Flight Validation and Update of LCA TEJAS Aerodynamic Database using System Identification Techniques

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ABSTRACT

For a high-performance aircraft, an accurate aerodynamic model is required for various applications such as flight envelope expansion, high fidelity ground-based simulators and control laws design. Validation and update of the aerodynamic database of Tejas aircraft were carried out using system Identification techniques applied to flight test data. An incremental model update approach, based on aerodynamic coefficient matching, was used to update the aerodynamic database towards the Final Operational Clearance of LCA Tejas. The updated aerodynamic database was validated by matching the nonlinear simulation predictions with the flight measured responses. This paper highlights the critical issues encountered during the database validation and update process through System Identification techniques, such as optimal control input design for flight testing at higher angles-of-attack, sensor characterisation in the presence of process noise, discrepancies in the baseline aerodynamic model structure, real-time monitoring for safe envelope expansion and store grouping techniques to reduce the flight test effort.

Keywords: System Identification, Flight Testing, Aerodynamic Database, Parameter Estimation.

1. INTRODUCTION

Indian aerospace research laboratories and industries have received a significant technological boost with the LCA Tejas aircraft programme. A number of indigenous state-of-the-art technologies have been developed viz., digital flight control system, avionics, systems' testing methodologies, hardware-in-the-loop rig development, etc. Aerodynamic model validation and update is one among them and an essential part of any aircraft design and development program. An accurate mathematical model is required if it is to be used for applications such as flight envelope expansion, high fidelity simulators and tuning of control algorithm gains. In the past few years, significant efforts have been expended in this area that has led to the safe and systematic flight envelope expansion of all variants of LCA Tejas. Analysis of data from several flight tests led LCA Tejas to attain its Final Operational Clearance (FOC) Type-Certification in February 2019.

The aerodynamic database of an aircraft is generally developed by means of various sources such as analytical and empirical methods, CFD analysis and Wind Tunnel tests. However, the aforementioned methods have their own limitations, so pilots used to feel discrepancies in handling qualities of the aircraft during flight tests compared to what they practiced in the simulator. Trajectory matching of measured responses and simulated responses supplemented the pilot's comments. Hence, validation and update of the aerodynamic database using system identification techniques were carried out using flight test data to improve the simulator fidelity, which in turn helped in the refinement of control algorithms and safe envelope expansion. This process of improving the accuracy of the aerodynamic database requires analysis of flight data from specifically designed maneuvers using System Identification techniques [1]. The process becomes quite involved for an aircraft like LCA, which has relaxed longitudinal stability and can be flown only with the aid of complex control laws implemented on a flight control computer.

This paper discusses the methodology adopted for aerodynamic database validation and update of LCA Tejas and also focuses on various critical issues encountered during the process [2, 3]. An incremental error modelling approach, based on aerodynamic coefficient matching, was used to update the aerodynamic database. Validation of the identified updates for the aerodynamic database was carried out by comparing the simulated trajectories with flight responses from a complementary dataset. The paper highlights some of the critical issues addressed during the course of the database update, which was indeed crucial to the program's success. Optimal control input design for flight testing at higher angles-of-attack, data consistency checks and sensor characterisation in the presence of process noise at the envelope boundaries, inconsistencies in the baseline aerodynamic model, real-time monitoring for test point clearance and store grouping techniques for reducing the flight test effort are some of the key points discussed in the sections below.

2. METHODOLOGY

System Identification has proved to be an effective technique for the validation and update of the aerodynamic database from the flight test data. It is used to estimate the aerodynamic coefficients or the stability and control derivatives from flight data, which can be compared with the analytical, Wind Tunnel or CFD predictions [1, 2, 3]. A coordinated approach (Quad-M) involving flight testing, mathematical modelling and data analysis techniques are required for successful aircraft system identification. The schematic of various stages involved for successful aerodynamic database validation and update is shown in Figure 1 and is discussed below:

