CESSNA CITATION CJ1 FLIGHT-TEST DATA GATHERING AND LEVEL-C SIMULATOR MODEL DEVELOPMENT

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Abstract

The National Research Council of Canada's Institute for Aerospace Research (NRC Aerospace) Flight Research Laboratory (FRL) was contracted by Mechtronix Systems Incorporated (MSI), Montreal, Canada, to conduct flight-test data gathering and simulator model development for the Cessna Citation CJ1 business aircraft. The data collected and the models developed conformed to the FAA Advisory Circular 120-40B Level C Airplane Simulator Qualification.

NRC Aerospace created the complete simulator model from end-to-end; developing aerodynamic, engine performance, engine gauge, reversible flight control, and ground dynamics models following the collection of flight-test data. The engine performance modelling was unique since the novel NRC in-flight propulsion identification technique (IPSI) was used to develop the model solely using flight data. Engine gauge, reversible flight control and ground dynamics models were added to the existing NRC aerodynamic modelling capability to form an enhanced simulation environment and were qualified to Level-C standards.

This program has clearly demonstrated major improvements in modelling efficiency and a reduction in time to six months required to develop an end-to-end simulator mathematical model for a fixed wing aircraft using flight-test data.

Fig. 1: The Cessna Citation CJ1 Test Aircraft

1 Overview

Mechtronix Systems Incorporated (MSI), Montreal, Canada, and Canada's National Research Council (NRC Aerospace) Institute for Aerospace Research, Flight Research Laboratory (FRL) embarked on a joint program to develop a high fidelity simulator model of the Cessna Citation CJ1 aircraft (Fig. 1) from flight-test data. The data was collected for the purpose of building a Full Flight Simulator (FFS) to the standards of the FAA Advisory Circular 120-40B [1].

The flight-test data suite for the Cessna Citation CJ1 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.). Flight tests were conducted, logging approximately 75 hours of flight time, to collect simulator-modelling data. Approximately 921 test points were executed over the course of the program. The flight-test program test matrix was optimized to investigate the effect of changes in aircraft altitude, airspeed or Mach number, weight, Centre of Gravity (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, and major aircraft sub-systems and aircraft sounds were also investigated.

The aerodynamic model was derived using the proven NRC maximum likelihood estimation (MMLE) time-domain parameter estimation process [2]. The stability and control derivatives that resulted from this analysis were formulated as functions of flight condition and configuration to form the global aerodynamic mathematical model. Also, the model was expanded to cover the entire flight envelope using residual error analysis techniques.

The CJ1 engine performance model was developed through collaboration between NRC Aerospace's Flight Research Laboratory (FRL) and Gas Turbine Laboratory (GTL) using the In-Flight Propulsion Identification Technique (IPSI). The cost of this method was the addition of flight test manoeuvres to the flight test plan, with the advantage being that the entire thrust model was derived from the collected flight test data. Hence the engine model was no longer subject to the availability and cost of an engine cycle deck. An engine gauge model, relating the engine gauge readings to the engine state, was also developed.

A reversible flight control model was developed using multiple-parameter regression to capture the mechanical characteristics of the flight control system and the aerodynamic hinge moments as functions of pilot control input and aircraft states.

The ground dynamics model was formulated in collaboration with Carleton University. The physical model formulation consisted of oleos and tires modelled as spring damper systems, a physical model of the nose wheel steering mechanism, and included tire forces required for rolling resistance, runway friction, braking, and nose-wheel steering. All of the parameters were identified from the required FFS validation manoeuvres, i.e. no additional manoeuvres were required in the flight test plan.

The primary objectives of this paper are to discuss:

1. Flight-test data collection and air data calibration using DGPS;
2. The efficient development of the full flight simulator mathematical models, i.e. aerodynamic, engine, flight controls and ground reaction models; and
3. The techniques of model validation performed in the NRC MATLAB/Simulink® environment.

2 Aircraft Description

The CJ1 is a six/seven seat light business jet, powered by two Williams-Rolls FJ44-1A turbofan engines, each with 1900 pounds of static thrust at sea level. The aircraft has a certified ceiling of 41,000 feet, a maximum cruising speed of 381 KIAS, and has a maximum takeoff weight of 10,600 pounds. It has a wing span of 46 feet 4.56 inches, and overall length of 42 feet 7 inches, and an overall height of 13 feet 9.25 inches [3]. It has a wing area of 240 square feet and the wing aspect ratio is 9:1.

