KING AIR 350 FLIGHT-TEST DATA GATHERING AND LEVEL-D SIMULATOR AERODYNAMIC MODEL DEVELOPMENT

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Abstract

A joint program between NLX Corporation, Virginia, USA and the Flight Research Laboratory (FRL) of Canada's National Research Council (NRC) was initiated to develop a high fidelity simulator mathematical model for the Raytheon King Air 350 business aircraft (Fig. 1). The flight-test data, as well as the aerodynamic model developed from the data, conformed to JAA's Level-D Simulator data standards [1] and IATA's Flight Simulator Design and Performance Data Requirements [2]. Efficient data system architecture, in terms of both software algorithms and hardware processing, has been employed to meet the stringent requirements of a Level-D simulator mathematical model. Additionally, novel hardware and software techniques have been applied to the calibration and measurement of the fundamental in-flight parameters such as air data. The small perturbation stability and control derivatives were formulated versus parameters such as Mach, alpha, beta, thrust and flap setting to develop a global model of the aircraft. The flight data used for model validation conformed to the FAA's Qualification Test Guide (QTG) manoeuvres specifications [3]. This program has clearly demonstrated major improvements in the efficiency and time required to develop a simulator mathematical model for a fixed wing aircraft, from flight-test data.

This paper 1) describes the test aircraft and the instrumentation suite, 2) outlines the techniques employed to perform simultaneous calibration of the air data sensors, 3) describes the selection of 2-3-1-1 manoeuvres for modelling, 4) provides a brief description of the flight-test manoeuvres performed to develop and verify the aerodynamic model, and 5) discusses some of the challenges involved in producing a high fidelity aerodynamic model of the King Air 350. The paper concludes with a discussion of lessons learned.

Figure 1: The King Air 350 Test Aircraft

1 Overview

A joint program between NLX Corporation, based in Sterling, Virginia, USA, and the Flight Research Laboratory (FRL) of Canada's National Research Council was embarked upon to develop a high fidelity JAR-Sim Level-D quality simulator model of the Raytheon King Air 350 business aircraft. Once a suitable test aircraft was identified and leased, an eight-week effort was initiated to instrument over 100 channels of data parameters.

The NRC/NLX joint program addressed several challenges in the areas of flight-test data gathering and high fidelity aircraft aerodynamic modelling, such as:

i. Developing a highly accurate instrumentation system with distributed data acquisition modules,
ii. Integrating optimised flight-test techniques and analysis to develop the aerodynamic model,
iii. Developing the capability to calibrate all air data sensors simultaneously in flight through the use of nose cone airflow sensors and Differential Global Positioning System (DGPS),
iv. Implementing an efficient global model development routine, and
v. Validating the aerodynamic model.

The flight-test data suite for the King Air 350 model development and validation included standard fuselage response parameters, differential GPS (DGPS) and over 100 other parameters (including engine parameters, control surface positions, landing gear oleo compression, etc.). The data acquisition system consisted of the NRC designed PACNet distributed node network operating at a sample rate of 64 Hz, and a commercial off-the-shelf GPS system. All of the required parameters were sampled concurrently in order to eliminate the skew error associated with sampling parameter data consecutively. Vibration at the pilot seat rail location was sampled at 1024 Hz in order to provide high fidelity reproduction of vibration cues for takeoff/landing, turbulence, and stall conditions.

The calibration technique employed for the fundamental air data parameters (i.e., pitot-static air data plus airflow angles) uses DGPS and a global search minimisation technique to allow for rapid and accurate calibration of air data parameters. The tests flown to perform the air data calibration consisted of a special set of 'wind box' flight manoeuvres used to identify and account for the dynamic changes caused at pressure probe locations due to upwash and sidewash effects.

The engine model was developed in a collaborative effort between NLX and NRC's Structures, Materials and Propulsion Laboratory, based upon the Pratt and Whitney Canada's PT6A-60A turboprop engine cycle deck and was validated by the flight-test data and dynamic response of the engine flight-test points.

The flight-test program was completed in approximately 90 flight hours between 15 December 2000 and 6 February 2001 with 47 sorties and over 1300 flight-test manoeuvres which consisted of:

- 166 trim "snap-shots" and 2311 manoeuvres,
- 17 stalls,
- 7 wind boxes
- >350 ATG/IQTG manoeuvres for final model validation

The flight-test program test matrix was optimized to investigate the effect of changes in aircraft altitude, airspeed or Mach number, weight, CG location, power setting (by rate of climb and descent and engine out cases), flap setting, speed brake setting, gear position, and ground effect on the aircraft dynamics. In addition, the ground handling dynamics, flight controls, major aircraft sub-systems and aircraft sounds were also investigated.

Data analysis was performed to compute the static derivatives using the steady state trim cases. Once the trim model was established, the resulting dynamic responses of the aircraft model were evaluated in a time-domain parameter estimation process. The stability and control derivatives that resulted from analysis of the 2-3-1-1 manoeuvres were grouped to form the global aerodynamic mathematical model. Comparison of the static derivatives was made between the trim data and the 2-3-1-1 test points to verify the model. Discrepancies between this model and the flight data time histories led to the revision of the derivatives/aerodynamics of the mathematical model.

