Mathematical Modeling Part III

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MATHEMATICAL MODELING PART III: CONTENTS

FLIGHT MODELING TOOLS

The need to process significant quantities of tabular information in the form of wind-tunnel data, flight-test data and simulation output, has dictated the evolution of a number of simulation development and analysis tools. While the type of toolset employed ranges from developer to developer, a number of applications that are of great utility are described in the sections below

Data Manipulation Tools

The complexity of compiling an extensive wind tunnel, computational, and flight test database into a structure suitable for a simulation has traditionally been one of the factors driving engineers to simplify the simulation aerodynamic model. In order to take advantage of this more comprehensive database, the development of data plotting, analysis, and manipulation tools are required in order to ensure all functionalities are properly modeled and included. To support model development of this type, an extensive data manipulation tool set is generally developed to permit the rapid maneuvering of test data into data structures appropriate for simulation modeling. The tool functions typically needed in the database development applications are as follows

a) Database importation - A method for importing a wide range of data structures and formats into the editing environment is a requirement. This would include the ability to import the various data formats and restructure the data into a form compatible with the simulation. The data types will range from tabular wind tunnel test data (typically configured as a row of aerodynamic coefficients versus a specific wind-tunnel test parameter, i.e., angle of attack), to flight test (typically expressed as a columns of flight parameters versus time) as well as other simulation formats that may be used as part of the database development.

b) Database plotting and editing – This important function will allow the developer to examine the various data sets plotted against the relevant functionalities of the data. The plot capability should allow the user to easily realign the plot functionality in order to comparison plot data of different functionalities (i.e. plot Lift coefficient (CL) versus angle of attack for selected sideslip angles or plot CL versus sideslip for selected angles of attack). The ability to graphically edit selected curves is also very useful in rapidly updating selected tables as well as resolving differences between the simulation tables and other data sources, such as flight test.

c) Simulation table manipulation - This application allows the user to perform a range of matrix operations on the simulation tables themselves. Since the simulation tables are typically generated as the function of a number of dependant variables, such as angle of attack, sideslip, mach number, etc., the manipulation of the order and structure of these tables in the assembling of the database is always required. These manipulations range from re-ordering of the table functionality, table subtraction, addition, argument interpolation, table merging, mirroring, table incrementing, and other complex table manipulations. The ability to operate on both individual tables as well as multiple tables in a batch mode is desired.

A number of commercial software tools have been used to perform some (or all) of the applications described above. Microsoft Excel provides a number of plotting and table manipulation capabilities, and if the data tables are in a conventional ASCII format, their importation into the software is easy. Some of the operations required require a significant familiarity with the software and are very cumbersome, however other operations cannot be accomplished. The MATLAB and Matrix X matrix manipulation environments are both very powerful data manipulation and visualization software, and in the hands of an experienced user, are capable of virtually any of the operations needed for database development. Other model developers, such as Bihrle Applied Research and many of the airframe manufacturers, have developed their own in-house toolsets to provide the model database manipulation capability.

Simulation Tools

The integration of the model into an operating simulation typically requires numerous operations before a validated/verified simulation is ready for production operation by a user. The traditional practice used in the development of simulation “environments” was to build a main executable code routine that utilized a variety of subroutines, libraries, and data blocks, custom developed for the particular flight model. This hand built application generally provided the user with little or no analytic capability, and any analysis and model refinement/development took place external to the simulation environment in the form of operations on the saved simulation output. This time honored but cumbersome practice has made model development a very labor intensive operation, with many externally set up batch runs, followed by post processing of large quantities of simulation output in external software tools. A number of newer simulation environments are attempting to change this vertical model development structure by making the simulation environment separate from the model dependant portions of the simulation itself. This structure then supports the inclusion of imbedded analytic tools in the simulation environment that can be reused as a new simulation is brought into the environment. Some of the tool applications that are useful in the model development and analysis are described below.

a) Interactive simulation output plotting - This important capability allows the user to visualize the results of the simulation run(s) concurrent with the operation of the simulation. This feature should allow the comparison plotting of a number of simulation outputs versus any other simulation variable. Further, there should be a capability of importing flight test or other simulation runs for comparison plotting. Plots should be available as a post run batch capability as well as user configurable real time strip charts.

b) Flexible simulation inputs – The ability to drive the simulation inputs with a variety of user definable inputs is a key feature in the development and validation of a simulation database. This capability enables the user to provide control inputs in a real time form, i.e. through a piloted control interface such as a joystick, or even keyboard inputs. In addition, a batch mode that lets the user drive the control stick inputs or control surface inputs as needed is also required. The ability of the developer to “fly” the simulation during real time operation allows the user to build and demonstrate typical control inputs. This operation would then be used to validate the flight model’s response to typical pilot inputs and maneuvers without the use of an extensive hardware environment. The batch modes should also allow the user to build custom input time histories, as well as import time histories from flight or other simulations.

c) Flight test importation and analysis tools – Because so much of the simulation development and validation centers around the comparison of the simulation response to flight test, the availability of the simulation environment to utilize these data interactively is very useful. This can range from the ability to drive the flight controls or surfaces to the ability to overdrive selected portions of the model to isolate model fidelity or validation issues. The capability to selectively drive the flight controls, engine or aerodynamic model components with other flight or simulation output allows the isolated evaluation of these model components without errors propagating from other parts of the model. The analysis tool should also enable the user to extract the aerodynamic forces and moments from a particular flight-test file for comparison with the simulation predicted terms. Finally, some inherent flight-test data manipulation tools (i.e., filtering, wild point editing, consistency checking, signal cropping and signal offset and multiplication, etc.) should also be available for any requisite processing of the flight test data prior to evaluation in the simulation.

d) Graphical database visualization and editing – During model development and validation the need to visualize the table data used in the model and edit their contents frequently arises. Rather than exiting to another application for this, it is very useful to have some capability internal in the simulation environment for this purpose. This tool should enable the user to examine graphically the contents of any table function and if necessary edit the contents interactively during the simulation session. When combined with the flight test data analysis tool described above and an embedded database configuration control mechanism, this capability is very a effective simulation evaluation and update application.

A number of simulation environments are currently structured to provide the developer with analysis tools such as these. The US Navy's Flight Vehicle Simulation Branch at Patuxent River, Md. uses the Controls Analysis and Test Loop Environment, CASTLE, with companion analysis modules SCOPE, SCIDENT and IDEAS to enable the type of analyses described above. Manufacturer simulation environments, such as Boeing St. Louis' MODSDF and Lockheed's ATLAS also provide some levels of embedded analysis tools, albeit in a batch simulation mode. Bihrle Applied Research's D-Six is an example of a COTS simulation environment developed to provide these types of analysis and development capabilities.

