PC-Based Simulation of the F-16/MATV

Matthew J. O'Rourke[*], **John N. Ralston**[†], **Jeffery W. Bell**[‡]
Bihrle Applied Research, Inc.
Hampton, Virginia 23666

Stanley F. Lash[§]
Wright Laboratory
Flight Dynamics Directorate, Flight Control Division
WPAFB, OH 45433

Summary

The Wright Laboratory (WL) F-16 simulation model has been re-hosted on a personal computer running a unique six-degree-of-freedom simulation environment. This model contains over 1000 two-dimensional aerodynamic data tables and a complex flight control system (FCS) modeled by thousands of lines of FORTRAN computer code. The FCS model can emulate several different configurations including a standard Block 40 F-16 and the F-16 Variable In-Flight Stability Aircraft (VISTA) with Multi-Axis Thrust Vectoring (MATV) in numerous modes. In addition to re-hosting the WL F-16 model, the high-angle-of-attack database was extended to include nonlinear effects at moderate to high angles of attack. These additional data greatly improve the ability of the simulation model to predict the in-flight maneuvering characteristics of the F-16 with active MATV.

Introduction

Bihrle Applied Research (BAR) has been conducting simulation studies of stalled, departed and spinning flight of fighter aircraft for over twenty years. To facilitate the modeling and simulation of the complex dynamic behavior encountered during these and other extreme flight conditions, BAR has developed, D-SIX, a six-degree-of-freedom simulation environment for the PC. One distinguishing feature of this software is the unique capability to rapidly re-host aerodynamic databases, flight control system (FCS) code and/or other complex computer code which model subsystems such as weapons, sensors and mission equipment. Due to the complex nature of the computer programs which model these systems, it is important that as much code as possible be reused when a simulation model is re-hosted in another operating environment. This is done not only to minimize the level of effort required, but also to ensure that the accuracy of the model is preserved.

One such simulation model which exists is the USAF Wright Laboratory (WL) F-16/MATV simulation model[1], operated by the Flight Dynamics Directorate, which includes an accurate representation of both the Lockheed Martin F-16 aerodynamic database and FCS. The FCS can be configured to model both the standard Block 40 F-16C and the Variable-Stability In-Flight Simulator Test Aircraft (VISTA) with Multi-Axis Thrust Vectoring (MATV), shown in Figure 1. Each configuration modeled by the FCS, in most cases, employs the identical code used in the Lockheed Martin simulation and has been validated to match throughout the entire flight envelope.

---

[*] Engineer
[†] Engineering Manager
[‡] Engineer
[§] Principal Scientist, Control Dynamics Branch

In a recent study performed by BAR, a new high-angle-of-attack database was developed to more accurately model the complex aerodynamic characteristics displayed by the F-16/VISTA while flight testing the MATV nozzle.[2] A detailed description of this database is presented in Reference 2. To build upon this effort, BAR has been tasked to re-host the previously mentioned F-16/MATV simulation operated by the Flight Dynamics Directorate at WL using the D-SIX simulation environment, while simultaneously updating the high-angle-of-attack database with that described in Reference 2. This paper will address the differences between the WL F-16/VISTA high-angle-of-attack database and the high-angle-of-attack database assembled by BAR. In addition, experience and lessons learned from re-hosting the FCS will be discussed. Finally, the re-hosted simulation will be validated against the WL simulation as well as flight test.

Brief D-SIX Simulation Environment Description

D-SIX is a MS Windows-based 6-degree-of-freedom simulation environment designed to address issues associated with many of the current complex engineering simulators. Coding requirements are minimized with the extensive use of graphical interface for all simulation functions such as multidimensional table-look-up, flexible plotting capabilities, and data editing. Real-time operation coupled with a low-cost, accessible control interface and visual output permits timely pilot-in-the-loop evaluations of FCS and aerodynamic characteristics. Existing modules from other simulation codes can be incorporated through Dynamic Link Libraries to avoid extensive re-coding and re-validation. Additionally, many tools associated with flight test data are incorporated to allow dynamic, real-time trajectory replay and flight parameter extraction for model validation and refinement. The project-based setup permits simple exchange of simulation models between users, and any capability upgrades in the D-SIX simulation environment is automatically propagated to all existing models. .