3 Aircraft Instrumentation

The FRL instrumentation system was designed and built around the NRC-developed 'PUMA' (Precise μ(micro)-processor Measurement Array) distributed data acquisition and recording system operating at a 100Hz sample rate, and a commercial off-the-shelf GPS system. An eight-week effort was initiated to instrument and calibrate over 100 channels of data parameters. The flight test data suite for the CJ1 included standard fuselage response parameters (such as [x y z] position, angular attitude, linear and angular rates, linear and angular accelerations), differential GPS, engine parameters, pilot control forces and positions, control surface positions, landing gear oleo compression, as well as numerous discrete parameters. In order to eliminate the skew error associated with sampling parameter data consecutively, all of the required parameters were sampled concurrently in the central processing unit. Vibration at the pilot seat rail location was sampled at 1000 Hz in order to provide high fidelity vibration data to be used to develop the vibration models for different modes of flight such as takeoff/landing, flight in turbulence, and stall conditions.

A spare aircraft radome was modified by the addition of sensors designed to measure the airflow angles (angles of attack and sideslip) by the use of a flush air data system. The Simultaneous Calibration of Air Data Systems (SCADS) technique [4], developed at FRL, was used to calibrate these radome airflow angle sensors. 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.

Crucial to the efficiency of the flight test program was the ability to monitor the collected data in real time to identify any instrumentation issues as they arose. The Flight Test Engineer observed all of the data in flight via Ethernet in real time. A customized Labview display performed automatic data checking in addition to presenting time history plots, dials, and gauges.

4.1 Flight-Test Program

The flight and ground tests were carried out between 21 July and 27 August, 2005. The aircraft was on site at FRL for 14 weeks.

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 FAA AC 120-40B standards.

Five areas were covered by the test program with respect to the mathematical modelling. These five areas were 1) aerodynamics, 2) engine dynamics, 3) flight control systems, 4) aircraft performance and handling qualities on the ground, and 5) flight deck environment, which includes level of sound, vibration and buffeting conditions.

For the purposes of flight test planning, the flight envelope of the aircraft was covered as follows:

1. Altitude bands (5k, 10k, 25k and 35k feet);
2. Airspeed bands chosen at approximately equal angle of attack intervals;
3. Flap settings (0°, 15° and 35°);
4. Landing gear position;
5. Speed brake settings;
6. Aircraft weight (the takeoff weight of the aircraft was varied between 8,000 and 10,500 pounds); and
7. CG location varied between forward and aft limits (240 to 249 inches FS).

4.2 Model Development Test Manoeuvres

The aerodynamic model was developed using modified 2311 (M2311) control inputs as the primary model development test manoeuvre. Reference 4 provides the baseline reference for executing an M2311 type of control input (alternating steps of 2-3-1-1 second duration). At each test point, elevator, aileron and rudder M2311 control inputs were performed with the yaw damper (YD) off.

The manoeuvres required for the engine performance model development included level acceleration/deceleration, longitudinal manoeuvring stability, and roller coaster manoeuvres at a range of altitudes covering the entire CJ1 flight envelope.

The remaining model development used the validation manoeuvres outlined in the FAA AC 120-40B.

5 Full Flight Simulator Model Development

The model development sequence, depicted in Fig. 2, was used to develop and validate the full flight simulator mathematical models.