The time-domain parameter estimation process used a maximum likelihood estimator as the core of the optimisation algorithm. This estimation technique has matured to the point of now being a state-of-the-art industry standard. To support this efficient algorithm, a PC using Visual FORTRAN performed the floating-point computations. The model development computer had direct batch-mode operations that interfaced to the aircraft data and parameter estimation input files. The process of data analysis was automated to combine the small perturbation mathematical model and trim flight data to form the global model.

The primary objectives of this paper are to describe:

- flight-test data collection,
- development of the parameter estimation software,
- innovative measurement of air data (nose-cone),
- the in-flight air data system calibration
- global aerodynamic model development and validation using a PC computing architecture, and
- integration of the aerodynamic model into a fully functional, real-time Level-D flight simulation code.

2 Aircraft Description

The Raytheon Super King Air 350 is a 17-seat (maximum) business aircraft, powered by two Pratt and Whitney PT6A-60A turboprop engines. It is a fully cantilevered, all-metal, low-winged monoplane with a T-tail empennage. The wings are an efficient high aspect-ratio design with NASA-designed winglets to further improve performance. The aircraft has a certified ceiling of 35,000 feet, a maximum Mach number of 0.58, and a maximum gross ramp weight of 15,100 pounds.

3 Aircraft Instrumentation

The project instrumentation system for the King Air 350 was designed and built around the NRC developed 'PacNet' (Parameter Acquisition Network) distributed data acquisition and recording system. It consisted of several nodes distributed throughout the aircraft and connected to groups of sensors. Each node received analog signals at a sampling rate of 1024 Hz from the sensors in its group via its interface, filtered the signals using a 48 tap Finite Impulse Response (FIR) low pass digital filter with a cutoff of 10 Hz, and output the filtered data at 64 Hz onto a network. Vibration data was filtered via a separate 100 Hz low-pass FIR filter, which was powered by batteries. Unfiltered parameters included digital, discrete events, air-data, Litton LTN-90 inertial data (digital), wind and time data parameters.

Control surface positions were measured directly at the surfaces in an effort to reduce the dynamic effects of the control system in the surface position measurement. The signals from the PacNet node network were recorded centrally at 64 Hz on an IBM Thinkpad notebook personal computer mounted in one of two project racks in the cabin of the test aircraft. A second rack housed the video and audio recording equipment.

The project instrumentation system was either powered directly from the aircraft's electrical power supply via the non-essential bus, or independently, from an internal battery mounted on the instrumentation rack. The battery allowed the project instrumentation to operate uninterrupted through the voltage transients associated with engine start-ups and shutdowns.

3.1 Inertial Parameters and Air Data Sensors

Aircraft inertial data was measured using redundant inertial measurement systems, consisting of a Litton LTN-90-100 Inertial Reference System (IRS), and MicroPac, the FRL's own high precision inertial measurement unit (IMU). The Litton unit was hard-mounted to the cabin floor near the nominal planar center of gravity of the aircraft. The FRL MicroPac Inertial Measurement Unit was mounted on top of the Litton IRS. The Micropac IMU was calibrated just prior to a previous simulator development program to ensure high accuracy. The accelerations and rates from this unit were favoured over those of the Litton IRS for data analysis purposes, since the filtering of the IMU data was performed post-flight using a forward and backward Butterworth Infinite Impulse Response filter resulting in zero phase lag.

The inertial data was corrected post-flight to refer back to the aircraft's instantaneous center of gravity location.

Aircraft static and dynamic pressures were obtained by connecting the aircraft's co-pilot side pitot-static air data pressure lines to two Honeywell pressure transducers, mounted on a tray in the nose compartment of the aircraft. The static and dynamic pressure data was corrected for position errors using post-flight processing, and was then used to derive altitude and airspeed quantities.

A five-hole flush nose-cone air data system was used to measure airflow angles in flight. This system comprised of a cruciform configuration of four pressure ports distributed along the normal and lateral axes of the nose-cone, with a central port used as a redundant total pressure source. The four 0.125-inch-diameter pressure ports, were each connected by 3-ft-long, 0.25-in.-diameter sections of plastic tubing to two differential pressure transducers. These transducers were thermally modeled, with a resulting accuracy of 0.01 percent of full scale.

3.2 Air-Data System Calibration

3.2.1 SCADS Background

Several years ago, the FRL developed an off-line technique for the simultaneous determination of pitot-static position error and the calibrations for angle of attack (α) and angle of sideslip (β), known as SCADS (Simultaneous Calibration of Air Data Systems) [4]. The technique uses DGPS position data, along with the usual attitude/heading, angular rate and air data parameters.