Aerodynamic Database Structure and Upgrade

Typical of most current high-fidelity flight simulations, the WL F-16/MATV model provides an accurate representation of controlled, maneuvering flight below maximum lift. However, like most highly-developed fighter simulations, extensive portions of the database have been linearized. In particular, some control deflections such as aileron and rudder have been linearized with deflection, which, for the F-16, are known to be nonlinear at moderate-to-high angles of attack. In addition, no dependency of control effectiveness or basic airframe pitching moment on sideslip is modeled. Basic airframe lateral-directional characteristics of the WL F-16/MATV simulation database are modeled with a linear dependence on sideslip. Reference 2 indicates that a highly nonlinear lateral-directional database accounts for some of the unexpected lateral-directional flight dynamics encountered at high angles of attack during MATV flight testing.

Although the effort described in Reference 2 produced a high-angle-of-attack database, its structure remained significantly different from that of the WL F-16/MATV data structure and included no high-speed aerodynamic effects. Therefore, the challenge existed to incorporate the BAR-developed high-angle-of-attack database with the existing low-angle-of-attack and high-speed database of the WL F-16/MATV simulation without compromising the integrity of either. In addition, to avoid discontinuities as the simulation transitions from the low-angle-of-attack to the high-angle-of-attack database, it is was necessary to include the entire low-speed database in one data set, modeling the Mach and altitude effects as increments taken from the WL database to that unified data set. However, this required that the low-angle-of-attack data, included in the BAR database and used for the low-speed portion of the unified data set, match the low-angle-of attack and low Mach data of the WL F-16/MATV database. This was done to ensure that the Mach and altitude increments yield values identical to the WL F-16/MATV database when added to the unified low-speed data set.

The changes to the database were made in two basic classifications: those to the basic airframe data set and those to the control increments. As stated previously, the basic airframe data were taken from the low-speed dataset in Reference 2 and the WL data were incremented from that (Mach=0.2) data to create basic airframe increments to all six force and moment coefficients as a function of Mach and altitude. The control increments were treated differently, however, due to the very different model structures of the nonlinear control data and the WL control data. To compensate for this, the WL control data were converted to multipliers on the low speed data as a function of Mach and altitude. This allows the full nonlinear control data to be used with the control power augmentations / reductions with Mach and altitude properly modeled. Great care was taken to ensure that the multipliers are realistically represented when low-speed data values are small.

Flight Control System Re-Host

Both the WL F-16/MATV simulation and the D-SIX simulation environment contain sections that perform identical calculations such as equation of motion integration, stick inputs, coordinate transformation, sensor modeling, etc. However, the FCS is a function of many of the quantities calculated in the these sections of code external to it. Therefore, the external variables which are input to the FCS code in the WL F-16/MATV simulation were identified and mapped to the appropriate D-SIX variables so that the FCS could fit seamlessly into the D-SIX environment. Using code development environments such as Microsoft Visual C++, the FCS can be compiled in its native language (in this case FORTRAN) and linked directly to D-SIX in the form of a dynamic link library.

Correlation With Simulation Check Cases

In order to ensure that the data and FCS have been implemented properly, validation runs have been made in various stages. The first were made in comparison to check cases generated using the WL F-16/MATV simulation. This was done using the original database to ensure that the FCS was transported to D-SIX accurately. The validation runs were performed simply by driving the re-hosted simulation model with the trimmed conditions from the WL simulation output and the control stick time histories. Figure 2 shows a maximum roll input for the Block 40 F-16. Figure 3 shows a roll doublet at 35° α with MATV on. Comparison of both time histories shows good agreement, especially considering that small differences in the high angle of attack database exist between the current WL model and the one used to generate the check cases.