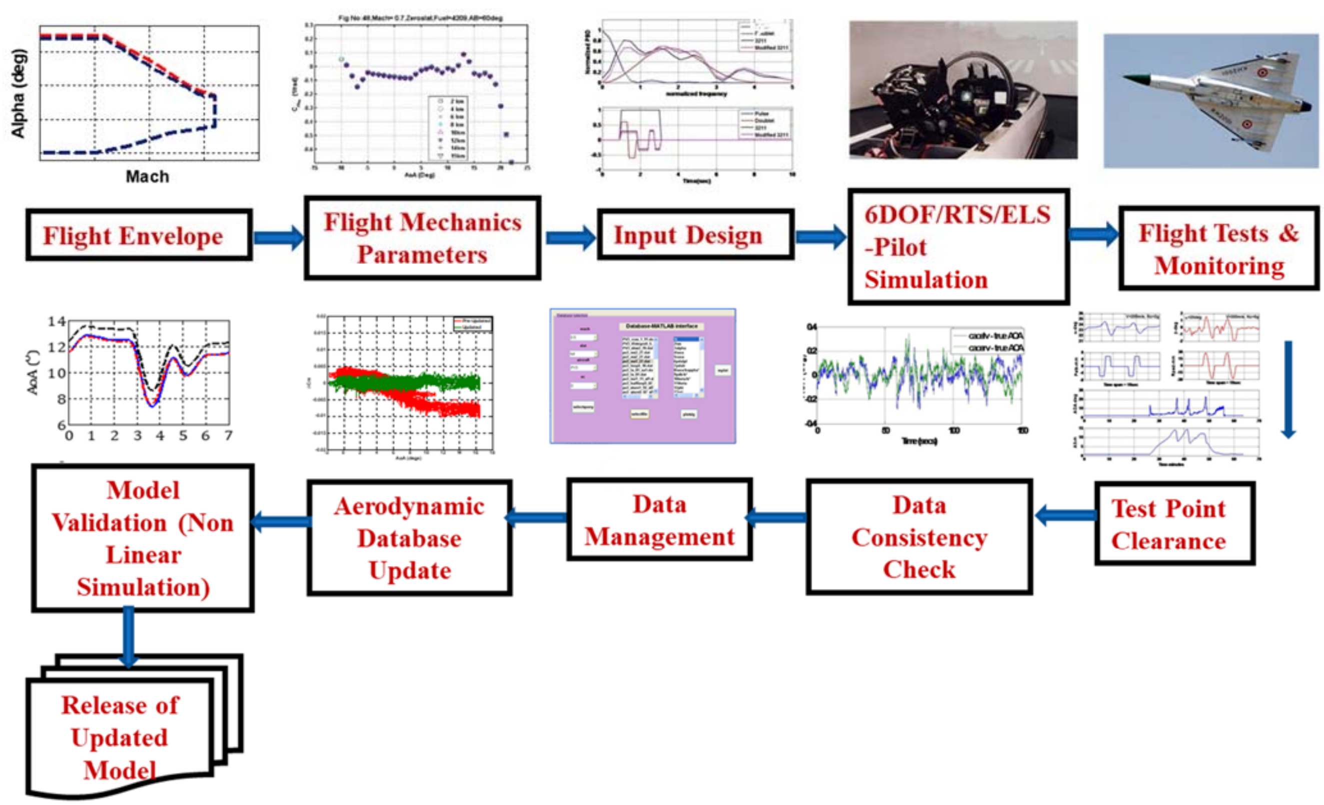

Figure 1. Methodology for Aerodynamic Database Validation and Update

2.1 Generation of the flight test matrix

Validation and update of the aerodynamic database over the complete operational envelope needs a comprehensive flight test program covering all possible configurations and flight conditions. Since the aircraft behaviour varies with flight conditions (such as angle-of-attack, Mach number, angle-of-sideslip, etc.), suitable test cases need to be arrived at by carefully examining the flight mechanics parameters ($Cm_{\alpha}, Cl_{\beta}, Cn_{\beta}$ etc.) in the different pockets of the flight envelope. This procedure of generating flight test requirements was carried out for operational clean configuration with slats extended/ retracted, airbrakes extended/ retracted and undercarriage retracted/extended, and also for various external store combinations.