3.2.2 Wind Box Flight Manoeuvres

A set of the special wind box air data calibration manoeuvres, used in the SCADS technique, consisted of:

- a 1 minute leg at constant heading, accelerating

from 120 knots to 250 knots airspeed;
- a 90° turn with bank angle of 30°;
- a 1 minute leg at constant heading, decelerating from 250 knots to 120 knots airspeed;
- a 90° turn, accelerating up to 180 knots;
- maintain constant speed and track angle while performing 'beta sweeps' keeping wing level or minimizing bank for a minute – i.e., slowly increasing angle of sideslip from 0° up to 10° in each direction;
- another 90° turn, accelerating up to 225 knots;
- another set of 'beta sweeps' with amplitude of 10° while maintaining 225 knots airspeed.

Figure 2 shows the horizontal flight track of an actual wind box manoeuvre.

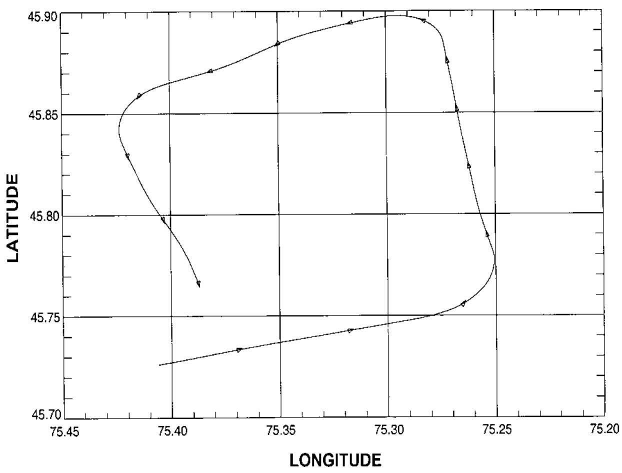

Figure 2: Wind Box Manoeuvre

The fundamental philosophy underlying the SCADS manoeuvre is to ensure adequate variations in α, β and TAS (true airspeed) for proper estimation of the associated calibration coefficients, and to ensure that the horizontal wind components are observable by varying the aircraft heading as shown in Figure 2. For the manoeuvre described above, α varied between 0° and 8° as airspeed decreased from 250 knots to 120 knots; β varied +/- 10° during the 'beta sweeps'; and TAS varied between 120 knots and 250 knots.

Reference [4] contains the equations relating the dynamic pressure and static pressure to position error corrections. The up-wash and side-wash effects were modelled to calibrate the angles of attack and sideslip measured at the nose-cone. A linear time varying wind model was used to describe the spatial wind effects. The TAS (containing the calibration coefficients) was resolved in the Earth axis and vectorially added to the wind vector, with the calibration wind coefficients, to obtain the computed ground speed. In the post-flight analysis, a Direct Search Complex Algorithm method was used to minimize the error between the inertial computed and the GPS ground speeds by iteratively modifying the air data calibration coefficients (Position Error Correction, up-wash, side-wash and wind components).

4 Flight-Test Program

The flight and ground tests were carried out between the 15th of December, 2000 and the 6th of February, 2001, covering some 1300+ individual test-points, logging approximately 92 hours of air-time or 109 hours of flight time.

The following five areas were covered by the test program with respect to the mathematical modeling:
- Aerodynamics,
- Engine dynamics,
- Flight control systems,
- Aircraft performance & handling qualities on ground, and
- Flight deck environment – level of sound, vibration and buffeting conditions.

Two main objectives of the test program were:
1. To obtain data for the development of the flight simulation mathematical model and
2. To obtain validation data to satisfy the requirements of JAR-SIM standards.

For the purposes of flight-test planning, the flight envelope of the aircraft was divided on the basis of altitude, airspeed, flap setting and aircraft weight, as follows:
- altitude (1000, 8000, 15000, 23000, 30000 feet),
- airspeed (bands placed at approximately equal angle of attack intervals),
- flap setting (0°, 14° and 35°)
- aircraft weight (the takeoff weight of the aircraft was varied between 12000 and 15000 pounds).
- centre of gravity location (195-205 inches FS)

At each of the above test conditions, the model development manoeuvres described in the next section were flown.

4.1 Model Development Test Manoeuvres

The modified 2-3-1-1 (M2311) manoeuvre was used as the primary test manoeuvre. Reference [5] provides the baseline reference for executing an M2311 type of control input. The M2311 manoeuvre provides adequate information to allow the estimation of the stability and control derivatives at a test condition and has therefore been routinely used as the test manoeuvre for the modeling of fixed- and rotary-wing aircraft.

The M2311 control input technique was developed to reduce data contamination from cross-coupled inputs and avoid excessive deviations from trim conditions. The manoeuvre starts and ends in a trim condition. During the M2311, the pilot applies alternate step inputs, in 2-3-1-1 seconds with the input size of the 3-second segment reduced to two-thirds of the magnitude of the other three segments. Secondary axis pulse control inputs are applied as necessary to prevent large deviations in the cross-axis.

Care must also be taken during the M2311 to ensure that the pilot does not generate large amplitude inputs at higher frequencies. The procedure is performed using an elevator input followed by aileron and then rudder inputs, preferably in calm conditions.