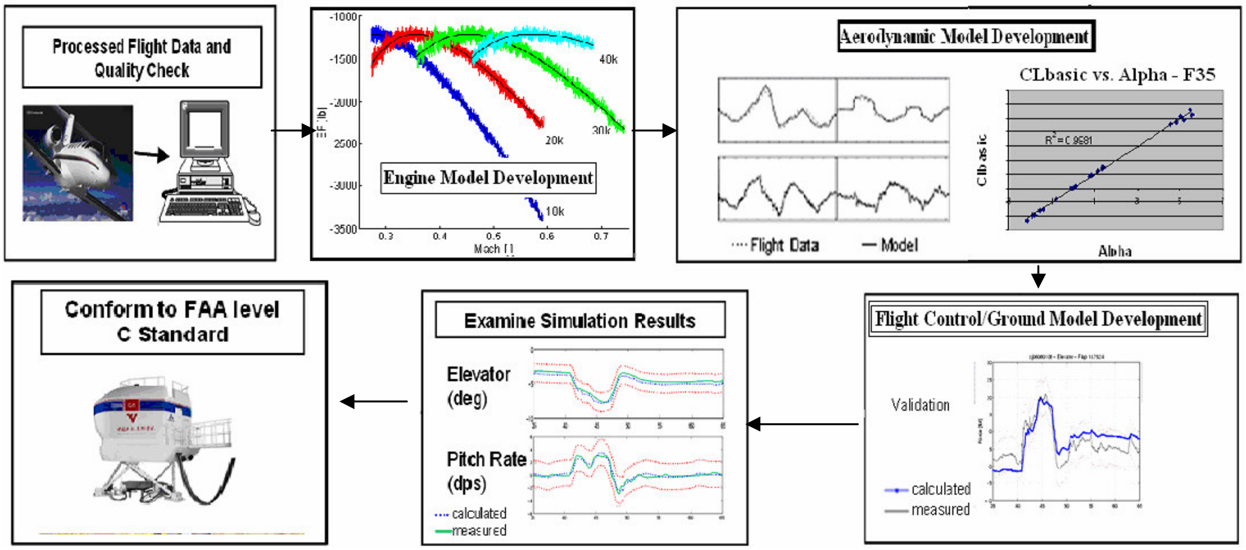

Fig. 2: End-to-End model development chart

5.1 Aerodynamic Model Development

The aerodynamic model consisted of coefficients for each of the rigid body degrees of freedom of the aircraft [5] [6]. The force coefficients (C_D, C_L, C_Y) were computed in the wind axes reference frame and the moment coefficients (C_l,C_m,C_n) were defined in the body axes reference frame. In order to obtain the aerodynamic drag function C_D, a thrust model was required. This thrust model was developed using NRC's IPSI technique with flight-test data collected during the program. IPSI is described in more detail in section 5.2. The following steps best summarize the aerodynamic model development approach employed on the CJ1 data:

1. Development of trim point stability and control derivatives – A parameter estimation process used a modified maximum likelihood estimator (MMLE) as the core of the optimization algorithm to analyze the aircraft dynamic responses of M2311 manoeuvres. This analysis produced the point-identification stability and control derivatives which represented the aircraft dynamics of small perturbation manoeuvres around a trim condition;
2. Curve fit of trim point stability and control derivatives - The stability and control derivatives that resulted from analysis of the M2311 manoeuvres were formulated as functions of parameters including angle of attack, sideslip angle, Mach Number, coefficient of thrust, landing gear position, CG, and flap deflection and speed brake position to form the initial aerodynamic mathematical model of the aircraft covering various aircraft configurations and flight conditions;
3. Trim data analysis –flight data was analyzed to compute the trim terms using the steady-state flight segments where the aircraft was in-trim. The trim data was also used to estimate the error statistics for the angles of attack and sideslip and the trim control positions to ensure the model accuracy in-trim;
4. Residual analysis – This analysis was used to extend the aerodynamic model over the entire flight envelope. It is a regression technique which minimized the difference between the forces and moments required to reproduce the measured aircraft response and the predicted forces and moments of the linear aerodynamic mathematical model. The final aerodynamic mathematical model is called the global model of the aircraft; and

5. Model validation – The aerodynamic mathematical model resulting from Step 4 was validated using the FAA AC 120-40B standards.

5.2 Engine Performance Model Development

The CJ1 engine model was developed through collaboration between GTL and FRL, using the NRC's IPSI technique (Fig.3). The thrust model consisted of functional relationships used to estimate net thrust from parameters derived at ambient conditions (Mach number, pressure altitude, ambient (static) pressure and temperature), and fan rotor speed corrected for total temperature. Flight test data was processed with the IPSI algorithm to predict net thrust and develop/validate the engine model. Installation corrections were estimated for electrical power and bleed extraction. Estimates were also developed for drag due to windmilling and locked rotors.