In addition to providing extensive data manipulation capability, The Math Works' Matlab and Simulink are very useful simulation tools. In recent years, The Math Works has developed the Aerospace block set for use with Simulink for flight simulation.

EXAMPLES OF FLIGHT MODEL DEVELOPMENT

The following case studies review the model development process for two different modeling activities. The first, the development of a JPATS trainer simulation for flight test support, examines the process used in the development of a complete model from wind tunnel data. The second case study, the update of the Navy's F-18 C/D simulation, reviews the activities undertaken in an extensive model database revision.

Terminology

Provided below are descriptions of symbols and terms in the context used in the case study presented here.

Angle of Attack (AOA, α)

The angle of attack is the angle of inclination of the aircraft body axis to flight path or velocity vector.

Angle of Sideslip (AOS, β)

The angle of sideslip is the angle of azimuth of the aircraft body axis to the flight path or velocity vector.

Static Data

The term "static data" refers to data collected from a model in a wind tunnel at fixed angle of attack and sideslip with no angular rate. The data are typically in the form of nondimensional coefficients derived from force and moment measurements with an internal strain-gauge balance.

Dynamic Data

The term "dynamic data" refers to data collected from a model in a wind tunnel at some dynamically changing condition. Motions can be steady-state as is the case with rotary balance testing where the model is rotated at steady rate, Ω, about the aircraft velocity vector. Rotary balance data are typically used to analyze and model aircraft spins and recovery. Motions can also be unsteady as is the case in forced oscillation where a model is oscillated about any of the three body axes. Oscillations are routinely defined with a harmonic function of angular position, often a sine wave. The harmonic frequency for the test is chosen based on a desired maximum angular rate (p q r) to be achieved during the motion as well as the maximum change in position to be achieved. Forced oscillation data are routinely used to compute body axes damping terms that can be linear or nonlinear in nature. Measurements during both test techniques are typically made with an internal strain-gauge balance.

Case Study: Flight Model for a Military Trainer Configuration, Part I

The use of airplane simulation has an extensive history in the training community, which has used simulator databases that have traditionally evolved well after the subject airplane has flown. The math models used to describe these configurations were generally very simple, derivative based, and usually hand adjusted by engineers, guided by pilots' subjective inputs and flight test results. As the expense of flight test has increased proportionally with the cost of military fighters, and with the introduction of automatic flight controls, the importance of developing high fidelity simulations prior to flight has also increased. Successful utilization of simulation in the throughout the test vehicle's flight envelope would significantly enhance the safety of the flight test program as well as permit the timely optimization of flight control systems. Even though improvements in computational power have permitted increased model complexity over earlier rudimentary models, in general the confidence in a simulation's predictive capability is limited enough that its use is secondary in support of initial flight test. Because of a highly compressed flight test schedule that resulted from JPATS competition requirements, an attempt was made to develop an approach to the math model development and deployment that would enable the simulation to be an integral part of the flight test program with the highest possible a priori fidelity. Further, the ability to immediately update the simulation database as flight test results became available was imperative. These requirements dictated the careful development of the wind tunnel test programs and the review of the results for the most comprehensive yet well -structured model. Because the JPATS program required specific stall and spin characteristics, the simulation was expected to accurately support this portion of the flight regime as well.

The jet trainer configuration examined in the present study (Figure 1) was an evolution of an earlier ducted fan configuration and was developed to compete in the Joint Primary Aircraft Training System (JPATS) competition. The configuration was the subject of considerable static and dynamic testing during its evolution, (Table I) and these data were used as the basis for the formulation of a large angle of attack simulation dataset. The simulation itself was developed in a very compressed schedule in order to permit validation and re-hosting on the flight test site's simulation facility. The following discussion reviews the development, deployment, and interactive use of this large angle, non-linear simulation in a flight test program that explored the normal flight regime as well as high angle of attack.

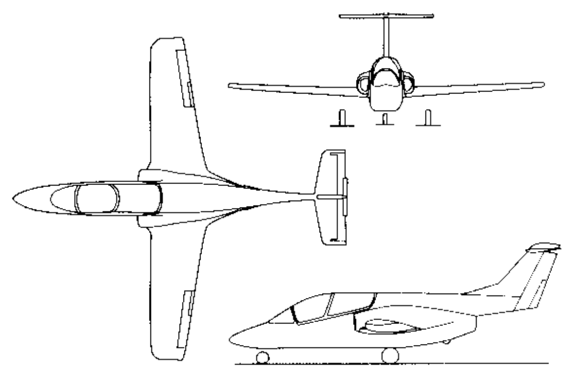

Figure 1. Military trainer three-view diagram

There have been many attempts to improve the aerodynamic modeling of an airplane's behavior from normal flight through the stall/post-stall region [1,2,3,4] and ultimately improve the simulation's predictive capabilities for flight control development, flight test, and training. Most of these attempts have focused on the development and evolution of large non-linear databases. Further, there has been increased attention on the dynamic characterization of the airplane, as well as the appropriate mechanization of these terms in the simulation. As a result of these efforts, several simulation databases have shown

Table I. - Summary of Wind Tunnel Test Programs

Wind Tunnel	Data Range	Application in Aerodynamic Model
CONVAIR 7 X 10	-10 to 60°α, ±30°β	Static stability of baseline Control effectiveness Config. modification
Rockwell Trisonic	0 to 15°α	Static stability of baseline Mach effects
Bihrle Applied Research LAMP	Static & Rotary: -30 to 90°α, ±30°β	Static stability of baseline Control effectiveness Rotary (wind axis damping) effects Config. Modification
	Forced Oscillation: 0 to 90°α, 0°β	Body-axis roll & yaw damping Config. modification (ventral fins, strakes, etc.)

significant improvement in the ability to predict and model complex aircraft motions ranging from departure, post-stall motions, spins as well as other large angle excursions. While some of these simulations are currently being used to support flight test, none have been successfully used in interactive, a priori flight test support of high-angle-of-attack flight test. The evolution of simulations and their usefulness in support of flight test has evolved from earlier attempts to use flight-extracted increments overlaid on a simple linear model, to the incorporation of more complex non-linear data sets. The recent successful application of these data sets shared the general approach to the aerodynamic database development, and these were used in the application discussed herein; the key points are summarized below.