The M2311 manoeuvres were flown with the yaw damper off and with the SAS off. With the SAS off in forward flight, the aircraft remained stable during the main axis control inputs and virtually no cross-axis control inputs were required. Elevator, aileron and rudder control inputs were performed at each speed and repeated throughout the aircraft's flight envelope.

4.2 Flight Data Quality Assurance

Good data quality is vital to the success of any modelling effort; therefore, care was taken to ensure data quality, both during and after each flight. During each flight, the instrumentation suite was continuously monitored to make sure that it was functioning correctly. This same monitoring process also detected faults, as soon as they occurred, so that they could be fixed or the flight aborted.

Upon landing, flight data was transmitted remotely to playback computers via wireless data transfer, thus reducing data download time. The data was examined immediately to ensure inertial compatibility and accuracy. Any data dropouts and erroneous measurements were noted and rectified before the next flight. Finally, the flight data was archived for storage on CD-RoM. In spite of all the above precautions taken, data problems did arise during the flight-test program. One such problem and its solution are described in the following section.

4.3 Flight Path Reconstruction

A significant data problem did arise towards the end of the flight-test program. It was noticed that the plastic tubing of the air-data system had been cut accidentally by a component of the aircraft weather radar. As a result, some of the preceding flight data-sets had erroneous angles of attack and sideslip data. The airflow angle sensing system was immediately rectified and tested, to allow the flight-test program to be continued.

In order to correct the airflow angle data from the above-noted affected flights, techniques of flight path reconstruction were used. The NRC flight path reconstruction technique [5] uses either a least-squares or a global optimization process to minimize the error on the redundant measurements (e.g. pitot, static pressures, aircraft inertial states) to estimate the angles of attack and sideslip and sensor biases.

5 Aerodynamic Model Development

Upon completion of the flight-test program, the flight data calibrations were fine-tuned, corrections applied and processed DGPS data was integrated with the main data.

The parameter estimation technique described in [5] was used to extract a mathematical model of the aircraft aerodynamics, from the above data. (Fig. 3). The aerodynamic model was developed and validated in a period of 4 months, from mid-June to mid-October 2001.

Based on our experience in flight-test data collection for modeling, the availability of calibrated flight data immediately after each flight, is highly desirable. One objective of this program was to demonstrate the feasibility of immediate post-flight calibration of flight data and aerodynamic model identification. The aim was to develop a system, which will give the best aerodynamic derivatives possible in the shortest possible time. This immediate post-flight parameter estimation technique satisfied the requirement for efficient post data processing.

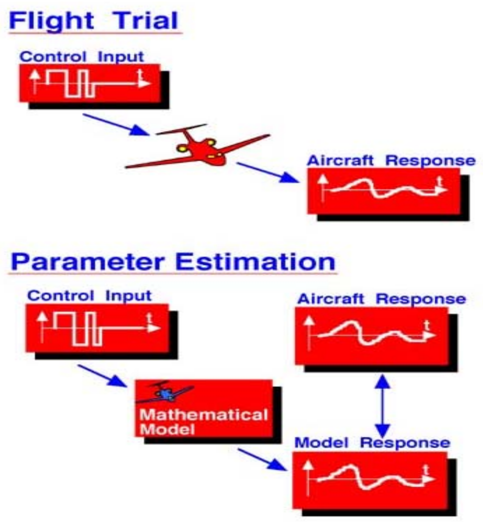

Figure 3: Aero. Model Identification Concept

By examining the results immediately after the flight, an algorithm was developed to provide immediate feedback to the pilot regarding how well the manoeuvre was performed. This activity provided confirmation of the quality of the manoeuvres, which enabled iterative modification or improvement to the manoeuvre for a subsequent flight.

In addition, minimal post flight processing is desirable, in order to shorten the overall flight-test program. However, this approach does require that all sensors be calibrated before flight, with the exception of the air data systems, which are calibrated after the first flight. The workload for the flight-test engineer and the data processing team is increased by the requirement to examine the incoming data for anomalies. A user-friendly data checking routine was developed to facilitate the data analysis process, thus allowing the flight-test engineer to easily examine the data quality.

5.1 Model Structure Formulation

All of the model development analyses presented in this paper are based on the use of the time-domain software. The decoupled linearized aircraft equations of motion are derived and used in the parameter estimation MMLE software. These equations assume a rigid body and a flat nonrotating earth. The equations are written in body axes referenced to the center of gravity. Symmetry about the XZ – plane is assumed, so I_{yz} and I_{xy} are 0.

The analysis of the aerodynamic model was based on six dimensionless coefficients for each of the rigid body degrees of freedom of the aircraft. The force coefficients (C_D, C_L, C_Y) were chosen in the wind axes reference frame and the moment coefficients (C_l,C_m,C_n) were defined at the body axes reference frame. In order to obtain the aerodynamic drag C_D, a thrust model was required. This thrust model was developed using the OEM's performance manual and was validated with flight-test data collected during this program.

