in D-Six. This allowed BAR engineers to choose between the native BAR database structure and lookup algorithm and the trainer database and lookup algorithm. The selection of database access was performed by the setting an initial condition flag prior to a simulation run. The verification of the database conversion was performed by executing simulation runs using identical input and comparing the resulting simulation output, Figure 7. Once verified, the database and new model code were ready for transmittal to the trainer. This process ensured that immediately compilable code and data were available for use in the trainer.

Evaluation Using Direct Simulation Overdrive

In cases where no test was specified in the AFT for a particular maneuver, direct simulation overdrive was employed. This technique involved importing flight data or recreating flight data from reports and driving simulation input during a simulation run. Overdriving specific inputs allow the simulation to respond to precise conditions specified by flight or by a user. This techniques allows engineers to drive an entire flight model by driving pilot input, or engineers can isolate a model by overdriving specific input to that model, Figure 8.

An application of this technique was the analysis of abrupt longitudinal inputs. Flight data were acquired from the US Navy for use in the development effort. These data contained aircraft state information as well as pilot input data and surface deflections. For the analysis, the data were imported into the simulation and used to create overdrive signals for the AV-8B control surfaces. The simulation runs were executed by trimming to the desired aircraft state, then running the simulation in a batch mode. This technique allowed the engineers to examine the response of the six-degree-of-freedom simulation to flight measured input. Overdriving the control surfaces removed the control system from the simulation loop. Figure 9 contains diagram illustrating the overdrive loop with an sample comparison from the task.

Evaluation Using Desktop Piloted Simulation

The desktop-piloted evaluations were performed using commercial-off-the-shelf joystick and throttle hardware. Other pilot-input such as nozzle, gear, and flap position were provided by assigning joystick and keyboard buttons. Flight information was provided to the pilot via head-up display (HUD) super imposed with an out-the-window (OTW) view of a flat terrain and engineering simulation variable display (ESVD). The HUD provided the pilot with a graphical indication of pitch, roll, heading, and flow angle changes, as well as altitude. It also provided digital display of airspeed, Mach number, angle of attack, and bearing and range to a runway. The ESVD allowed the to display any variable used by the simulation. This display was particularly useful for displaying nozzle deflection, flap deflection, and surface deflections etc. Figure 10 contains a screen shot of the out-of-the-window display and HUD with the ESVD.

Each piloted simulation session was run with the objective to execute maneuvers for which flight data were available in hard copy form only. This allowed BAR engineers to "fly" the simulation to aircraft states defined in histories of flight data and then execute maneuvers using the same technique used during flight tests. An example of this was in the evaluation of control power and lateral-directional characteristics at high angles of attack. The maneuvers in question were to be initiated in a wind-up turn to establish Mach number and desired angle of attack. Such maneuvers were difficult to execute using the AFT given limited resources, therefore they were performed using DPS.

At the start of each DPS the engineer would set all appropriate initial conditions including loading, flap setting, weight and center of gravity location, and aircraft state. The engineer would then start the simulation session employing the OTW graphics with HUD and execute the desired maneuver. Once completed satisfactorily, the data from the simulation run was either saved to disk or plotted for analysis and comparison with truth data. Figure 11 contains sample output from a high-angle-of-attack 360 degree rudder roll.

The ability to perform DPS and evaluate response of the flight model greatly reduced the amount of piloted time using trainer hardware.

As maneuvers were executed, simulation results were compared with flight data. If discrepancies were discovered, the area of the model was examined and solutions for model improvement were found and implemented. Using the available tools to in D-Six, very little time was required to modify the simulation model and run the simulation in real time. Therefore, engineers were able to perform model modifications and testing rapidly.

Phase III Trainer Validation

With stages of Phase I and Phase II complete, the new model was implemented into the trainer to be interfaced with hardware and "flown" by an AV-8B pilot. Part of all trainer acceptance criteria is the piloted evaluation. During this evaluation, the pilot assesses simulation hardware, control feel, and the overall flight fidelity of the simulation. This phase of a trainer's acceptance can become the most difficult, especially with fixed-based simulations where pilot perception is based on visual cues and limited "seat-of-the-pants feel." During the piloted evaluations of Device S2F176 most time was spent gathering pilot opinion on the fidelity of the flight model where limited "truth" data existed, for example, transitions between wing-born and semi-jet born flight, take-off and landing handling qualities, "extreme" air combat maneuvers.

Since simulation development time in Spain with AV-8B pilots was minimal, the flight model development team needed to make the most of time with the pilots. During evaluation trips to Spain, BAR engineers carried a portable computer with the D-Six software and Aeroport. This allowed BAR engineers to modify model code and aerodynamic data quickly and test changes for implementation into the trainer and pilot reevaluation later in the day. An example of this was in the modeling of a ground effect during short takeoffs and landings.

The AV-8B, while in the STOL, configuration, nozzle deflections greater than approximately 30 degrees and flaps also deflected greater than 25 degrees, exhibits a unique behavior in longitudinal flight characteristics when in ground effect. A nose down pitching moment is caused by the reflection of jet blast on the ground and a resulting impingement on the aft portion of the aircraft, Figure 12. During takeoff, the pilot begins a ground roll with nozzles at 10 degrees. Once to the prescribed airspeed, based on weight, the nozzles are rotates to a prescribed angle, again based on loading and fuel. The rotation of the nozzles changes the thrust vector and lifts the aircraft from the ground. Shortly after lift off, the aircraft exhibits a nose-down pitch followed by a pitch-up once out of ground effect. The amount of pitching moment is a function of thrust setting, nozzle deflection, and aircraft center of gravity. Conversely, on short landing, as the aircraft approaches the ground the reflected blast impingement on the aircraft causes a nose-down moment. As a result, to perform a safe landing, the pilot is required to apply aft stick input that varies depending on aircraft center of gravity and power setting. Figure 13 contains a diagram illustrating this characteristic.