1) The most important requirement to improve the aerodynamic fidelity of the simulator is the correct and complete representation of the static data. This rather intuitive statement implies the modeling of <u>all</u> static dependencies for both the basic airframe, as well as control effects. Past simulation models have relied on minimal definition of the basic airplane characteristics, i.e., linearized stability derivatives derived from small sideslip data. A more appropriate model incorporates a fully non-linear database with sideslip effects modeled through a sideslip range appropriate for configuration and the anticipated application of the simulation itself. This may require a significant tabular description of sideslip characteristics, up to 30° or more for a configuration such as this trainer. Control surface effects have also been highly simplified in the past, but non-linear variation with deflection, sideslip, and the effect of other controls must be identified and incorporated in the database (Figure 2 illustrates how the effect of sideslip and symmetric tail deflection can change the effect of differential tail in yaw from proverse to adverse in the stall region[5]). The identification of all of the basic airplane and control functionalities <u>requires</u> a well planned and comprehensive wind tunnel test program, and the data manipulation tools to compile this data into simulation data tables.

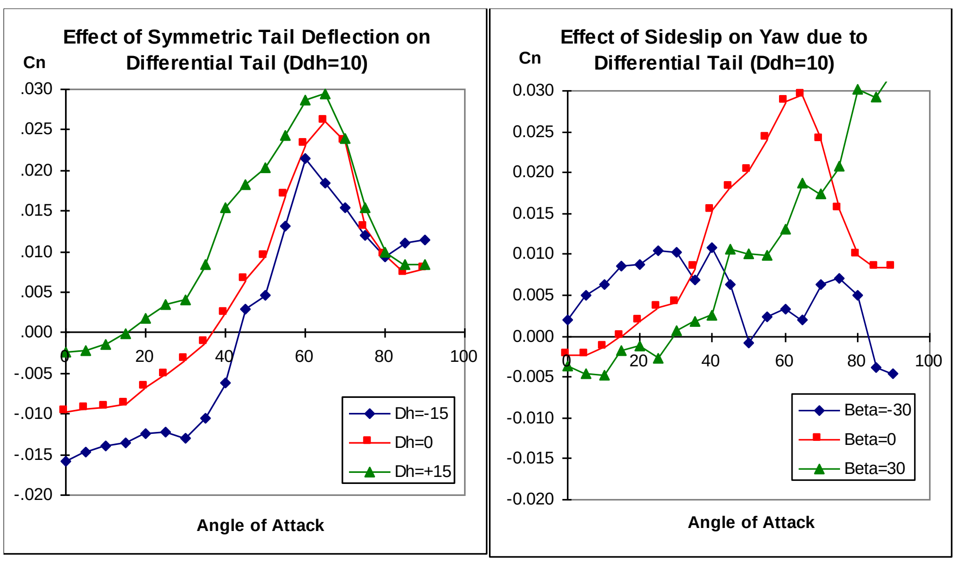

Figure 2. Effect of horizontal tail deflection and sideslip on differential tail effectiveness

2) The acquisition of the required dynamic data (frequently omitted and the starting point of considerable post flight "adjustments" is also a significant requirement for the accurate modeling of all aircraft motions. Analysis of the database requirements based on flight test motions[4] have shown that as the airplane progresses from coordinated to

uncoordinated flight, into spins and through recovery, the vehicle transitions through a wide range of wind axis and body axis centered rate excursions. Further, representation of the rate damping required is not adequately described by relying solely on the small perturbation body axis rate derivatives that have typically been used to define a configurations dynamic characteristics. These motions require the use of wind axis damping (rotary balance test data) as well as body axis damping data collected at test conditions representative of the flight motions and expressed as a function of all appropriate dependencies (i.e. rate, sideslip, controls, etc.).

3) The use of both body axis and wind axis damping data requires an appropriate method of mechanizing these two sets of dynamic data. Traditional mechanization has used the body axis rate derivatives multiplied by the total body rate and the incremental dynamic roll moment is summed as shown in the example below:

$$\Delta Cl_{dyn} = C_{lr} * rb/2V + C_{lP} * pb/2V$$

The assumption of linearity for the small perturbation data does not apply throughout the airplane's flight regime. Moreover, recent research has shown that independently tested body axis rate terms cannot necessarily be summed to represent a motion that excites both rates simultaneously anywhere other than at low angles of attack (i.e. during a coordinated roll at 10° angle of attack, both body axis roll and yaw rates are developed). A more appropriate mechanization scheme, as proposed by Kalviste[6], distributes the aerodynamic damping effects based on the relation of the airplane motion to the actual wind-tunnel test motions used to derive the various damping terms. This is determined by examining the relative position of the velocity vector (V_T) and the rotation vector (Ω). In the simplest terms, when the two vectors are aligned, i.e., in a coordinated rolling maneuver, the damping terms utilized would come from the rotary balance test data since the test motion is a velocity vector roll. When the rotation vector lies on either the x or z body-axes, the dynamic damping would be derived from either the body axis roll or yaw rate damping data respectively, again, because these motions are replicated by the test technique. For conditions where the rotation vector lies between these axes and the velocity vector, the dynamic damping is allocated by resolving the rotation vector (Ω) between the velocity vector (V_T) and the adjacent body axis, as shown in Figure 3. This mechanization has been successfully used in a

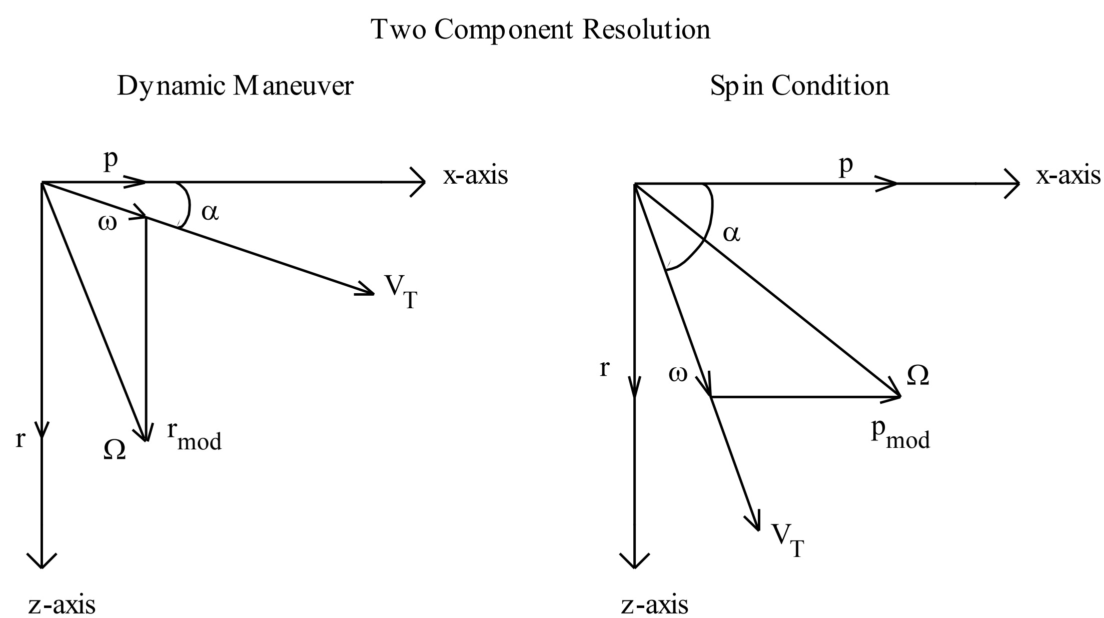

Figure 3. Vector schematic of Kalviste mechanization of dynamic data

number of high-angle-of-attack simulation models to date[5,6], and was recommended for this particular application.