The derivatives with respect to α–dot and q are usually strongly correlated and therefore were difficult to determine. The same was true for the β–dot and r derivatives, therefore the coefficients for α–dot and β –dot were set to zero. Experience has demonstrated that this seemingly arbitrary choice has no impact on simulation quality, especially for non-aerobatic aircraft.

The state-space representation of the aircraft model was applied to small perturbation manoeuvres about trim flight conditions; i.e. a linear aerodynamic model was assumed. The numerical values of the stability and control derivatives were formulated as functions of the flight conditions and the aircraft configuration.

Some of the initial stability and control derivatives which were used as starting values for the iterative processes of MMLE were derived from historical aircraft simulation results and the others were obtained using engineering judgement in defining the aircraft response.

Traditionally, the parameters that are estimated with the least confidence are left out of the model structure in order to produce a robust mathematical model. Recent experience [6] has, however, shown that the even such parameters - defined here as derivatives with a CR bound value greater than 20% or correlation greater than 95% - could also be retained in the model structure, without adversely affecting the model robustness. Such derivatives should be averaged and their values nominally fixed at the mean value, at a later stage (curve-fit phase). This strategy was fully exploited and it greatly reduced the MMLE processing time. In the King Air modeling program, pre-processing software was used to produce the input files and the trim conditions, for MMLE. Next, the MMLE program was executed to generate the stability and control derivatives, for the full flight envelope of the King Air aircraft, in less than an hour's time.

5.2 Global Model Development Process

The point-identification of stability and control derivatives from small perturbation manoeuvres lacks Mach, thrust and flap change effects. To develop a global mathematical model of the King Air 350, two types of identification were used to construct a comprehensive aerodynamic model in an iterative process. These two types are explained below.

Type-I identification is the result of the point-identification of stability and control derivatives - from small perturbation manoeuvres around a trim condition, covering various aircraft configurations and flight conditions. In this type, the results are combined into functions. In general, these functions are formulated as a function of Mach, angles of attack and sideslip, centre of gravity and coefficient of thrust.

By combining the point-identification results, an aerodynamic model valid over a broader range of the flight envelope is derived. The global model is formulated by incorporating linear and non-linear functions of angles of attack and sideslip, Mach number, and coefficient of thrust. This process is repeated for all flap settings. For the King Air, a set of equations was developed for each of the three flap positions. The global model interpolates within flap settings to compute aerodynamic forces and moments.

Type-II identification is a regression technique which minimizes the force and moment residual errors resulting from the Type-I force and moment coefficients. The following strategies were used to estimate the cross-axis stability and control derivatives, landing gear dynamics, stall, one engine inoperative (OEI) dynamics, ground effects and other related effects, for the King Air 350:

1. Develop a complete model, based on the 2311 manoeuvres and compute the residual forces and moments for some of the extended manoeuvres.
2. Use the existing model and manoeuvres such as OEI to identify differential thrust effects.
3. Use multiple regression to identify the effects of stall dynamics, including non-linear effects.
4. Use flight path reconstruction to correct the measured angles of attack and sideslip for ground effects, leading to a ground effects model.

6 Results

6.1 Summary of model validation process

As mentioned earlier, each derivative was formulated as a function of aircraft configuration and flight conditions, in order to form a global model. This formulation was then validated by comparison to the MMLE determined derivatives. Figure 4 shows the development of Cn_p - yawing moment due to roll rate coefficient - as a function of alpha.

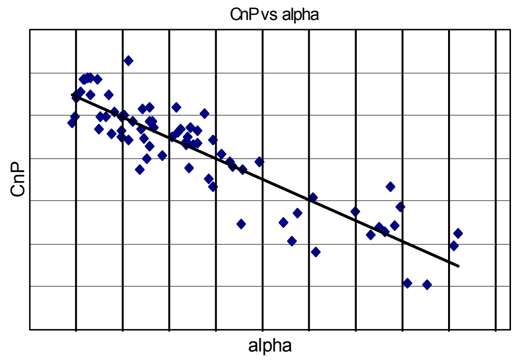

Figure 4: Cnp, as a function of Alpha

Figure 5 shows a validation of Cn_p (Cn_{pc} is the computed value and Cn_{pm} is the MMLE-derived value). The 45-degree slope of the line that fits the data implies a good agreement between the two quantities Cn_{pc} and Cn_{pm}.