2.2 Design of control inputs

In general, System Identification comprehensively depends on the amount of information present in the data for parameter estimation. Therefore, flight test data must contain adequate information in terms of flight parameters excursion from the equilibrium state to estimate the relevant parameters. This is achieved by designing the specific control inputs which could excite different frequency ranges of the vehicle. The excursion in control input is decided on the basis of prior knowledge of the aircraft's behaviour from simulation built using Wind Tunnel or CFD data. Designing of control inputs involves the following steps:

1. **Spectral analysis of the control input**: In order to accurately estimate the aerodynamic derivatives, those frequencies ranges need to be appropriately excited, where the contribution to each aerodynamic derivative is appreciable [1]. The frequency content in each of the control inputs with different pulse widths and shapes are checked as shown in Figure 2, and the decision is taken based on the frequency range-of-interest, which corresponds to the aerodynamic derivatives to be estimated [6].

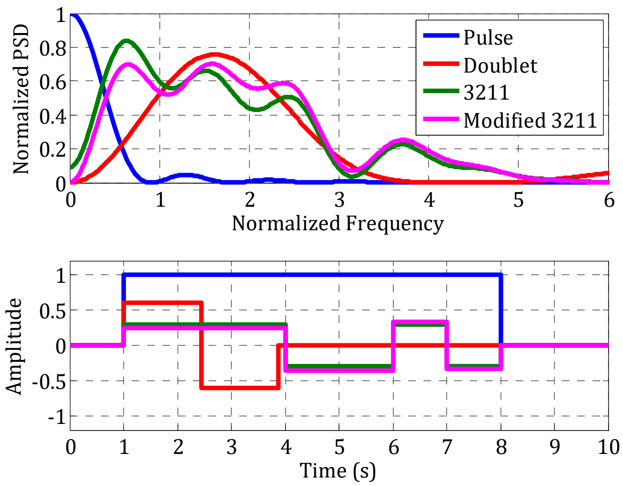

Figure 2. Energy spectrum analysis for different types of inputs

2. **Parameters' excursion analysis**: This is done by generating the aircraft responses in a simulated environment for a set of control inputs with varying amplitude and pulse width. This procedure ensures adequate excursion in the responses, which should be neither too small to have less information content nor too large to get into the nonlinear flight regimes.

While simulating these designed test cases, the aircraft is initially trimmed at different conditions using appropriate trimming maneuvers such as wings level, pull-ups, steady turn, wind-up turns, etc., by solving the equations-of-motion with constrained optimisation. After determining the control surface deflections required to trim, the pilot command is found for the trimmed control surface position. This is done to check the feasibility of the simulated trim condition for actual flight testing. After that, time trajectories are generated with a set of control inputs with varying amplitude and pulse width to examine the parameters' excursion. The designed inputs, particularly at demanding and challenging conditions, are practised at Real-Time-Simulator (RTS) to verify the extent of excursions and ensure flight safety. These inputs were then used to gather the data for system identification.

2.3 Data Consistency Check & management

The raw data gathered from flight tests need to be corrected for systematic sensor errors such as scale factors, biases and time shifts before using it for system identification. These errors can affect the convergence and accuracy of the estimates, which may lead to incorrect insights and wrong conclusions. Hence, flight data was checked for its consistency and cleaned by Flight Path Reconstruction (FPR) procedure to ensure the measurements are consistent and error-free. Figure 3 shows the block diagram for FPR, where the measured linear body accelerations and angular rates were integrated to generate the aircraft responses using kinematic equations. Systematic errors in sensors are modelled and estimated using optimisation techniques such as Output Error Method (OEM) or Extended Kalman Filter (EKF).