As one would expect, the correct modeling of this situation is vitally important to student training. Unfortunately, during the early-piloted evaluations of the S2F176 trainer, the ground effect model was found to be deficient. BAR engineers then removed the old ground effect model and proceeded to construct a new ground effect.

The updated ground effect model was constructed in two parts, conventional and jet-reflection. The conventional portion of the ground effect model employed, as the name indicates, conventional ground effect modeling equations and were exercised then incorporated into the aerodynamics database as a function of height above ground. The second portion of the ground effect was more complex. Lacking test data, the model was structured to provide a physical representation of the jet blast reflection and impingement. The independent variables that effect the pitching moment of the aircraft were chosen to be gross thrust, height above terrain, and nozzle deflection. Airspeed also plays an effect, but was assumed to be negligible in the model. Assumptions were made pertaining to the jet-blast footprint and reflection thrust decay as height above terrain increased. These estimates were then used to determine a pitching moment coefficient based on the strength of the blast reflection and its impingement on the aircraft. The result was incorporated into the aerodynamics database as a function of gross thrust, nozzle deflection, and height above terrain.

This new ground effects model provided the trainer with a physically based model that is used for all modes of take off and landing. The model was implemented in the PC-Based simulation, tested, and evaluated. Engineers verified that the effect was in the model and operational. During the verification the effect was correlated with available trend information however, data in this flight regime were limited and engineers had no way of determining if the model provided the appropriate "feel" to the pilot. As a result, it was acknowledged that pilot-based "tuning" needed to be performed. The updated aerodynamics model was then transmitted to the trainer for pilot evaluation. The AV-8B pilots flew a series of short takeoffs and landings with a number of loadings and center of gravity locations and provided comments. While in Spain, using the pilot comments, engineers modified assumptions made during the development of the blast reflection ground effect modified the model. The newly updated model was retested using DPS and transmitted to the trainer for pilot revaluation the next day. Figure 14, contains a comparison plot of two DPS hands-off short field takeoffs employing the new and old ground effect models. For each maneuver, the appropriate stabilator setting was used and pilot input consisted of only deflecting nozzles to 50 degrees. The plots reveal the effect of the increased nose-down pitching moment due to the blast reflection impingement.

Since this engineering development was being performed in the PC-base environment, the trainer was free to be used for the evaluation other areas of the flight model and visual displays. After several iterations, a physically based, high-fidelity ground effect model was incorporated as part of the trainer.

Concluding Remarks

Using its commercially available PC-based simulation environment, Bihrle Applied Research met the challenge of hosting trainer flight model software, modifying a critical component of it, and then exporting a fully compatible aerodynamics model and database for use with trainer hardware. The development effort of the Device S2F176 aerodynamics model is a perfect example of how time and money can be saved during trainer flight model development by employing a flexible desktop real-time simulation environment and commercial-off-the-shelf hardware. Flight models designed for flight training can be extensively tested in real time to evaluate many of the flight model issues before delivery to the trainer hardware provider. While this use of a PC-based simulation environment can significantly reduce trainer piloted evaluation time, it does not replace it. Nevertheless, this process can make piloted sessions in the trainer more efficient, so they can be dedicated to the evaluation hardware interface issues rather than extensive flight model validation.

Acknowledgements

The author wishes to thank the Indra DTD for giving BAR the opportunity to employ D-Six simulation environment in support of a military trainer development program. The author also thanks Mr. Tom Galloway and Mr. Jeff Calvert of NAWCTSD in Orlando, Florida for providing information vital to the execution of this task.

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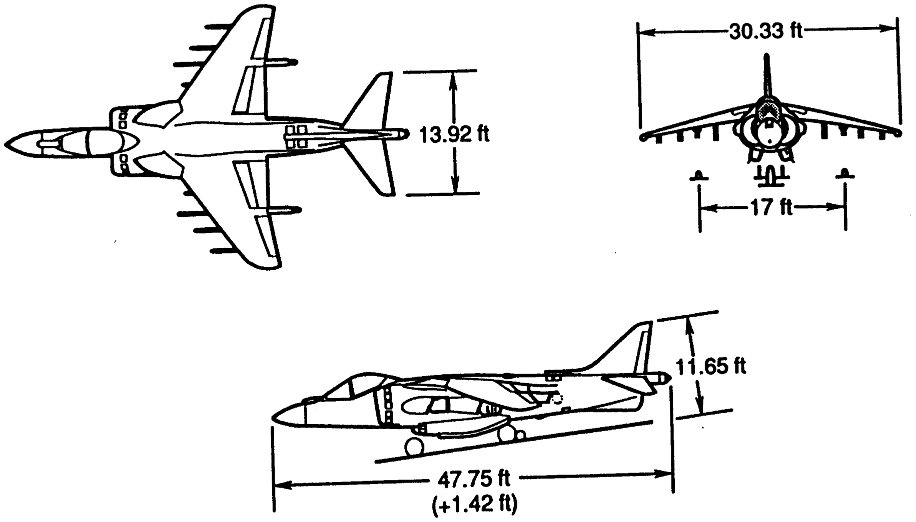

Figure 1. Three-view diagram of the AV-8B II +.