Correlation with Flight Test Data

Once it had been established that the WL F-16/MATV simulation was accurately transported into D-SIX, the BAR high-angle-of-attack database was implemented as discussed previously. To ensure that this database was more representative of the high-angle-of-attack flight dynamic characteristics, the Overdrive feature of D-SIX was used to extract the force and moment coefficients from flight test data gathered during flight testing of the MATV. These data were compared to predictions obtained by running the flight test state parameters and control deflections with the new, fully non-linear database. A more detailed description of the Overdrive feature is presented in Reference 2. Figure 4 provides a flow chart which summarizes the Overdrive function and process. Although this phase of database validation was completed for the high-angle-of-attack database alone in Reference 2, the database validation time histories presented in the this paper use the unified data set described previously. Two examples of the comparison of the total flight-extracted rolling moment coefficient to that predicted by the updated database are presented in Figures 5 and 6 using a flight of the F-16 VISTA/MATV executing a 35° α roll . Figure 5 shows the comparison using the mostly-linear data set in the current WL model, and Figure 6 shows the comparison using the fully non-linear model. Not only does the comparison show that the nonlinear data set matches much better, but the following section will show how these differences are amplified when executing actual maneuvers with the six-degree-of-freedom simulation models. For a more detailed description of the process of database validation with flight test, please refer to Reference 4

Comparison of Simulation Models

Initially, a simple comparison of the current WL model and the fully-nonlinear model was done using a 360° roll at the angle-of-attack limiter with the F-16 in MATV mode, but with the limiter on. Figure 7 shows the time histories for the current WL and nonlinear models. Both models are trimmed at identical states and are driven with the same stick inputs. The sideslip excursion of the nonlinear model is slightly higher and the maximum roll rate is about 10 deg/sec lower than that of the current WL model. However, the two time histories represent very similar responses (unfortunately, at the time this study was completed, not flight test data were available for this maneuver). It now remains to compare the two models in the high angle of attack region where the flight dynamic characteristics are most nonlinear, i.e., 30 to 40 degrees angle of attack.

Since it is most important that the simulation model predicts the actual in-flight dynamic response, both the current WL model and the fully nonlinear model were trimmed to the flight test condition and driven using the flight test stick time histories. In addition, care was taken to ensure that all FCS functions were set according to the flight log. All weight and inertia information were calculated based on fuel state.

Although many test maneuvers were simulated, only one is presented here. A 35° α wind-axis roll maneuver (stick-driven) was selected because, like most aircraft, the F-16 exhibits the most nonlinear flight-dynamic characteristics near the stalled region. The flight is near trim at 35° α and descending slightly at 25,400 ft. The true airspeed is approximately 260 fps and the power is in military setting (this is the same flight used to generate the data in Figures 5 and 6). It should be noted that a significantly large amount of right stick was input by the pilot at the beginning of the maneuver to counter an apparent roll asymmetry which is included in the nonlinear database.

Figure 8 shows the response of the current WL F-16/MATV model to stick inputs identical to those of the flight data shown in the same Figure. The correlation is poor, showing lack of angle-of-attack hold (aircraft simulation pitches to over 60° α after 8 seconds) and a much lower wind-axis roll rate is exhibited by the simulation model. The inability to hold angle of attack is particularly detrimental in this case, due to an FCS mode that was set which inhibits rolling maneuvers at higher angles of attack. It should be noted that a 35° α wind-axis roll maneuver can be executed using the current WL model without pitching to higher α, however, the required stick inputs would be significantly different.

Figure 9 shows the same comparison using the fully non-linear model. The angle-of-attack hold compares well to that of flight test, as does the wind-axis roll rate. However, the sideslip, although showing similar characteristics at the beginning of the maneuver, becomes far too oscillatory. Since check cases evaluated in Reference 2 and the data presented herein had indicated that the static data are representative, modeling deficiencies in the dynamic data were suspected, specifically in the body-axis damping terms. This anticipated result was based on the revised low speed database's rigorous application of test data. The original linearized F-16 forced oscillation test data exhibited a wide range of non-repetitive values in the post stall region, and some judgment was required to define the baseline configuration from these data. Based on these and other considerations, the confidence level in this portion of the model was minimal. To illustrate the sensitivity of the post stall motion to these damping terms, the maneuver was repeated changing only the dynamic derivative which models body-axis rolling moment due to yaw rate, or C_{lr}. The stability of this derivative were increased between 20° to 45° α, but left unchanged elsewhere. Figure 10 shows the 35° α wind axis roll with this change. Notice that this simple change positively affected the correlation of all three parameters presented, distinguishing the strong dependence of high-angle attack maneuver modeling on dynamic data.