4) The review and incorporation of the model data should carefully examine the strengths and weaknesses of each data set. A well constructed test program will result in the testing and overlap of data between a number of test facilities and at different test conditions and Reynolds numbers. The comparison plotting of these data will reveal how these data agree or conflict and force the review of the test conditions and data fidelity as the results are distilled into a final database. While the Reynolds number is frequently used as the deciding consideration in the application of a particular dataset, the developer is cautioned that many other factors such as the model size versus the tunnel test section, application of correction factors, sting interactions, etc. can impact the database selection process. Further, several recent experiences have shown that the selection of the highest Reynolds number data may not always provide the best modeling of the configuration.[7] This is particularly true if the test data Reynolds number range falls within the region where the flow is transitioning between laminar and turbulent separation ($Re \approx 1.0X10^6$)

While analytic data in general have had limited application in the development of simulation aerodynamic databases, these results can be used to augment test data or for data verification or Reynolds number correction. The most common application has been used to develop the linear body axis rate terms such as C_{lp} from empirical sources such as DATCOM or through CFD methods. However, these data are typically only suitable for very low angles of attack and should be used only in the early design phases of a configuration, or if the configuration requirements are such that any more comprehensive test data is unnecessary (i.e., a configuration with flight envelope that is limited to low angles of attack only, and no other data functionality such as flaps or sideslip is expected).

Application of Methods to Trainer Configuration

The utilization of this approach for this configuration centered on the acquisition of the needed aerodynamic test data. The wind tunnel test programs developed specifically addressed the effects of the basic configuration, effects of controls, Mach effects, and dynamic characteristics through test entries as shown in Table I. Testing in the Rockwell Trisonic facility identified the basic low angle of attack stability levels and control effects, and was the primary source of any Mach effects that influenced these characteristics. More extensive entries in the Convair 7x10 low speed tunnel resulted in an expanded angle of attack and sideslip envelope with a greater emphasis on control power evaluations as well. A later entry was also used to assess the effects of several configuration modifications proposed later in the flight test program.

Several low speed test entries were undertaken at the Bihrle Applied Research Large Amplitude Multi-Purpose (LAMP) test facility. This facility permitted the acquisition of a substantial range of low speed test data ranging from basic static configuration characteristics at high angles of attack and sideslip through the collecting of both body axis and wind axis damping terms. The static and dynamic data collected in these tests also examined numerous control dependencies and interactions as well. The wind axis damping data (rotary balance data) was collected for a range of nondimensional rates ($\Omega b/2V$) from 0 to ± 0.3, angles of attack from -30° to +90°, and sideslip angles through ± 30°. Control effects in the dynamic conditions were also examined. Body axis damping data were collected for the basic configuration at a number of oscillation frequencies and amplitudes. The tested non-dimensional rates (e.g., $pb/2V$ values of 0.02, 0.04) and amplitudes (±10° and higher) were chosen to better represent the uncoordinated motion conditions typical of departure than those used in most previous wind tunnel test matrices (e.g. $pb/2V < 0.01$, amplitude of ±5 or less).

A later test entry was made to collect the necessary description of several configuration modifications. The testing conducted on these modifications ranged from static to both wind axis and body axis damping dynamic conditions.

The complexity of compiling this extensive wind tunnel database into a structure suitable for a simulation has traditionally been one of the factors driving engineers to simplify the simulation aerodynamic model. In order to take advantage of this more comprehensive database, the application of data plotting, analysis, and manipulation tools were required in order to ensure all functionalities are properly modeled and included. To support model development of this type, an extensive data manipulation tool set had been developed to permit the rapid maneuvering of test data into data structures appropriate for simulation modeling. These tools allow the transformation of multiple coefficient wind tunnel data formats into a formal single coefficient simulation data table and subsequently, any matrix operation required on this table, including graphical database editing, is permissible. Using these tools, the simulation aerodynamic database was developed, validated, and transferred to the flight test facility within two months following the end of the last tunnel entry.

An example of the subsequent aerodynamic database structure is shown in the equation below portraying the yawing moment buildup:

$$C_{n\ TOT} = C_{n\ BASIC}(\alpha, \beta, M) + DC_{n\ \delta a}(\alpha, \beta, \delta a, M)$$

$$+ DC_{n\ \delta r}(\alpha, \beta, \delta r, M)$$

$$+ DC_{np}(\alpha, Pb/2v) \times P_{MOD}b/2v$$

$$+ DC_{nr}(\alpha, Rb/2v) \times R_{MOD}b/2v$$

$$+ DC_{n\ ROTATION}(\alpha, \Omega b/2V^{*}SGN(\beta), |\beta|) \times SGN(\beta)$$

The coefficient is the sum of the basic airplane stability with effects of aileron, rudder, body axis and wind axis damping. The non-linear sideslip effects derived from the Convair test data at low angles of attack and low Mach number, while the Trisonic test data provided the effects of mach on the basic stability. These data were blended into the low speed test data taken from the LAMP test facility for the characterization of the directional stability at high angles of attack. Both the Convair and the LAMP data were used to extend the sideslip effects to 30° of sideslip. The Convair and Trisonic data was used to define the rudder and aileron effects at low angles of attack and the influence of Mach number. The LAMP test data was used to define the effect of these controls at high (post stall) angles of attack. In addition, this test data was used to incorporate the non-linear effects of sideslip and control deflections to the baseline controls. The wind axis damping data, taken from the LAMP dynamic tests, is expressed as a non-linear function of angle of attack, rotation rate, and sideslip. The LAMP test data also provided the body axis damping terms, which are expressed as a function of angle of attack and the non-dimensional rates. While the coefficient buildup is straight forward for this relatively simple geometry, considerable complexity and database range are incorporated in the coefficient components and their breakpoints. This is the simulation structure that was sent to the flight test center at the outset of the high angle of attack flight test program.