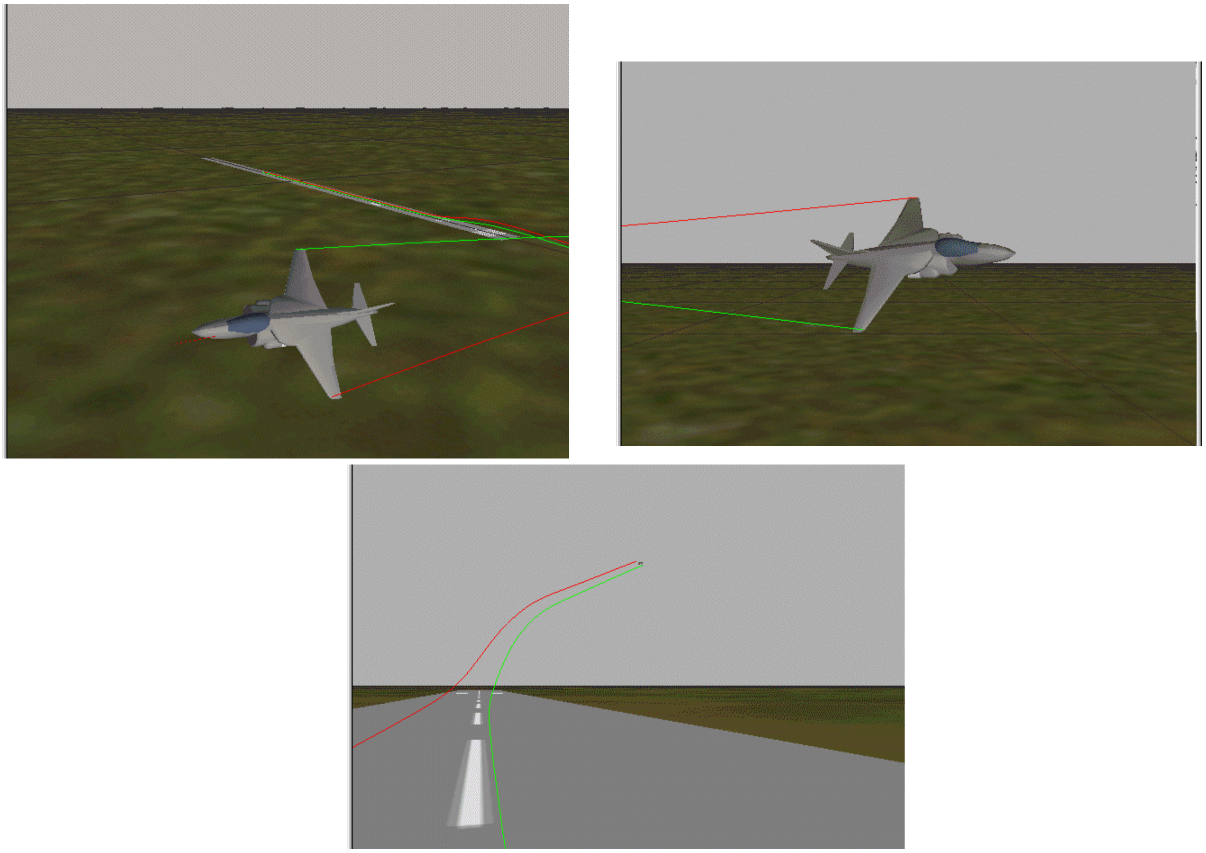

Figure 2. External views available in the D-Six PC-Based simulation environment

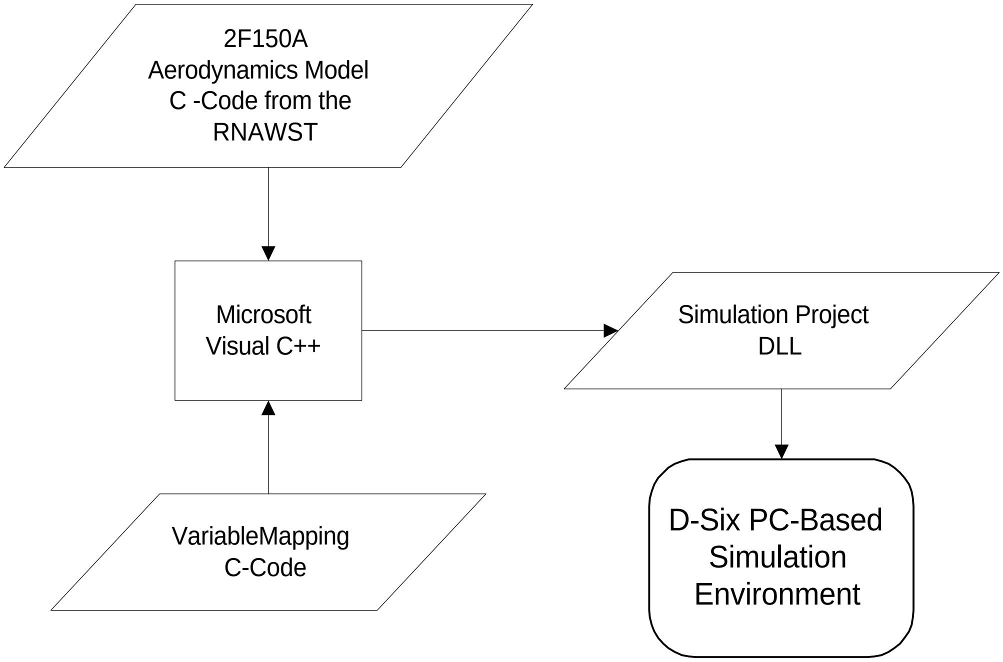

Figure 3. Diagram of aerodynamics model host in the D-Six simulation