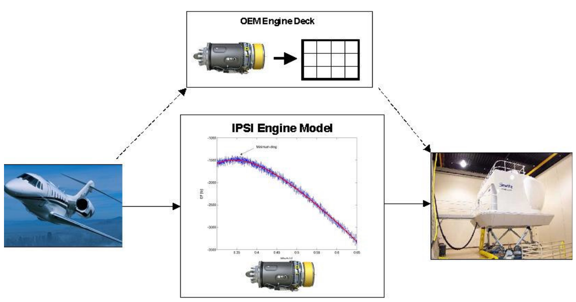

Fig. 3: IPSI technique

The IPSI procedure followed the steps outlined below:

1. Data collection using dedicated, high-speed computing hardware used to extract and process flight data from the test aircraft;
2. Data checking to ensure quality;
3. Estimation of excess force for the computation of the aircraft lift curve and drag polar in order to identify the aircraft performance model;
4. Standardization of the aircraft weight and load factor to obtain a consistent model;
5. Determination of the minimum drag Mach Number for engine model flight performance
6. Determination of analytical ram drag; and
7. Development and validation of the final thrust model.

Moreover, other manoeuvres such as in-air and on-ground engine start-ups and shutdowns, and engine accelerations and decelerations were also conducted for the development/testing of the engine model and the gauge model described in section 5.3. In the final step, the reduced dataset was used to produce a thrust lookup table, corrected to standard conditions. Further details about the IPSI technique can be found in Reference 7.

5.3 Engine Gauge Model Development

The engine gauge model was composed of a set of equations which related the engine gauge readings to the engine state. The development of the CJ1 engine gauge model consisted of two basic components:

1. The steady state model and
2. The transient model.

The steady state gauge model was developed from the flight test data where engine parameters, and aircraft parameters, were in steady state. True airspeed, body rates, and engine parameters such as turbine speed, and fuel flow rate, were used to identify steady state periods. Data from dynamic engine cases, such as engine accelerations and decelerations, was used to develop the transient gauge model. When required, time constant, τ, and time delay, were modelled for the engine parameters when required. The baseline model was augmented with secondary models for more advanced scenarios such as engine bleeds, engine start-ups, etc.

5.4 Flight Controls Model Development

The flight control system used on the CJ1 is classified as a "reversible" system, as aerodynamic forces caused by airflow over the control surfaces are re-transmitted through the mechanical system and cause the pilot controls to move [8].

The flight control model that was developed predicted the control surface positions and pilot control forces. Multiple parameter regression was used to derive these quantities as functions of pilot control input and aircraft state thus capturing the mechanical characteristics of the flight control system and the aerodynamic hinge moments where control forces were concerned. The data used for the regression was selected from the M2311 and the FAA AC 120-40B manoeuvres flown.

Models were developed for the full envelope of aircraft operation including up-and-away flight, takeoff, landing and static ground operation. Models were also constructed for special conditions such as engine inoperative flight where the differences in resulting aerodynamic hinge moments required separate regression equations. Particular care was taken to ensure a smooth transition between the various force and position relationships.

5.5 Ground Dynamics Model Development

The ground dynamics model for the CJ1 was developed in collaboration with Carleton University and consisted of parameterized physical models. The ground dynamics model was identified and validated using the standard FAA taxi, takeoff, and landing manoeuvres.

The oleo characteristics were derived first by applying the residual analysis previously described in the context of aerodynamic modelling. The residual forces and moments were computed for takeoff and landing flight test data and attributed to the ground dynamics model, or more specifically the oleo characteristics. Next, the ground deceleration flight test data was analysed. The rolling resistance and brake forces were determined and validated, also using the residual analysis. The lateral force model and the identification of the physical properties of the nose wheel steering mechanism were identified in the analysis of the minimum radius turn and turn rate versus nose wheel steering data. Finally, the tire side force was formulated as a function of the slip angle (the angle between the instantaneous aircraft velocity vector and the tire direction). The core model was then empirically adjusted such that all of the requirements for a Level C Full Flight Simulator were met.

6 Results

NRC Aerospace's MATLAB/SIMULINK proof-of-match (PoM) environment was used to develop the flight simulator model which was seamlessly transferred to the flight simulator. Section 6 outlines the results related to the CJ1 model development process for the Level C Full Flight Simulator.