Summary

The example case cited above describes a process of assembling a simulation flight model prior to the existence of flight test data. In this case, the formulation was driven by the application of the flight model itself and the available dataset. Careful test program development and selection of the needed test facilities resulted in the collection of a wide range of wind tunnel test data encompassing a range of angles of attack, sideslip, Mach number, controls and dynamic effects. These data were assembled into a complex non-linear database using a reasoned approach to the data selection and implementation of the static and dynamic effects. As a result, the deployment and use of the simulation flight model became an integral part to the success of both the conventional and high-risk portions of the flight test program.

Case Study: F-18C/D Flight Model Development

An aerodynamics model of the US Navy's F/A-18 multi-role fighter (Figure 4) obtained by NAWC/AD in 1983 from the airframe contractor adequately modeled the majority of the normal flight regime for the single-seat configuration. However, evaluation of simulation results versus flight test did reveal some areas of deficiency, particularly at high angles-of-attack and sideslip near the edge of the low-speed portion of the flight envelope. The model also did not contain sufficient aerodynamics data to simulate departures of the two-seat aircraft with centerline tank. An effort to introduce a more complete aerodynamic database into the model and "unify" the two-part, up-and-away model was undertaken by NAWC/AD, Bihrle Applied Research, Inc. (BAR), and Science Applications International Corporation, formerly Systems Control Technology, Inc. (SCT). The new aerodynamic data tables incorporate the results of parameter identification (PID) analysis as well as the aerodynamic increments associated with rotation about the velocity vector (rotary balance wind tunnel data). In addition, the effect of sideslip was expanded throughout the baseline model's functionality. The result is an aerodynamic database continuous in angle-of-attack ($-90° \geq \alpha \geq 90°$), Mach number ($0 \geq M \geq 2$), and sideslip ($-45° \geq \beta \geq 45°$) with representative modeling of the fringes of the low-speed envelope for both the single-seat and two-seat aircraft. Subsequent to this first effort, additional more recent work has focused on a more comprehensive model update and validation effort for the entire UP/AUTO, as well as the power approach portions of the flight envelope. This effort is a result of an attempt to address remaining simulation fidelity issues, as well as to merge the best portions of the respective NAWC/AD and manufacturer models into a single global F/A-18 aerodynamic database.

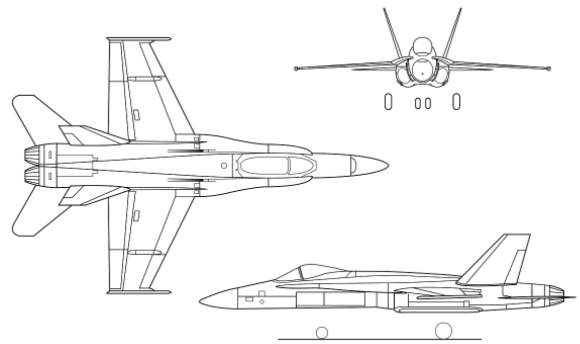

Figure 4. Three-view diagram of the F/A-18A/C.

The following discussion reviews the processes involved in the creation of the NAWC AD F/A-18 unified aerodynamic model, and present validation results, recommendations, and lessons learned.

History of the Model

A baseline simulation UP/AUTO (i.e., cruise) aerodynamic model was originally created as far back as 1974 by the McDonnell Douglas Corporation (MDC) using data supplied by Northrop from the YF-17. The first static wind tunnel testing on the F-18 configuration was conducted in 1976 by MDC using 6% and 16% scaled models at various wind tunnel facilities, with data for the dynamic derivatives collected using a forced oscillation technique. During subsequent data reduction by MDC, it was determined that the 16% model data was the most representative of the full-scale aircraft, and was thus favored for use in the simulation rigid body aerodynamic model. Aero-elastic flex/rigid ratios (based on theoretical and empirical analysis), drag data, and the high-angle-of-attack data were subsequently added, such that by August 1977, MDC had a workable simulation aerodynamic model covering the majority of the UP/AUTO flight envelope for angles of attack from -4° to 90° in the fighter escort (FE) store loading[8]. At this point, the model was configured as the integration of four separate models distinguished by state or configuration; low-angle-of-attack UP/AUTO ($-4° \geq \alpha \geq 40°$), high-angle-of-attack Up/AUTO AUTO ($40° \geq \alpha \geq 90°$); ½ PA flap setting, and full PA flap setting. The simulation transitioned between these distinct model configurations through the use of specialized ramping functions based on the transitioning state variables.

In late 1983, the entire MDC F/A-18 simulation was acquired by NAWC/AD, implemented into the Manned Flight Simulator's simulation architecture, and verified. Subsequent updates were received from MDC providing aerodynamic increments for the two-seat canopy, centerline tank (FCL) store loading, interdiction (INT) store loading, and leading edge extension fences, as well as to correct deficiencies in the original drag model. But by 1988, it became clear, through validation efforts and real-time use by NAWC/AD, that the low-speed aerodynamic model contained inaccuracies.

Additional Low-Speed Wind Tunnel Testing

In order to augment the existing low speed static and dynamic data, in 1988 NAWC/AD commissioned static wind tunnel and rotary balance test data acquisition and analysis on a 1/10-scale F/A-18 model in the National Aeronautics and Space Administration (NASA) Langley Research Center 20-foot vertical wind tunnel. Static and dynamic test data was collected for a total of seven different store loadings on the single-seat configuration, with the two-seat configuration initially tested in the FE loading only. However, it was later determined that additional wind tunnel testing was required on the two-seat configuration, both with and without the centerline tank (TFCL and TFE respectively), in order to more accurately reflect the incremental effects of these configuration changes on the baseline single-seat aerodynamic model used in the simulation. All combinations of canopies and store loadings were tested under static and rotational conditions both upright and inverted. The tests also examined a wide range of control deflections, both at full and partial conditions, as well as in the presence of other controls and sideslip.[9,10,11,12]

The rotary balance testing was primarily conducted to provide incremental effects due to wind axis rotation on the force and moment coefficients.[13] As discussed in the section above, this data has been successfully utilized in other simulations, using the techniques to accurately model aircraft coordinated rolling motions, departures, spins and recoveries.[14,15] Since part of this simulation improvement effort was to address this flight regime, these incremental effects were incorporated into the original MDC model. Initial validation of this hybrid aerodynamic model revealed poor correlation with the known F/A-18 departure and spin characteristics, and as a result, an extensive review of all static data in the model, initially focusing on the flight regime encompassing departure and beyond, was undertaken. This effort was conducted in concert with a parameter identification evaluation as described below, and many of the results from the wind tunnel / simulation evaluation concurred with the PID efforts. As mentioned earlier, additional testing and model development work was conducted as other deficiencies (e.g., two-seat departure modeling) became obvious.