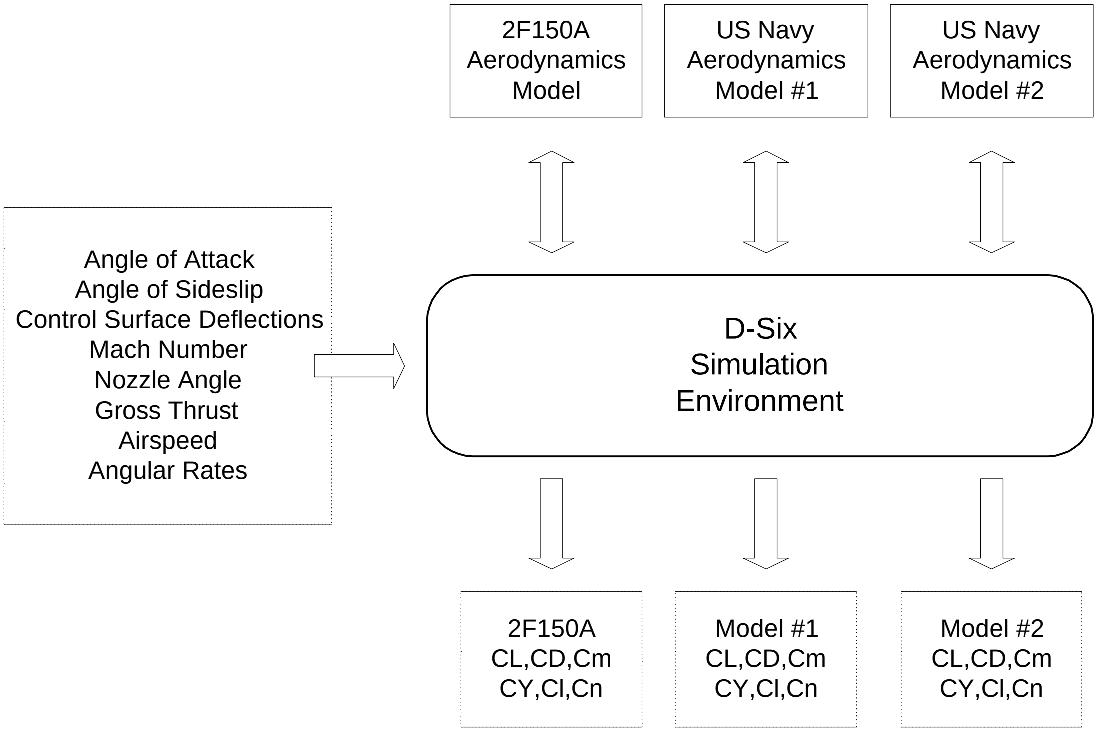

Figure 4. Diagram of aerodynamics model data extraction.

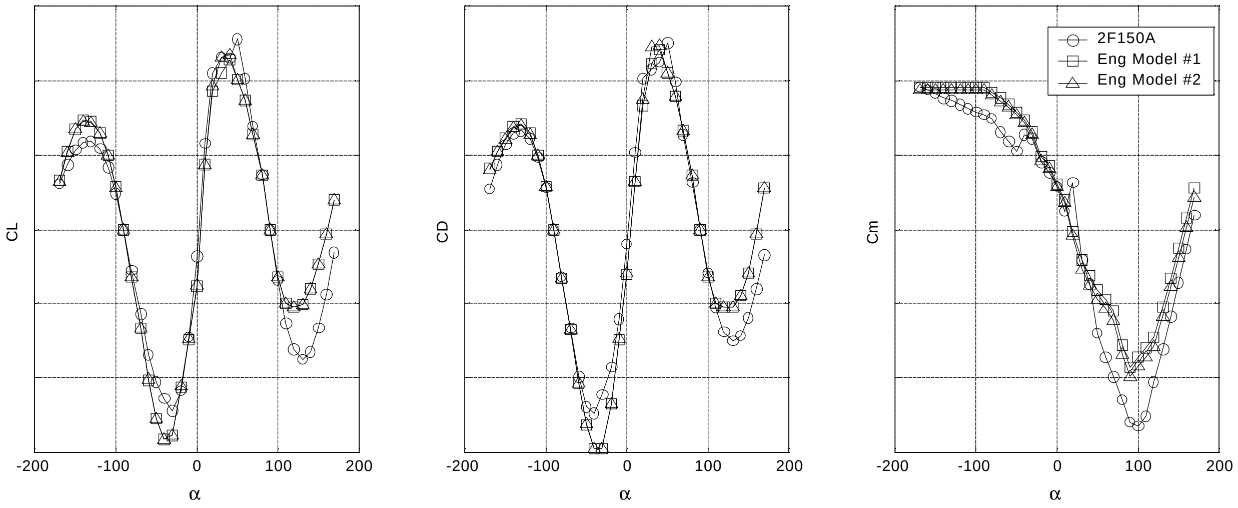

Figure 5. Sample aerodynamic coefficient comparison after model data extraction.