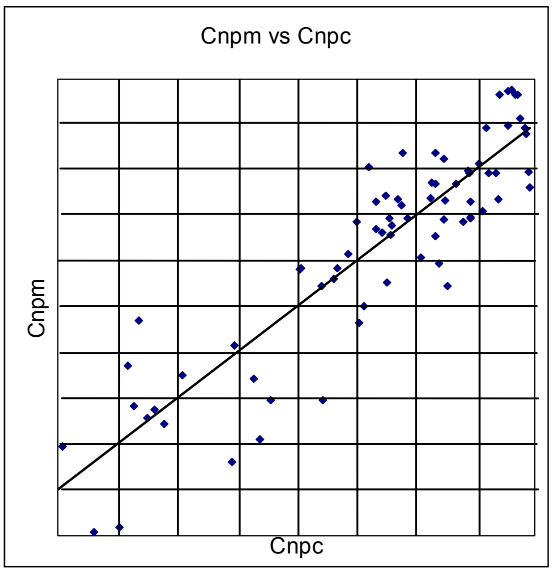

Figure 5: Cnp function, MMLE Vs Computed

The global model error in the three components of forces and moments was estimated using the 2311 and ATG trim flight data. The error statistics derived from both the force coefficients (C_D, C_L, C_Y) and moment coefficients (C_l, C_m, C_n) shows the robustness of the model for the full envelope of flight data. Model error was measured as either the equivalent control input required to compensate for the error, or the angle of attack or sideslip spread necessary to perfectly trim the simulated aircraft. All model error statistics were nominally within the tolerance of +/- 1 degree for the controls and +/- 0.5 degrees for the attitudes.

A set of force and moment equations was developed for each flap setting. This set of equations is called the “Derivative-model”. The Type-I and Type-II identification of the rigid body aerodynamics yields a set of derivatives for each flap setting that are combined into a single model by incorporating a linear interpolation, dependant on flap settings. The sequence followed in the proof-of-match (PoM) process was to match the 2311 manoeuvres; then the single axis control manoeuvres followed by the high angle of attack, engine dynamics, takeoff and landing. Figure 6 depicts the match of a 2311 manoeuvre, which was used to validate the set up of the proof –of-match software and the validity of the preliminary mathematical model.

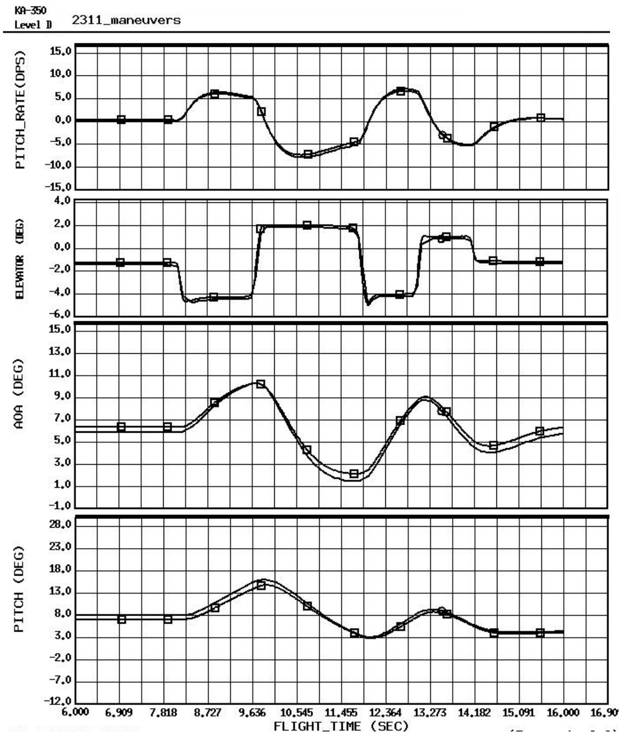

Figure 6: 2311 manoeuvre PoM

After the validation of the PoM software and the model, the next step was to enter and validate the simple single axis control and the longitudinal part of the mathematical model. Figure 7 shows a short period manoeuvre.