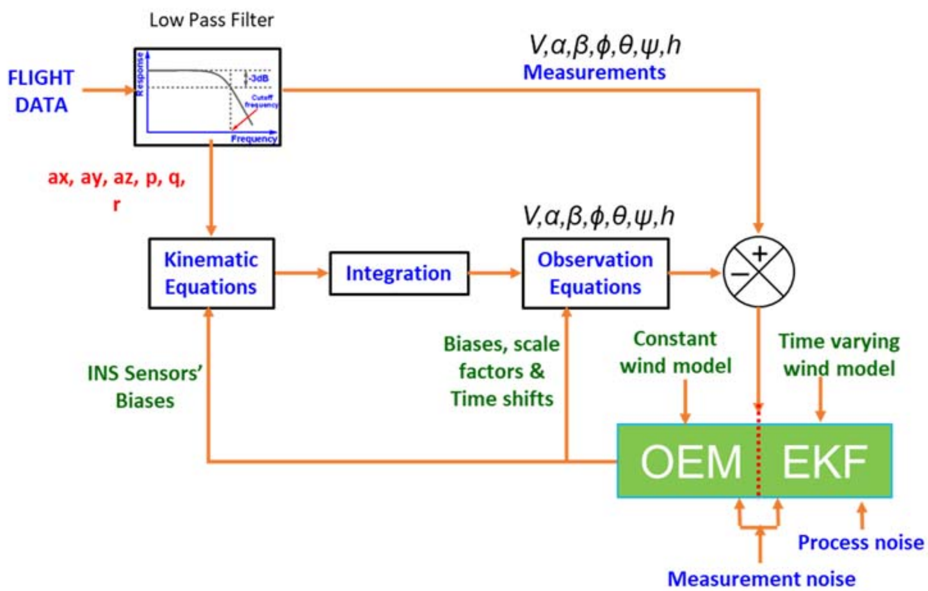

Figure 3. Flight Path Reconstruction

The state equations, observation equations and unknown parameters are shown below:

$$\dot{x} = A(x, \Theta) + B(u, \Theta, w), \; y = C(x, \Theta) + v$$

Where,

- x Aircraft states
- y Responses
- u Control inputs
- w Process noise
- v Measurement noise
- Θ Unknown parameters

$x = \{u, v, w, \phi, \theta, \psi, h\}$, $u = \{a_x, a_y, a_z, p, q, r\}$

$y = \{TAS, \alpha, \beta, \phi, \theta, \psi, h, V_N, V_E, V_D\}$

$\Theta = b_{aX}, b_{aY}, b_{aZ}, b_p, b_q, b_r, K_\alpha, b_\alpha, \tau_\alpha, K_\beta, b_\beta, \tau_\beta, w_N, w_E, w_D$

The choice of optimisation technique depends on several factors. One such factor is the meteorological condition during the data gathering. The atmospheric turbulence adds process noise to the system under observation.

- **Output Error Method (OEM)**: This technique is a deterministic approach that caters to measurement noise and not the process noise, as shown in Figure 3. The method is iterative and does not need measurement noise covariance matrix tuning. If the flight test is carried out in calm air conditions, OEM can accurately estimate the systematic errors in the data. This method works well for the segmented data where the wind is estimated as a constant bias parameter.

- **Extended Kalman Filter (EKF)**: This stochastic optimisation technique accounts for both measurement noise and process noise. This technique is recursive, and prior tuning of process and measurement noise covariance matrices are required. This technique can reconstruct the full flight trajectories by estimating time-varying wind as an augmented state, thereby improving the accuracy of estimated flow angles.

Presently, for LCA, reconstruction of flight trajectories is being done using EKF to account for atmospheric turbulence. FPR reconstructs the Euler angles, body velocities, true airspeed and true flow angles. Wind velocities are estimated by incorporating the inertial velocities into the FPR process [4, 5]. The reconstructed trajectories are then subsequently used for aerodynamic characterization.