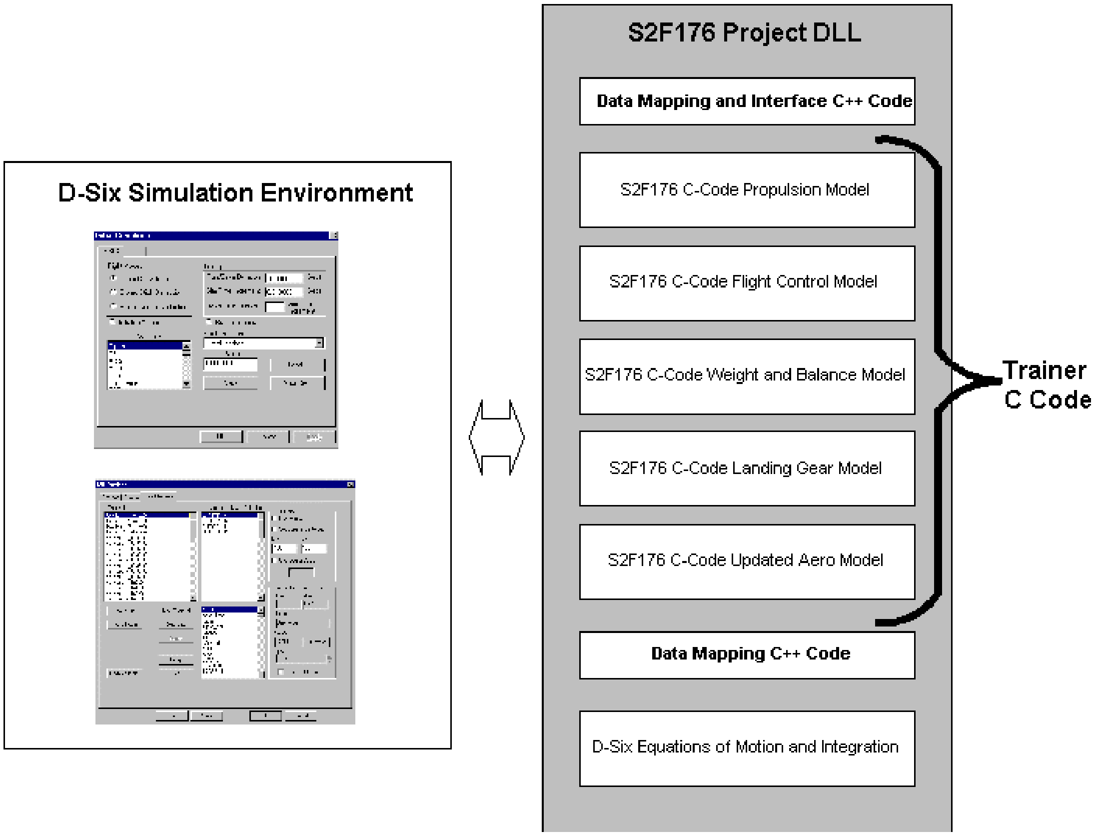

Figure 6. Diagram illustrating components in the S2F176 project DLL.

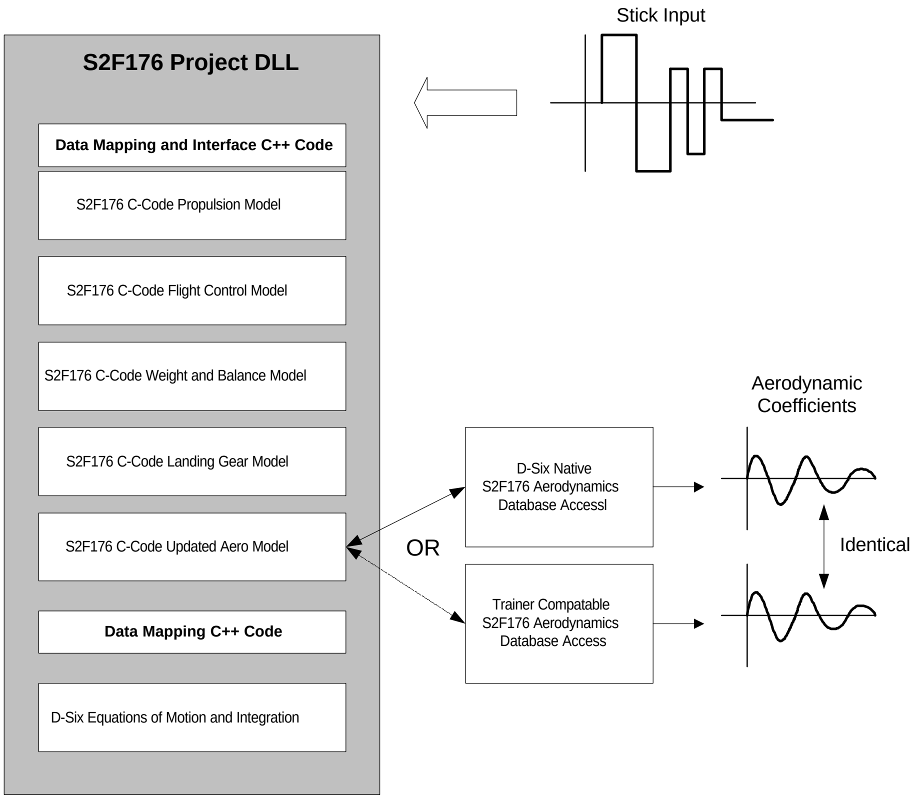

Figure 7. Diagram of the database conversion verification process.