Conclusions

The F-16 model currently used at Wright Laboratory has proven to be a highly effective tool for predicting flight response of the F-16 at low-to-moderate angles of attack. However, due to portions of the aerodynamic model that are represented by linearized data, enhancement of the database near stall and at high angles of attack and sideslip was required to increase simulation fidelity. This has been successfully demonstrated, but this study indicates that further investigation of dynamic effects, especially near stall, should be undertaken to further increase model fidelity.

In addition to showing how high angle of attack modeling of the current Wright Laboratory F-16/MATV model can be enhanced, this study has shown that today's personal computers provide the computational power necessary to accurately re-host the most complex simulation models of fighter aircraft being assembled. Re-hosting, evaluating and updating complex simulation models using PC-based tools such as those presented in this paper will significantly increase the efficiency of many aspects of aircraft development, from preliminary design to flight test, by transferring real-time, high-fidelity simulation from the expensive and shared-resource mainframes and workstations to the inexpensive and readily-available personal computer.

References

1. McKeehen, P., " F-16/VISTA High-Angle-of-Attack Aerodynamic Modeling and Analysis," WL-TM-91-304, February 1991.

2. Kay, J., Ralston, J., Lash S., "Development of a Non-Linear, Low-Speed Aerodynamic Database for the F-16/VISTA," AIAA-97-3576, August 1997.

3. Baxter, J. et. al., "Flight Test Demonstration Report for the F-16 Multi-Axis Thrust Vectoring Program," WL-TR-95-3086, January 1995.

4. Ralston, J., Kay J., "The Utilization of High Fidelity Simulation in the Support of High-Angle of Attack Flight Testing," AIAA-96-3354, July 1996.

F-16 with Multi-Axis Thrust Vectoring System
Photo Eric Schulzinger/LMTAS

Figure 1.- Variable-Stability In-Flight Simulator Test Aircraft with Multi-Axis Thrust Vectoring.