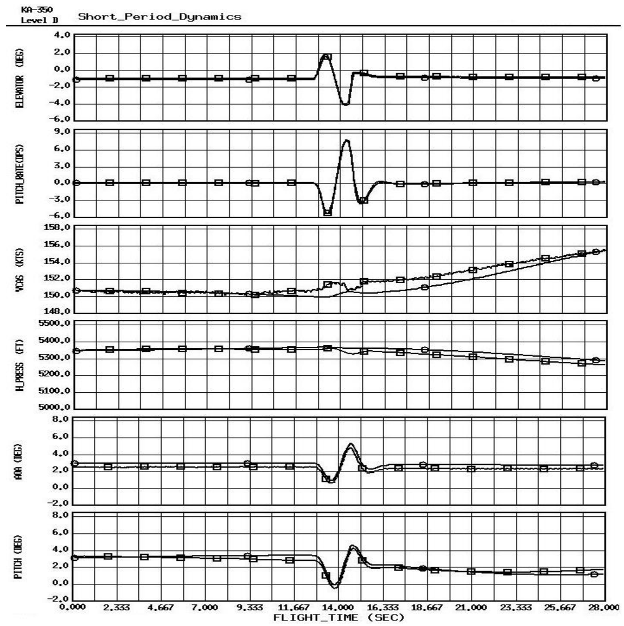

Figure 7: Short Period PoM

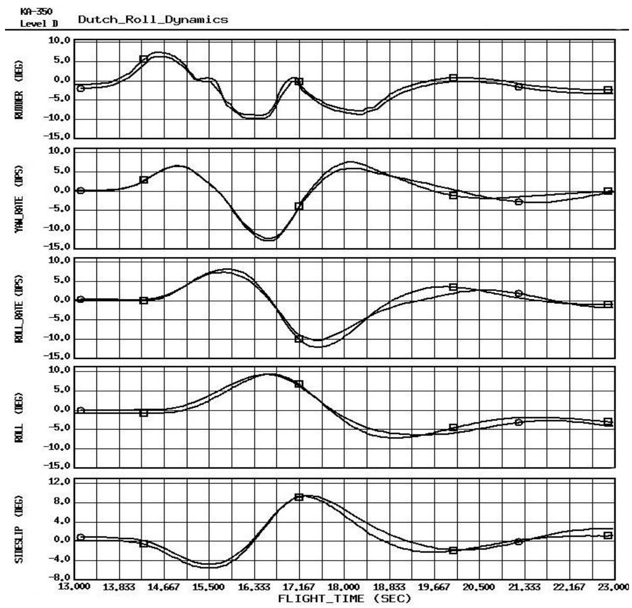

Figure 8: Dutch Roll PoM

Cross-axis dynamics are not usually significant for general aviation aircraft and are therefore seldom included in their modeling. However, in this work, cross derivatives were developed and included, where required, to improve the model.

The cross-coupled dynamics of the Dutch roll manoeuvre were identified by studying the pitching moment dynamics due to sideslip, using the type-II identification process, described previously. Figure 8 shows the Dutch roll manoeuvre that was used to validate the roll and yaw coupling dynamics.

Next, both the longitudinal and lateral dynamics were refined. The trim tab dynamics were added to complete the control surface models. To extend the flight envelope and estimate the aerodynamics of the aircraft in extreme conditions, once again, type-II identification was used. Figure 9 shows the proof-of-match of a stall case, representative of the stall manoeuvres used to extend the global model to high angles of attack.

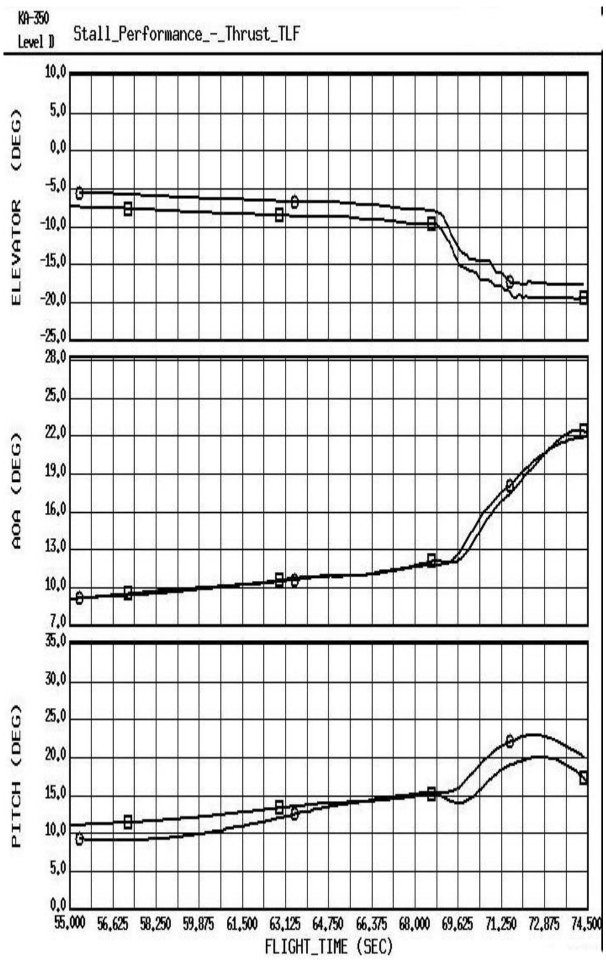

Figure 9: High Alpha / Stall PoM

A ground effect model was developed for take off and landing cases. The landing manoeuvres were found to be the most difficult ones to conduct proof-of-match. The tolerance on altitude for most cases is ± 50 feet but in a landing case the height above ground must be matched more strictly to achieve ground contact at the correct time (Fig. 10).