6.1 Aerodynamic Model Validation

The formulation of the aerodynamic model as functions of flight condition and configuration was validated by comparison to the MMLE determined derivatives. Fig. 4 shows an example of the development of the basic lift as a function of alpha.

The global model error in the three components of forces and moments was estimated using the M2311 and 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) showed the robustness of the model for the full envelope of flight data. The model error was measured as the equivalent control input, 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 +/- 0.5 degree for the controls and +/- 0.1 degree of airflow angles.

The sequence followed in the PoM process was to validate the M2311 manoeuvres; then match the single axis control manoeuvres followed by the longitudinal and lateral dynamic modes, high angle of attack, engine dynamics, takeoff and landing.

Fig. 5 depicts the match of a M2311 manoeuvre, which was used to validate the set up of the NRC MATLAB/SIMULINK PoM software and the preliminary mathematical model. For the PoM plots, the outermost dotted lines refer to the tolerance imposed by Level C Full Flight Simulator requirements. Solid lines correspond to the measured data and dashed lines correspond to the simulator model Proof-of-Match where x-axis represents time in seconds.

The phugoid test, depicted in Fig. 6 proved the longitudinal aerodynamic model accurately represented the aircraft.

Most cross-axis dynamics are not usually significant for general aviation aircraft and are therefore seldom included in their modelling. However, in this work, some cross derivatives were developed and included, where required, to improve the model. The cross-coupled dynamics of the Dutch roll manoeuvre (where the sideslip oscillation is dominant) were identified by studying the pitching moment dynamics due to sideslip, using the residual analysis process, described previously. Fig. 7 shows the Dutch roll manoeuvre that was used to validate the roll and yaw coupling dynamics.

To extend the flight envelope and estimate the aerodynamics of the aircraft in extreme conditions, once again, residual analysis was used. The trim tab derivatives were added to complete the control surface models. Also, a ground effect model was developed for take-off and landing cases using runway fly-bys at different heights above ground.

The landing manoeuvres were found to be the most difficult cases to match. The tolerance on altitude for most cases was ± 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. 8). Also, wind shear near the ground affected these cases making the matches difficult. The measured control inputs contain high frequency pilot inputs in response to real world wind conditions which could not be reproduced in the simulation environment. A proportional-derivative controller was used to fine tune the control inputs within 0.25 degrees (significantly below the FAA allowed limits) in order to account for these effects. The cases were matched with careful refinement of the ground effect model using the takeoffs and landings.