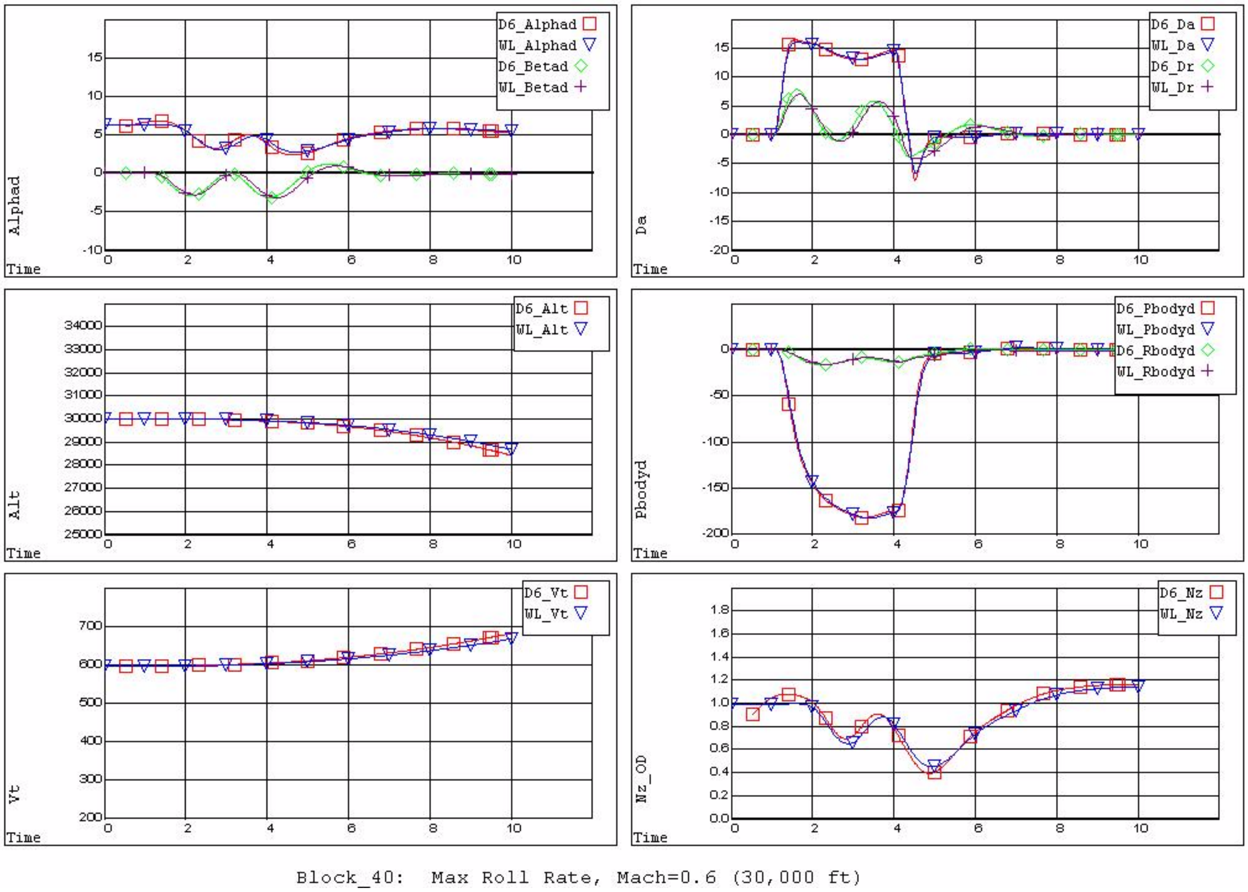

Figure 2.- Comparison of re-hosted model to WL model - F-16 Block 40 maximum roll command check case.