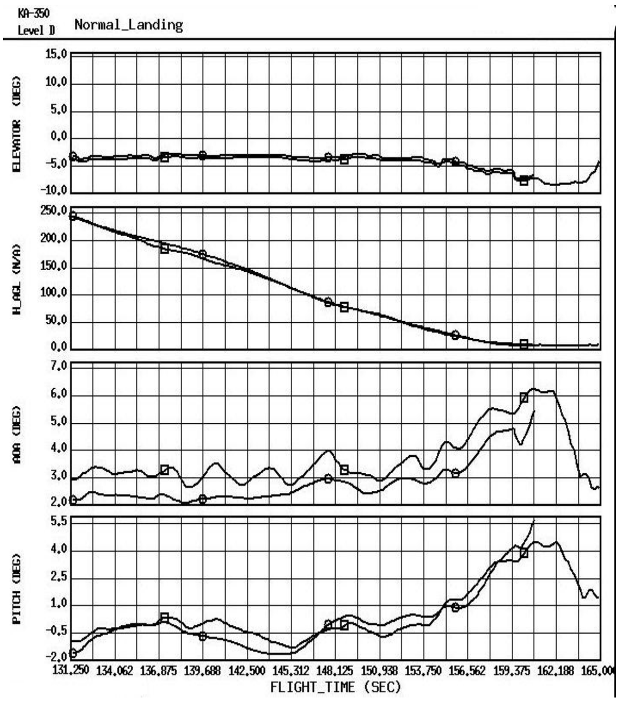

Figure 10: Normal Landing PoM

At this stage, the simulator mathematical model was deemed to be mature and was therefore frozen. Following the tradition in flight simulator development, the equation based Derivative model was converted to Table-Look-Up model. In this form, the Table-Look-Up model consisted of over 110 tables. The advantage of the Table-Look-Up Model is that it continuously interpolates the forces and moments, thus eliminating the discontinuities that may be present in a single Derivative-model, or in adjoining Derivative models.

6.2 Typical Limitations of Modeling Process

The derivatives were identified for each flap position and a separate aerodynamic model was formulated for each flap setting. The simulation of flap change dynamics was, therefore, only possible after all the parameters had been identified.

The resulting models required different trim offsets for each flap setting. As a result, during the simulation of a flap change manoeuver, it was not possible to fulfill the trim requirements at the start and the end of the flap change simultaneously. This was due to the model differences between the two flap settings and was resolved by formulating the derivatives using the same equation form and striking a compromise between the aerodynamic trim offsets of each flap setting. Type-II identification was applied to obtain a satisfactory match.

7 Conclusions

The following summarises the main conclusions and lessons learned while using the NRC Types I and II identification techniques to develop and validate an FAA Level-D flight simulator model for a Raytheon King Air 350 aircraft:

1. An aerodynamic mathematical model for an FAA Level-D, King Air 350 simulator, was developed in four months;
2. The SCADS technique was effective in determining position error corrections and calibration of airflow angles. Flight path reconstruction provided excellent estimates of angles of attack and sideslip.
3. The point-identification technique proved effective in formulating the Global mathematical model for flight simulator work; yet it posed some inherent practical problems (e.g. flap change dynamics).
4. The Type-II regression identification technique extracts the effects of cross-axis coupled derivatives, the effects of landing gear, stall, single engine and ground effect with high fidelity.

7.1 Future Work

Data quality is the highest priority in developing a flight simulator efficiently. Ongoing development will provide higher quality sensors and less intrusive installations than the current instrumentation system, to enhance time-sensitive flight-test applications. For example, a recent FRL development is an air-data 'nose-mask' sensor, to measure the airflow angles, alpha and beta. This self-contained and externally mounted smart sensor transmits data to the instrumentation network via a wireless link, reducing installation time as compared to currently used airflow angle sensor systems.

Software has been developed for in-flight data evaluation that checks for data dropouts and data range based on defined min-max tolerance values. The programs will be extended to include more advanced data compatibility checks. The focus of future work is to develop a system capable of performing near real-time identification of the aircraft stability and control derivatives. It is clear that for real-time execution of in-flight air data systems calibration and the parameter estimation program [7], all the data transfer processes need to be streamlined into a single process incorporating real-time plotting software to provide a graphical display of the manoeuvre being performed.

A future step will be to obtain the global mathematical model of the aircraft, while still in flight. In such a scenario, the same model could be used by the proof-of-match process, immediately following any specific manoeuvre, to validate the model using the FAA-specified "Qualification Test Guide" (QTG) tolerances.

References

[1] Anon. *ACJ-JAR-SIM 002, JAR-Sim standards for the qualification of aeroplane flight simulators.* JAA, 1996.

[2] Anon. *Flight simulator design & performance data requirements*. International Air Transport Association, 5th edition, 1996.

[3] Anon. *Airplane simulator qualification advisory circular, AC120-40B*. US Department of Transportation, FAA, 1991.

[4] Hui K, Srinivasan R and Baillie S. Simultaneous calibration of aircraft position error and airflow angles using differential GPS. *CAS Journal*, Vol. 42, No. 4, 1996.

[5] Hui K, Baillie S and deLeeuw J. Application of parameter estimation to identify the aerodynamic derivatives of the Dash 8 series 100. *Proc CASI Flight Test Symposium*, 1992.

[6] Hui K, Ricciardi J, Ellis K and Tuomey D. Beechjet flight-test data gathering and level-D simulator aerodynamic mathematical model development. *Proc AIAA Atmospheric Flight Mechanics Conf*, Montreal, AIAA 2001-4012.

[7] Hui K, Collins D, Leach B, Srinivasan R and Swail C. Proof of concept of an in-flight aerodynamic model identification technique. *Proc. AIAA Atmospheric Flight Mechanics Conference*, Denver, Colorado, August 2000.