Scope of the Parameter Identification Tests

Parameter identification of aerodynamic coefficients from flight test data was performed from 1985 through 1989. Using prototype aircraft F3, data was collected in the UP/AUTO configuration ($55° \geq \alpha$; $0.25 \geq M \geq 0.95$) for the single-seat F/A-18 with FE loading (wing tip AIM-9 missiles only). Two-seat F/A-18 data was also collected in the FE loading ($40° \geq \alpha$; $0.25 \geq M \geq 0.95$), using prototype aircraft TF1. In 1989, a test program was conducted involving the two-seat aircraft in four different store loadings: TFE (wing tip AIM-9 missiles only); TFCL (wing tip AIM-9 missiles only) plus two inboard pylons; TFCL (right wing tip AIM-9 missile only) plus two inboard pylons; and INT without the fuselage-mounted sensors/trackers. Once again using prototype aircraft TF1, data was collected during test maneuvers specifically aimed at PID analysis, while additional data was obtained from simultaneous non-PID flight test programs using aircraft TF30. This data covered a Mach range of 0.25 to 0.95 and altitudes of 25,000 to 40,000 feet, although the majority of the data was at Mach numbers less than 0.65. In all, a total of approximately 74 flights of two-seat data were made available for analysis. The majority of the data collected was at high altitudes, therefore the resulting analysis assumed an inflexible aerodynamic model.

It should be emphasized here that all the test data was not rigorously analyzed. Instead, maneuvers were chosen from each flight on the basis of best instrumentation quality and best excitation of the dynamic modes of the aircraft. Parameter identification software such as NAVIDNT/SCIDNT and Athena was used to perform the data analysis, and by 1986, reduction of the F3 flight test data was completed. The following year, the incremental aerodynamic effects for the two-seat canopy were estimated from the TF1 flight test data.[16,17]

Aerodynamic Model Unification

Having collected the additional PID and wind tunnel test data, efforts were made to utilize this extensive new data pool to improve the original model. A number of specific tasks were required in order to accomplish this overall goal. First, a rigorous analysis of the model's deficiencies, both in structure and data, was conducted in order to define the required upgrade task. Second, a technique needed to be developed for analyzing and incorporating the diverse (and often non-compatible) data sets into the model in a fashion coincident with the model's multi-variable table look-up format. Finally, the unified database would be re-validated and any remaining deficiencies identified and addressed.

Model data analysis was conducted by comparison with the other available data, including PID. This task required the development of model and data manipulation software that permitted the importation of simulation model, wind tunnel, and PID databases, and through various matrix operations, reformation of each into compatible forms. This included such operations as center of gravity (c.g.) shifting, interpolation of additional breakpoint values, and the “delinearizing” of derivative terms, since, in most cases, functions were modeled non-linearly. Following this reformatting, the available data sets could be comparison-plotted and discrepancies noted. The PID data (where available) were then used as a guide to determine the most representative data set and the model data was adjusted to match. Where flight data was not available, further analysis, based on data source limitations and past experience was used to dictate ultimate model definition. Even though these limited cases did require “empirical” adjustments to the model to achieve the desired results, it was felt the model development based on wind tunnel data and its non-linear progression with angle-of-attack, sideslip, control surface deflection, etc. insured that the simulation database reflected the most important data dependencies that would have been difficult or impossible to derive with any other method in the given flight regime (i.e., near- and post-departure). The following discussion describes some of the more pertinent data modifications made to the original modeling and their justifications.

Longitudinal

The initial PID analysis of F/A-18 flight data indicated that the simulation’s longitudinal model in UP/AUTO was very good,[16] which subsequently resulted in few model changes. These changes involved the revision of longitudinal dynamic derivatives and stabilator control power terms, and the overall structural changes that were made to the entire aerodynamic model. However, more recent analyses conducted independently by NAWC/AD, and others have not shown the degree of correlation between the longitudinal aerodynamic model and the aircraft as the initial SCT analysis had. These model short comings appear to be confined to the static portion of the aerodynamic model and are currently being addressed.

Lateral

Significant differences emerged in the analysis of the F/A-18’s lateral characteristics, typical of that shown in Figure 5, which illustrates that in the stall/post-stall region, for the applicable sideslip range of the sloped data (±5°), the flight-extracted data differs substantially from the data contained in the original model. As can be seen, the static data obtained from the rotary balance test more closely approximates the flight-extracted terms. The lateral stability differences observed in these data are very similar to the conflicts noted in earlier F/A-18 test data taken from several tunnels at differing Reynolds numbers.[18] It was concluded at the time that the lateral characteristics as mechanized in the simulation gave the best representation of the full-scale airplane. However, the results of the flight-extracted data from several independent evaluations have indicated that the lateral stability for the F/A-18 should, in fact, be more stable than originally modeled. Consequently, these data were modified using a representative wind tunnel data set.

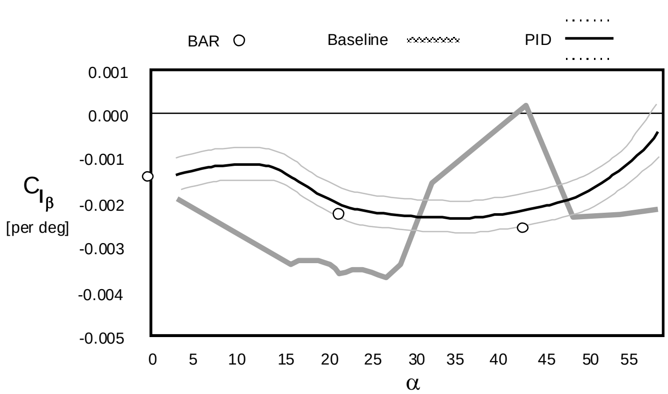

Figure 5. Simulation Dihedral Effect Comparison

More crucial than the lateral characteristics for the basic F/A-18, however, was the mechanization of the two-seat F/A-18, particularly with the centerline tank. Original incremental effects of these two configuration changes were very limited in the simulation envelope, as well as limited in the resolution of the independent breakpoints. Substantial work, comparing available test data, from sources such as reference 19 and 20, with newly acquired data for this purpose, was conducted to extend and refine the incremental effects. The extension of the sideslip breakpoint set to reflect the non-linear effects of these configuration changes in the stall region was imperative because of the importance of these characteristics on the departure modeling of this configuration. In addition, for the lateral case as well as any coefficient with sideslip dependency, the sideslip effects were extended with wind tunnel data to ±30°. This was done because of the frequent high sideslip excursions this configuration experiences during departure, and the significance of these large sideslip effects throughout the aerodynamic model. More recent testing and model revision has resulted in the expansion of the sideslip dependency to ±45° to provide a further increase in model accuracy, as sideslips of this magnitude are not uncommon in some of the more violent departures.