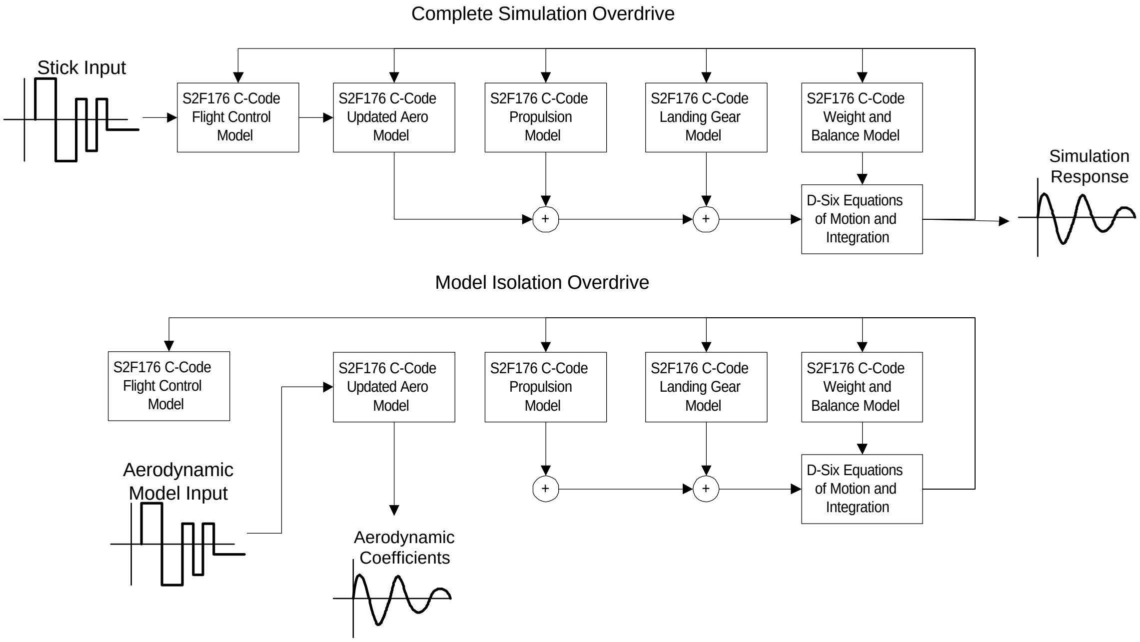

Figure 8. Diagram illustrating two overdrive processes.

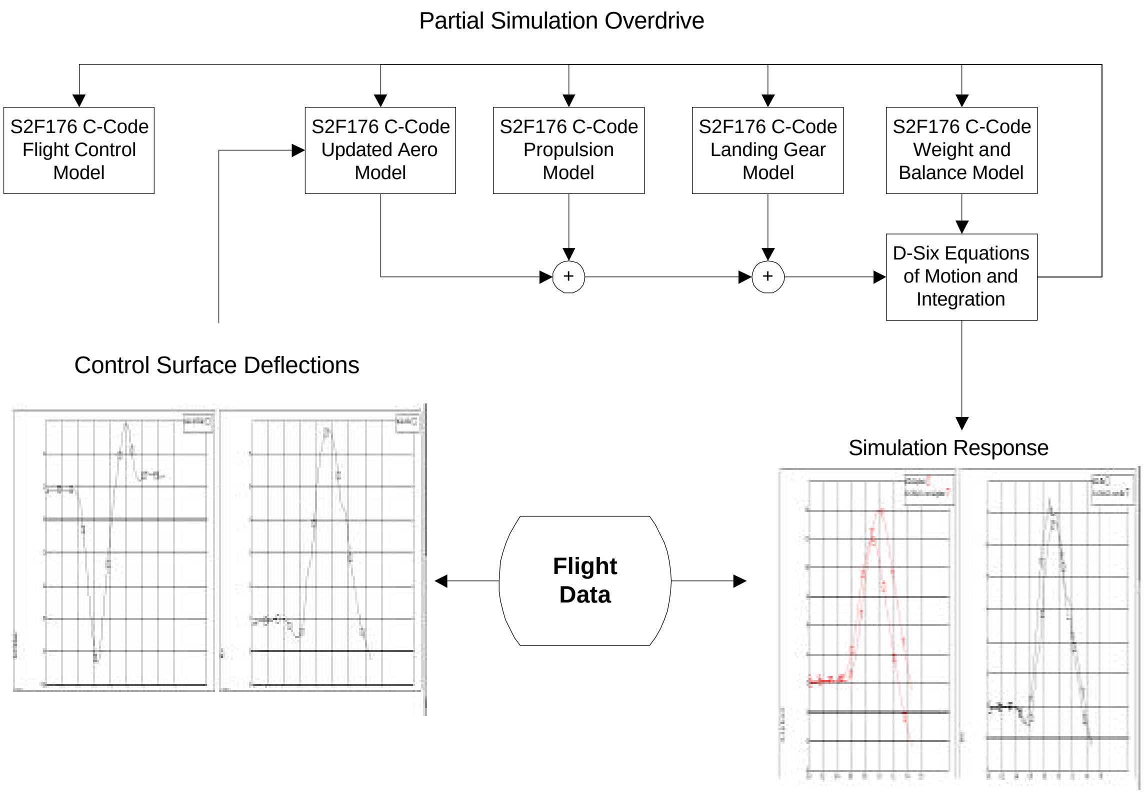

Figure 9. Diagram illustrating a partial simulation overdrive performed for the AV-8B and sample comparison plot.