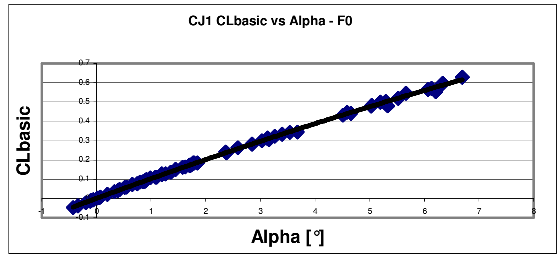

Fig. 4: CLbasic as a function of alpha

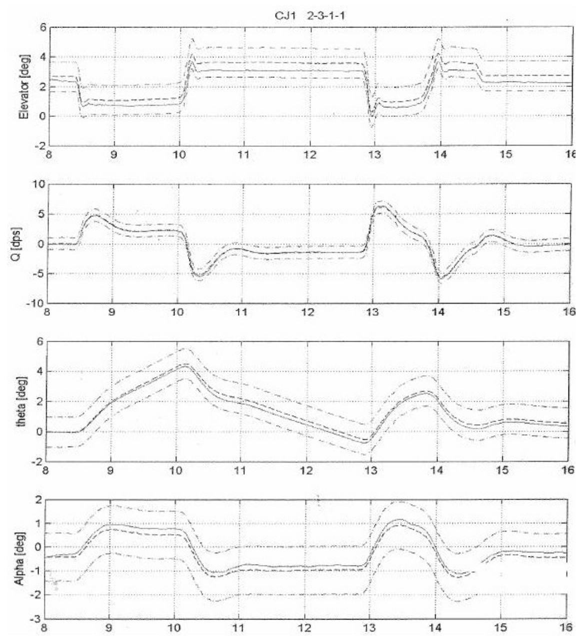

Fig. 5: 2311 PoM

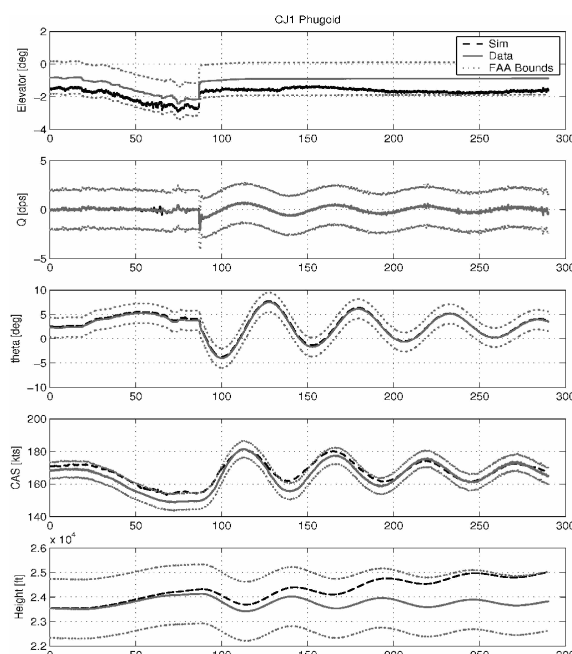

Fig. 6: Phugoid PoM

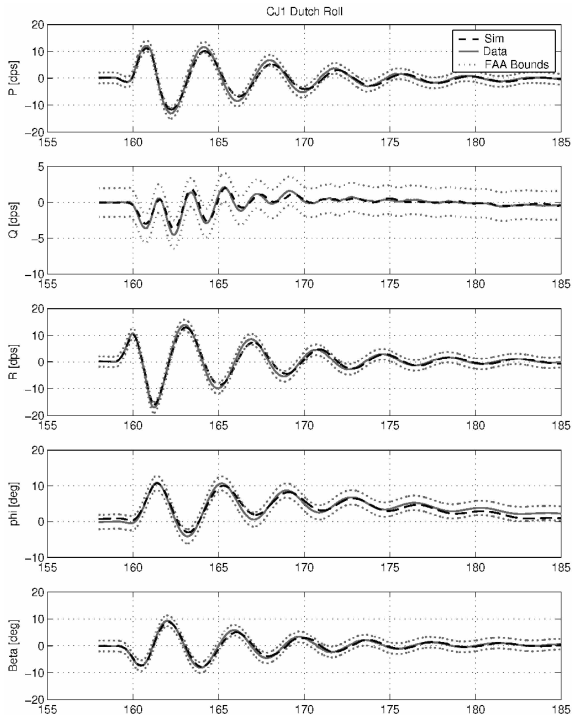

Fig. 7: Dutch roll PoM

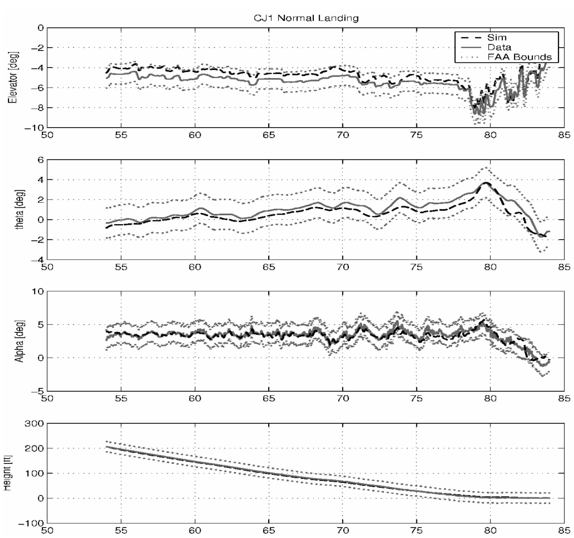

Fig. 8: Normal landing PoM

6.2 Engine Performance and Engine Gauge Model Validation

The engine thrust model was used to develop the aerodynamic drag model and the combined aerodynamic/engine models were validated for all Qualified Test Guide (QTG) tests matched to the Level-C simulator standard. Fig. 9 is an example acceleration manoeuvre match.