Directional

The basic F/A-18 directional characteristics below 40° angle-of-attack exhibited generally good correlation with the flight-extracted data and consequently only minor changes were made. As in the lateral case, the two-seat canopy and centerline tank increments were significantly different than recent test data, and were subsequently revised to improve their definition at both low and high sideslip angles.

Analysis of the high-angle-of-attack (a > 40°) data revealed the lack of any modeled yaw asymmetries at zero sideslip. Several wind tunnel test data sets, including high Reynolds number test data (Figure 6), exhibited this behavior, a typical result of asymmetric forebody vortex shedding at these angles-of-attack. Further verification of the asymmetric yawing moment tendencies is found in free-spin model and flight test spin records in which a given airframe favored a particular spin direction. It was also felt this asymmetric behavior is one of the primary aerodynamic forcing functions in the low yaw rate spin. Consequently, asymmetry effects were included in the unified database, with recent revisions to enable the user to manipulate the magnitude and sign of the offset. This modification was incorporated to reflect the variability of this forebody shed vortex phenomena. Further, the propagation of this effect into both sideslip and dynamic characteristics is modeled as dictated by the test data.

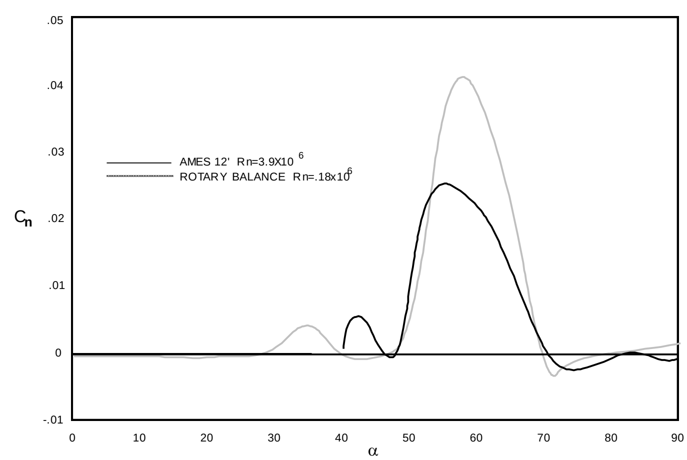

Figure 6. Wind Tunnel Static Yawing Moment Comparison

Control Effects

Analysis of the control effects for the basic F/A-18 revealed a number of conflicts, particularly at high angles-of-attack. An example of this is shown in Figure 7, which compares test data with baseline simulation data in yaw for full aileron deflection. Although the baseline data is considerably more adverse (uncoordinating) in yaw, both data sets exhibit similar trends with angle-of-attack up through 60°, whereupon the baseline data breaks from adverse to proverse, and remains proverse through 90° angle-of-attack. This model data would suggest that pro-spin aileron deflection would be in the direction of the spin, opposite that of most military aircraft and inconsistent with F/A-18 flight test or free-

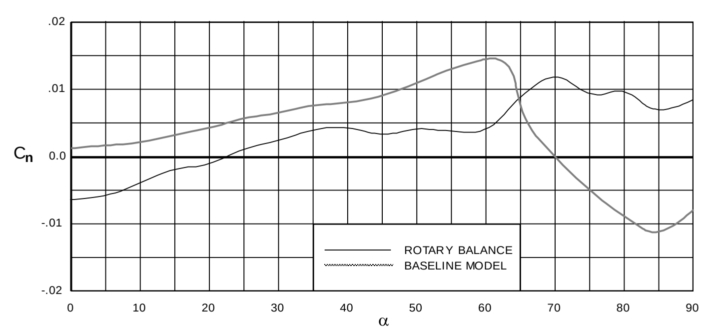

Figure 7. Effect on Yawing Moment of a 50° Aileron Deflection

spin tunnel data results. Therefore, the model data was modified to remove this high angle-of-attack effectiveness change.

The modeled differential tail effectiveness in yaw was also examined versus other available test data. The incremental yawing moment that results from a differential tail deflection of -10° superimposed on either a 5° or -20° symmetric tail is presented in Figures 8a and 8b.

For the aft stick data, the yawing moments obtained are in good agreement below 50° angle-of-attack. Beyond 50°, the static data taken from the rotary balance tests becomes adverse, while the simulation data set remains proverse through 70° angle-of-attack, then rapidly becomes adverse. On the other hand, the yawing moment produced by the differential tail with full forward stick becomes increasingly more adverse above 35° angle-of-attack, ultimately reaching extremely high levels of adverse yaw. These characteristics, in conjunction with the aileron yaw authority characteristics previously mentioned, result in an simulation aerodynamic model with little or no propelling yawing moment for a combination of aft stick and pro-spin roll controls (i.e., stick against the spin), and very large amounts of propelling yawing moment for forward stick. The airplane spin behavior observed in flight test and the free-spin tunnel,[21] as well as the spin modes predicted using rotary balance data[22] do not reflect these control characteristics.

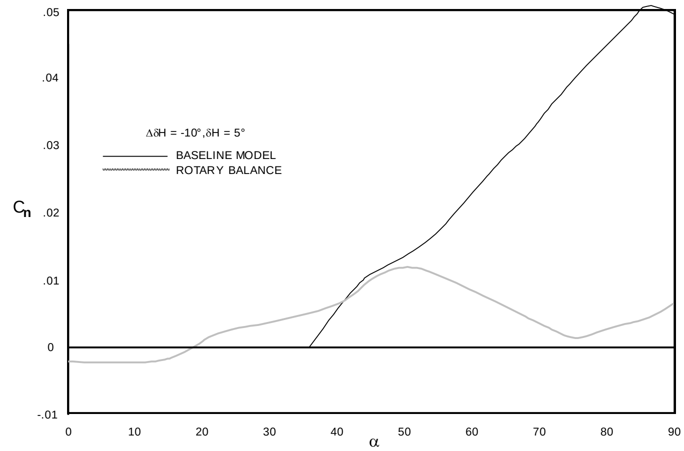

Figure 8a. Effect on Yawing Moment of a -10° Differential Tail Superimposed on a 5° SymmetricTail