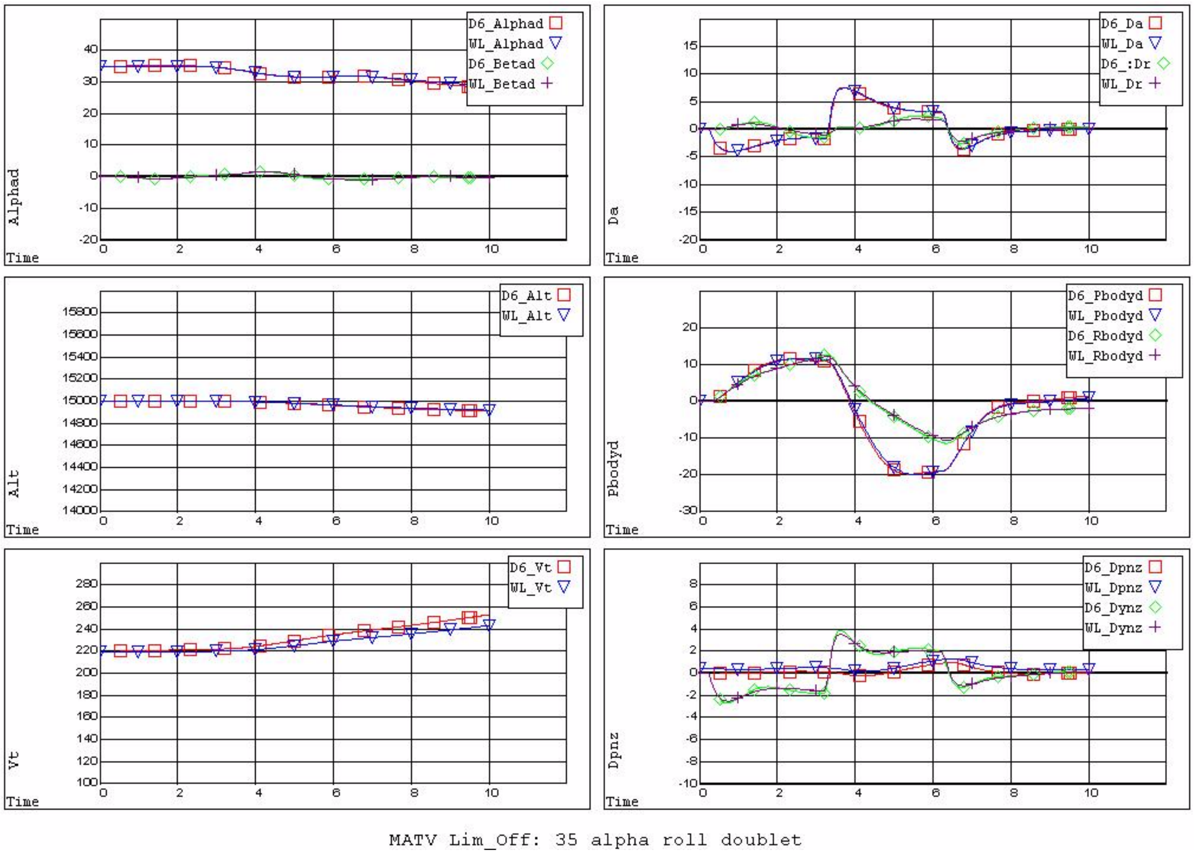

Figure 3.- Comparison of re-hosted model to WL model - F-16 with MATV on roll doublet check case.

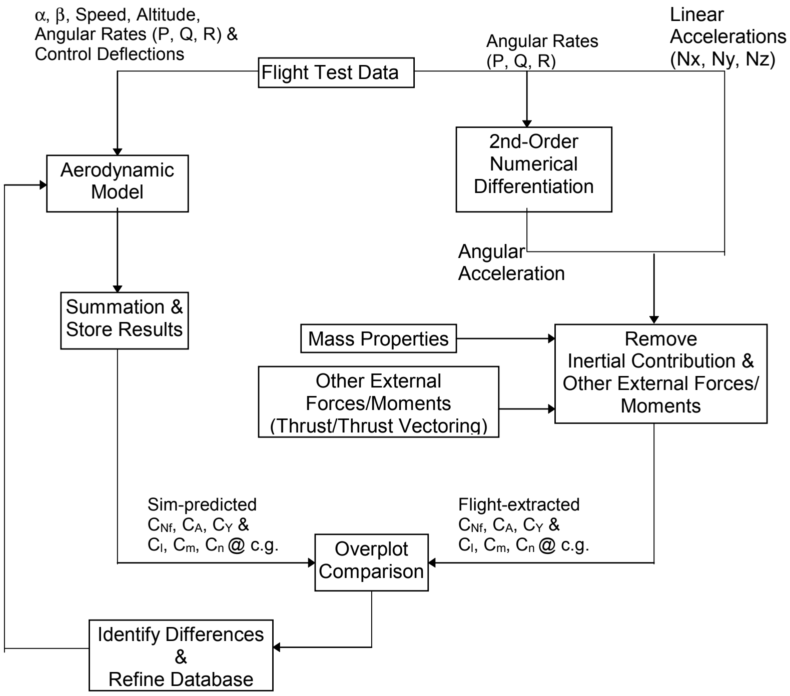

Figure 4.- Flow chart representation of the **Overdrive** feature of **D-SIX.**

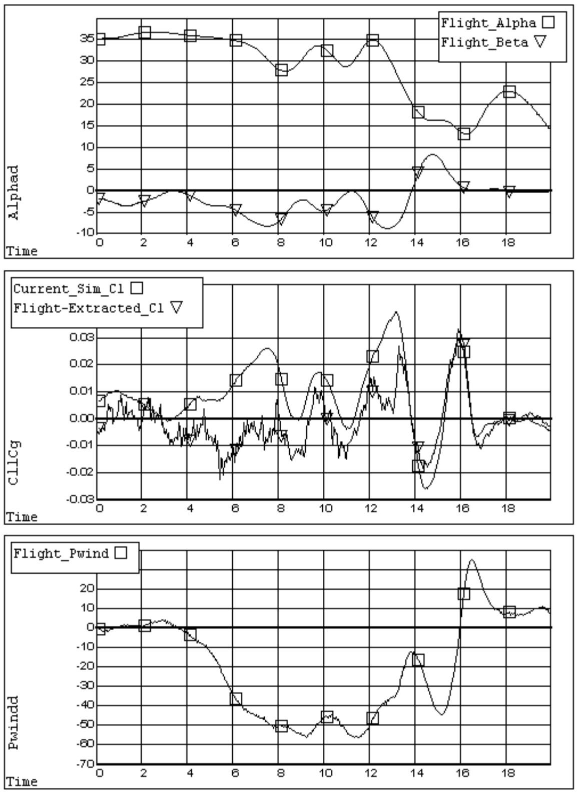

Figure 5.- Comparison of flight-extracted to simulation-predicted rolling moment coefficient using current WL database.