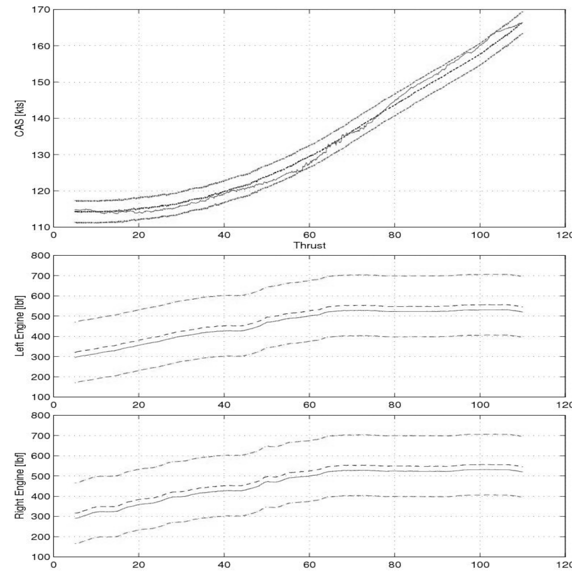

Fig. 9: Acceleration engine thrust

6.3 Flight Controls Model Validation

Many of the QTG tests had aerodynamic as well as flight control tolerance requirements. Fig. 10 shows a match of the elevator position and column force for a stall manoeuvre that has a required tolerance of 1 degree in position and 5 lbs in force in the QTG. The models were within tolerance in Fig. 10 up to the required g-break at about 93 seconds.

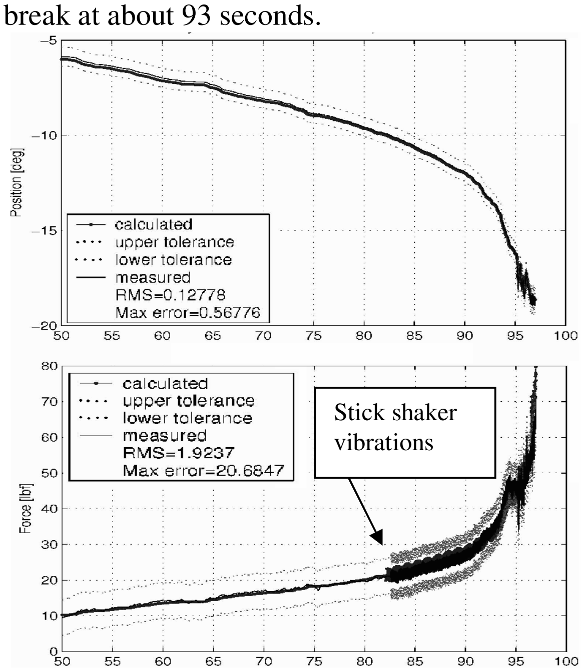

Fig. 10: Elevator position and column force match

6.4 Ground Dynamics Model Validation

The ground dynamics model parameters were identified in the following order:

1. Oleo stiffness and damping determined using residual analysis on landing manoeuvres;
2. Rolling resistance, drag as a function of flap setting, forces due to thrust attenuation, and braking forces were developed using residual analysis. Fig. 11 shows a match of these components of the ground dynamics model versus flight data runway position after a landing;
3. Nose wheel steering mechanism (bungee characteristics) was modelled (See Fig. 12); and
4. Tire side forces were formulated as a function of slip angle to match minimum radius turn and turn rate versus nose wheel steering tests (See Fig. 13).

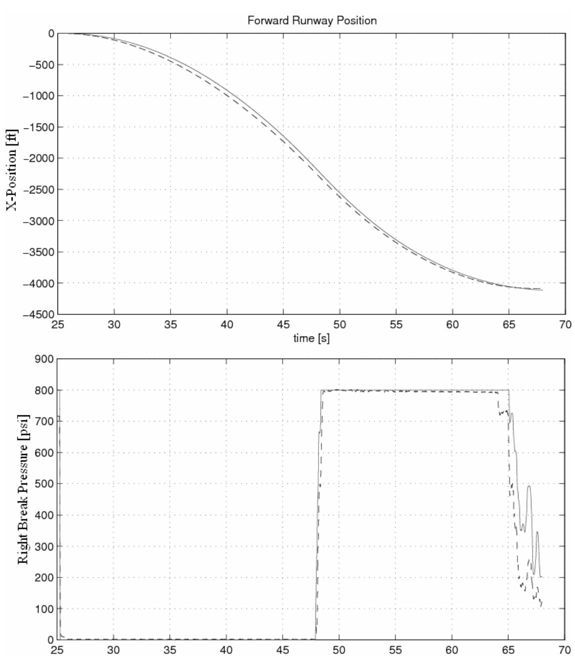

Fig. 11: Stopping

The ground dynamics model parameters were identified primarily using residual error analysis. For example, the side force that resulted from the bungee that centred the nose wheel was identified in turn rate versus nose wheel steering manoeuvres as shown in Fig. 12.