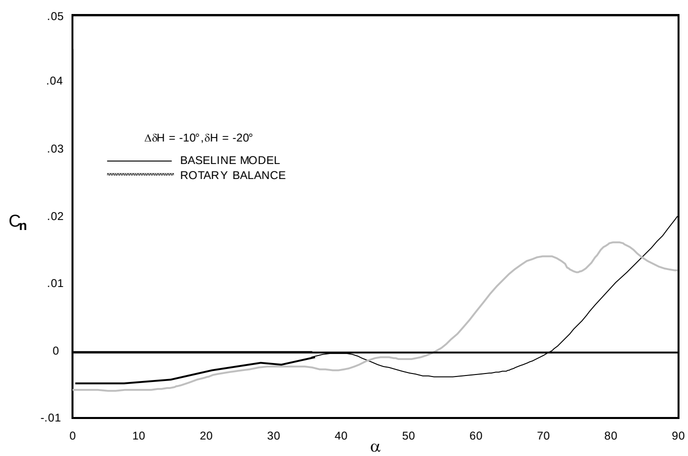

Figure 8b. Effect on Yawing Moment of a -10° Differential Tail Superimposed on a -20° Symmetric Tail

At low angles-of-attack and for full rudder deflection, correlation between the simulation data and other data sources was very good. However, analysis of the two-seat F/A-18 low angle-of-attack departure data revealed the simulation's rudder control effectiveness was low for the maximum rudder deflections allowed by the flight control system (approximately 11°) at the departure condition. Test data taken with additional rudder deflections revealed rudder effectiveness was more dependent on deflection angle than was modeled and so this effect was incorporated into the simulation data.

With the exception of small sideslip effects on rudder deflection at high angles of attack, no sideslip effect was modeled in the baseline aerodynamic data for any control surface. Past analyses have shown the important influence of sideslip on control effectiveness, particularly at the angles-of-attack and sideslips experienced during departure (e.g., Figure 9, showing the effect of sideslip on rudder power). The complete non-linear modeling of these effects was included for all control deflections.

Dynamic Derivatives

Comparison of the modeled dynamic derivatives with flight-extracted values revealed a number of conflicts. As a result, additional dynamic data were derived for the upright and inverted single-seat F/A-18 using a modified strip method, which uses the rotational slopes of the complete airplane, as well as airplane component data (both static and rotational) to formulate the derivatives. The derivative is calculated as pure rate terms (i.e., C_{l_p}) rather than a rate plus beta-dot term (i.e., $C_{l_p} + C_{l_b}$ sin a) that is typically the output of forced oscillation testing. The availability of this data set was useful in the further analysis and correlation of the dynamic effects, as illustrated in Figure 10, where the roll due to roll rate term (C_{l_p}) is compared for the available data sets.

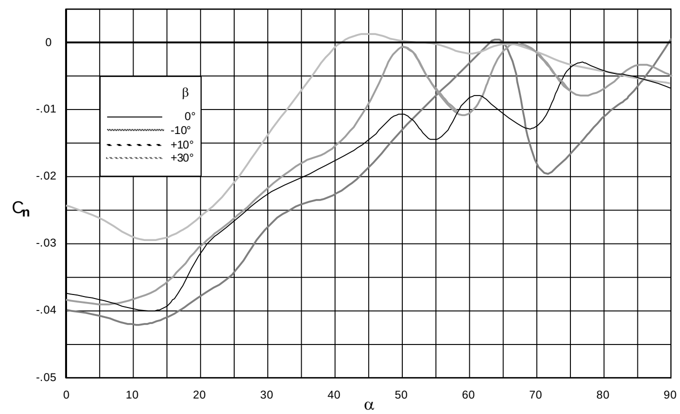

Figure 9. Effect of Sideslip on Yawing Moment due to a 30° Rudder Deflection

As shown by Figure 10, the flight-extracted data is considerably less damped than the baseline model in the stall region, but agrees well with the values calculated from the rotary balance tests. The sharp increases in the roll damping at stall exhibited by the original data set may have contributed in the selection of the original lateral characteristics described earlier, with the increased roll damping offsetting the reduced lateral stability evidenced by the baseline model at these angles-of-attack. As noted earlier, however, independent PID efforts have derived roll-damping terms that are less damped than originally modeled, and other analysis has shown that this sharp increase in damping at stall may be a result of the inclusion of the sideslip-angle effect in the total roll damping term.[23] As a result, the unified model made use of the calculated data where dictated by the PID results. Differences in the other derivative terms were similarly rationalized and corrected during the model unification process.

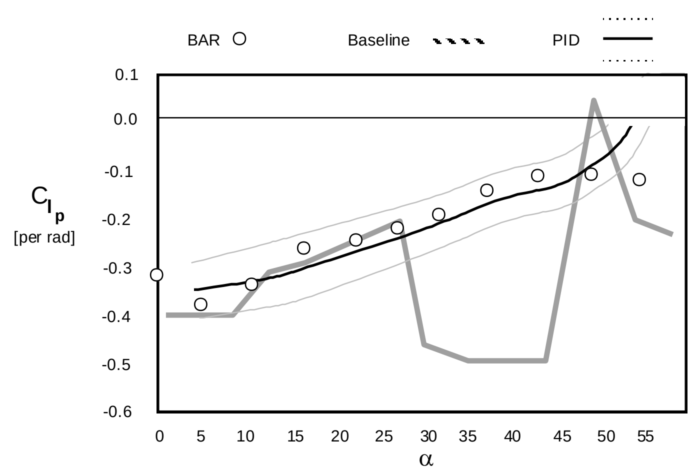

Figure 10. Simulation Roll Damping Comparison

Model Structure

Because the original database consisted of two static data regions describing angle-of-attack envelopes of approximately -4° to 40° and 40° to 90°, a ramping function was required to smoothly transition between these data regions. This requirement arose because of data discrepancies at the table end points, as well as dissimilarity in the actual breakpoints and table geometries at the break. Additionally, an inverted static low-speed database[11] as well as the rotational increments were to be combined to these two tables. Thus, following the revision of the actual upright data as described earlier, it was felt that this segmentation of the database was no longer satisfactory, and consequently, the merging of all discrete databases into a continuous, breakpoint-compatible form was conducted using the model manipulation tools. Many of the modifications made to the upright model itself had required reformatting of the -4° to 90° angle-of-attack region. Consequently, the addition of the inverted data resulted in a continuous simulation database from -90° to 90° angle-of-attack, ±45° sideslip, and Mach numbers from 0.2 to 2.0.

Summary

The net result of this model review and reconstruction was the significant improvement in fidelity through the integration of several data sources that were not previously available. Rather than merely adding incremental changes to the database to accommodate these updates, the entire content and structure of the model was examined. In several cases the form of the data was changed to accommodate the new data and/or the need for a more efficient data description. Further, the entire model was ultimately reconfigured to arrive at a model that expressed its primary functionality, angle of attack, as a continuous function. This configuration made it much easier for the simulation engineers to visualize the data, as well as improving the maintainability of the database as new configuration effects, or other new data became available for incorporation into the model. The success of this effort was evident in the improvement in the flight fidelity that resulted, as well as the Navy and Boeing's selection of this model as the starting point for the F-18C/D Common Database.

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