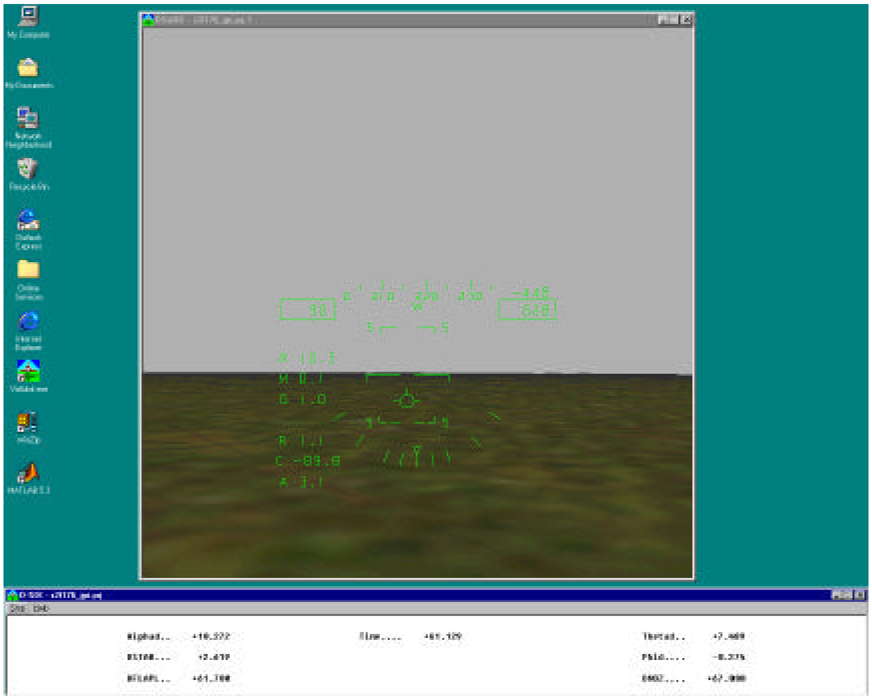

Figure 10. Screen capture during a desktop piloted simulation session.

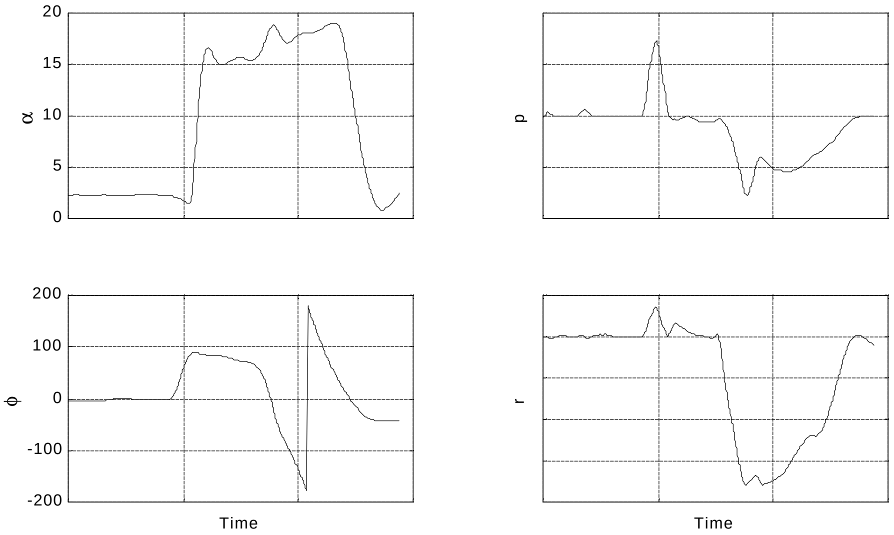

Figure 11. Sample recorded output from a DPS executed 360^o rudder roll at high AOA.

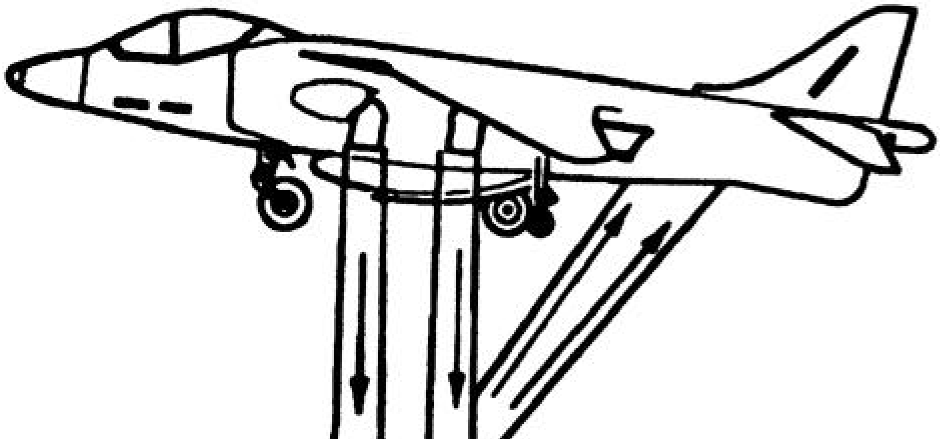

Figure 12. AV-8B NATOPS diagram illustrating jet blast reflection impingement with the aircraft.