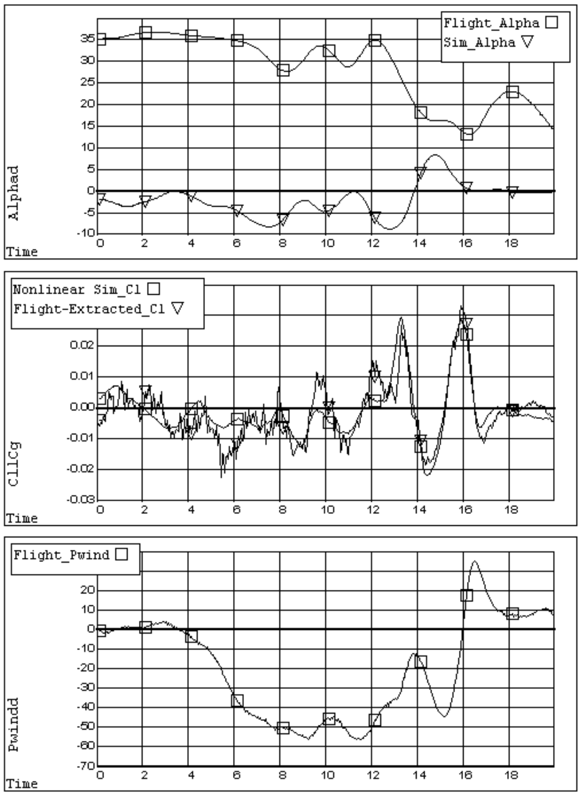

Figure 6.- Comparison of flight-extracted to simulation-predicted rolling moment coefficient using fully-nonlinear database.

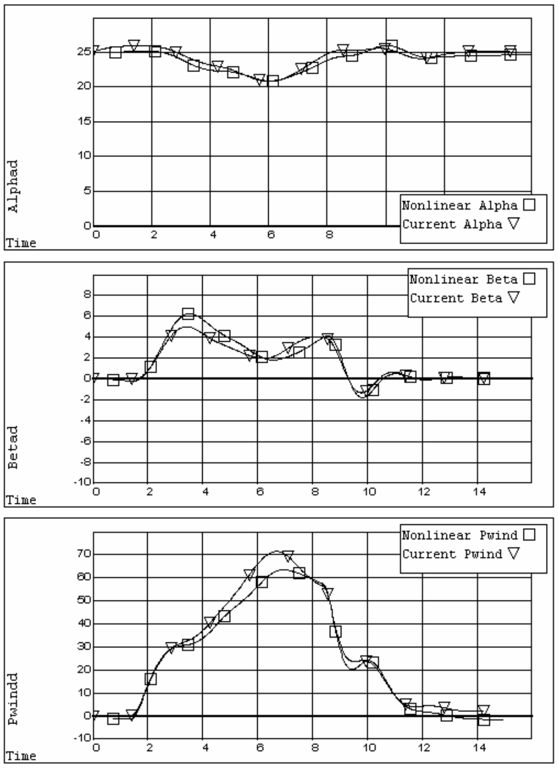

Figure 7.- Comparison of current WL model and fully-nonlinear models executing a limiter roll.