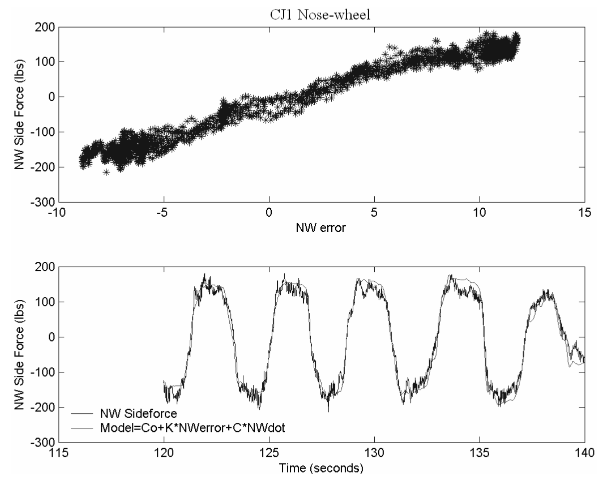

Fig. 12: Nose-wheel bungee force match

Using the bungee characteristics derived above with the tire side forces identified, the steering tests were also matched. Fig. 13 shows a good match of the aircraft yaw rate vs. nose-wheel steering using the bungee forces for the QTG rate of turn vs. nose-wheel steering angle test.

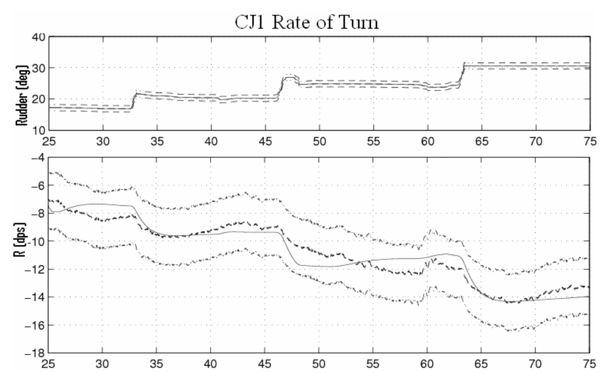

Fig. 13: CJ1 rate of turn vs. nose-wheel steering angle

7 The Final Table-Look-Up Model

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 a 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 was that it continuously interpolated the forces and moments, thus eliminating the discontinuities that may be present in the models.

8 Conclusions

This instrumentation and flight test program took 14 weeks to complete. The end-to-end Level-C flight simulator model was developed in 6 months after the completion of the flight test.

The parameter estimation tool, MMLE, was used to analyze over 100 - M2311 test points and generate the initial aerodynamic stability and control derivative model. The trim-point identification technique and residual analysis regression was used to extend the validity of the global model to "corners" of the tested aircraft envelope, by including the effects of cross-axis coupling, landing gear, stall, single-engine and ground-effect.

The engine performance model was derived using the NRC IPSI technique and validated using flight data. Static and transient engine gauge models were developed as well as engine bleeds and models for engine start and shutdown.

The ground dynamics model was derived and validated using only the required FFS validation manoeuvres. The reversible flight controls model was also derived from flight data to calculate the control surface positions and forces.

9 Future Work

NRC Aerospace is currently working on near real-time aerodynamic modelling [9] in order to substantially shorten the time it takes to develop simulator models. This includes the extension of the IPSI technique to propeller driven aircraft, streamlining flight control and ground dynamics models, and further automating aerodynamic model development. Other applications of this technique include aircraft health monitoring systems as well as flight control adaptation due to aircraft damage or malfunction, and rapid aerodynamic model identification during the prototyping stage of aircraft development.

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