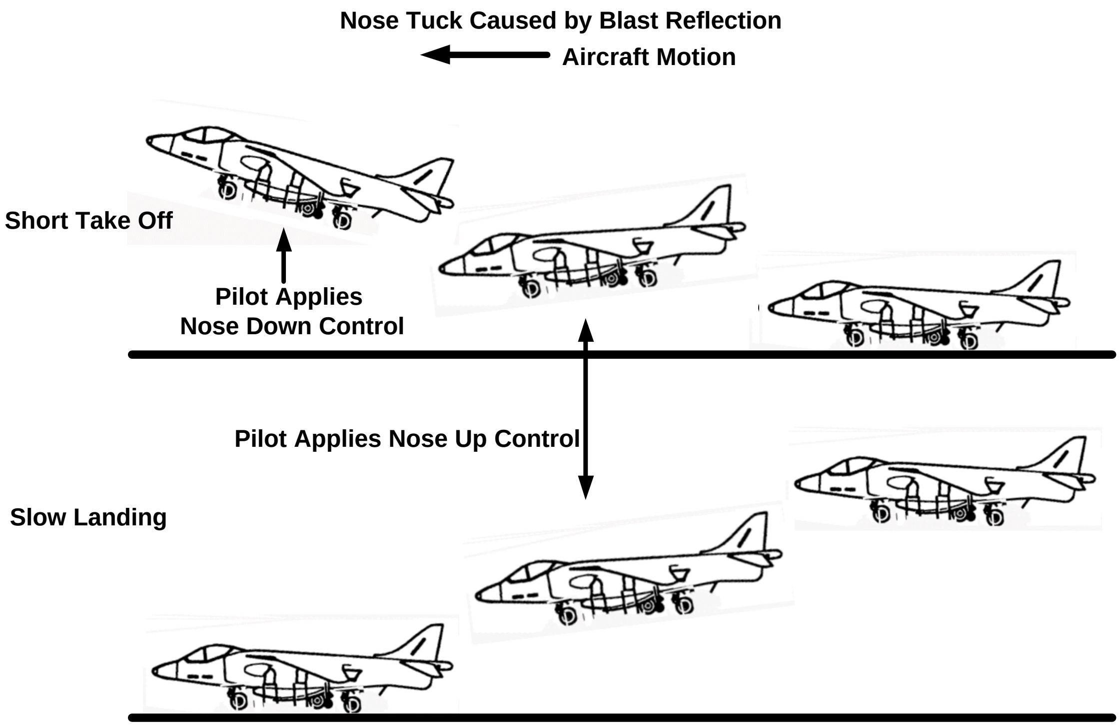

Figure 13. Diagram illustrating AV-8B motion due to jet blast reflection impingement with the aircraft during short take off and slow landing.

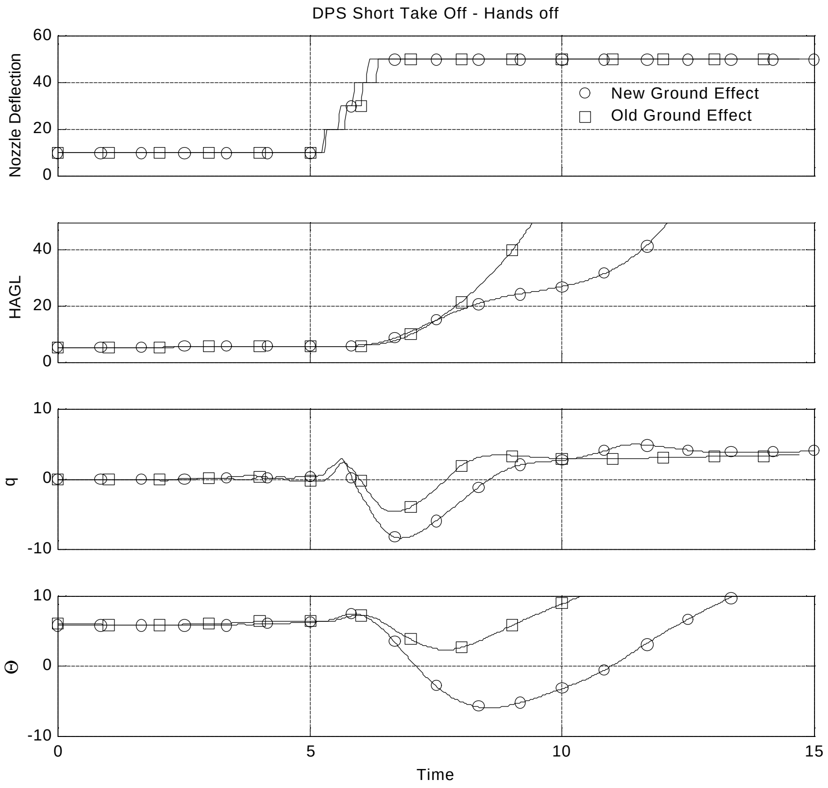

Figure 14. Hands off short take off using DPS employing new and old ground effect model.