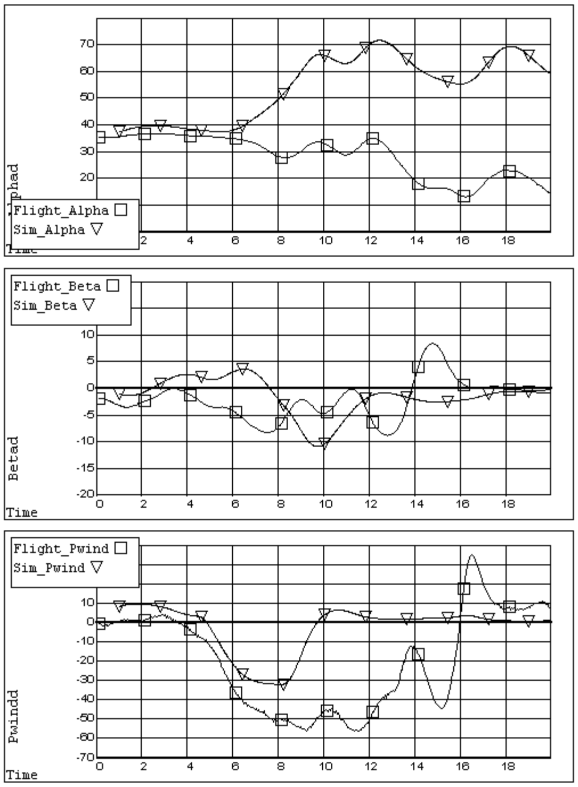

Figure 8.- Comparison flight test and simulation predicted 35° α rolling maneuver using current WL database.

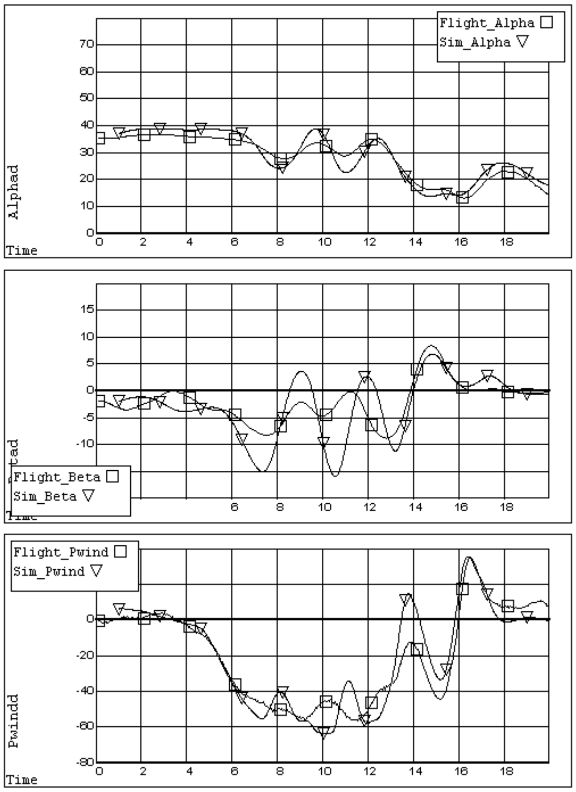

Figure 9.- Comparison flight test and simulation predicted 35° α rolling maneuver using nonlinear database.

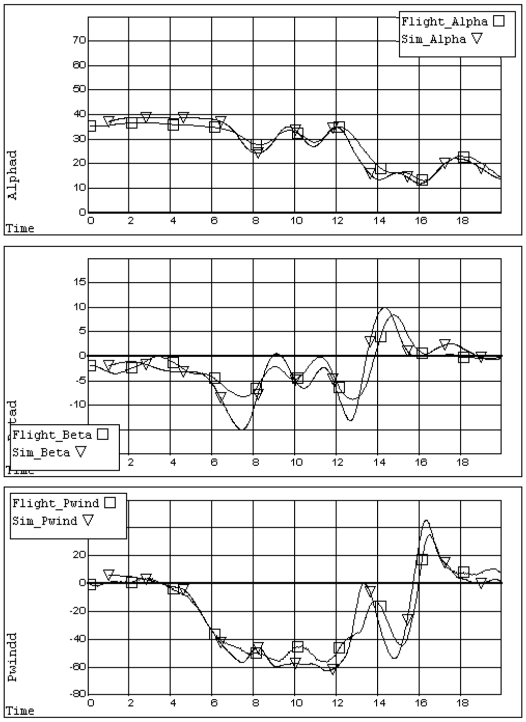

Figure 10.- Comparison flight test and simulation predicted 35° α rolling maneuver using nonlinear database with increased roll due to yaw near stall.