2.4 Aerodynamic Database Validation and Update

Different approaches are followed for identification of the aerodynamic model from flight data viz. point model identification, global model identification and incremental error model [3]. An incremental error model based on the Coefficient Level Matching approach is adopted for the validation and update of the aerodynamic database of LCA Tejas. This approach is discussed as follows:

1. Aerodynamic force and moment coefficients are obtained from the baseline Aero Data Set (ADS) developed from Wind Tunnel testing, CFD techniques, etc. This ADS is a look-up table of various flight parameters at Moment Reference Point.

$$C_{i(ADS)} = f(M, \alpha, \beta, \mathrm{Slat}, \mathrm{UC}, \delta e, \delta a, \delta r, \mathrm{configuration}, \dots), \;\; i = X, Y, Z, l, m, n$$

2. Aerodynamic force and moment coefficients are computed from the flight data using inertial measurements (linear body accelerations and angular rates) and are corrected for engine and inlet momentum effects. These coefficients are calculated at the aircraft's center-of-gravity and subsequently transferred to Moment Reference Point to compare with ADS.

$$C_{i(FLT)} = C_{i(Inertial)} + C_{i(Engine)} + C_{i(Inlet\ Momentum)}$$

   During this step, variation in the aircraft's center-of-gravity due to fuel sloshing during the maneuvering phase is also accounted for [2].

3. The difference between flight computed coefficients and ADS look-up coefficients are examined with respect to several independent flight parameters such as Mach number, angle-of-attack, angle-of-sideslip, control surfaces, angular rates, etc. A typical error plot for the coefficient of the yawing moment (C_n) with respect to the angle of sideslip (β) is shown in Figure 4 for different angles-of-attack.

$$\Delta C_i = C_{i(FLT)} - C_{i(ADS)} = f(M, \alpha, \beta, \delta e, p, q, r, \dots)$$

4. The error between the flight computed and ADS look-up coefficient is modelled using incremental error model structure [3]. The modelling is carried out using Equation Error Method, which assumes the error model to be linear. A nonlinear model is achieved with the piecewise linear fit at appropriate breakpoints. This is a two-step iterative process.

a. Initially, the error is modeled with respect to low-frequency flight parameters (such as angle-of-attack, angle-of-sideslip).
b. Examine the residual error and model the error with respect to high-frequency parameters (such as control surface deflections and angular rates).
c. Again, examine the error and repeat steps (a) and (b), till residual is zero mean.

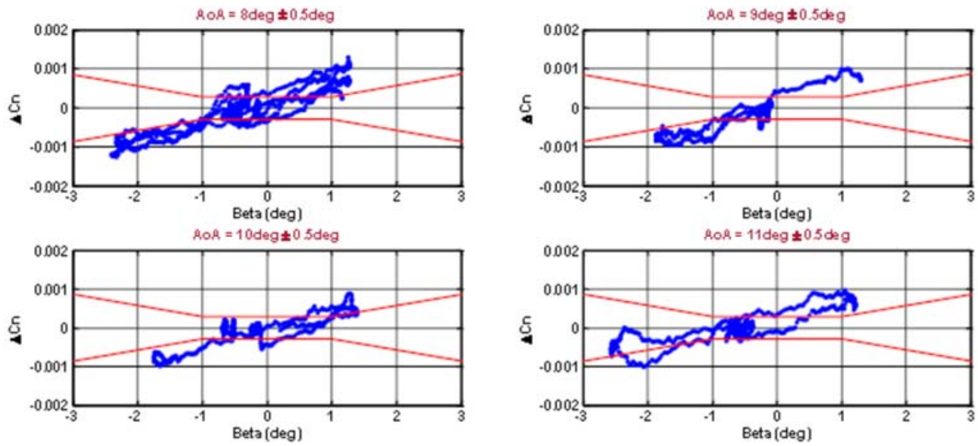

Figure 4. Error in Cn with respect to beta (β) at different AoA (α)

5. The identified incremental error model is then appended to the baseline aerodynamic data set, and updated aerodynamic data set, which becomes equivalent to flight, is released to the users after a thorough validation of the identified model.

$$C_{i(\text{Flight Updated})} = C_{i(\text{ADS})} + \Delta C_i(M, \alpha, \beta, \dots)$$

The entire procedure is repeated for various configurations on different variants. A comparison of baseline ADS and updated flight database for the coefficient of pitching moment with respect to angle-of-attack and elevator deflection is shown in Figure 5.

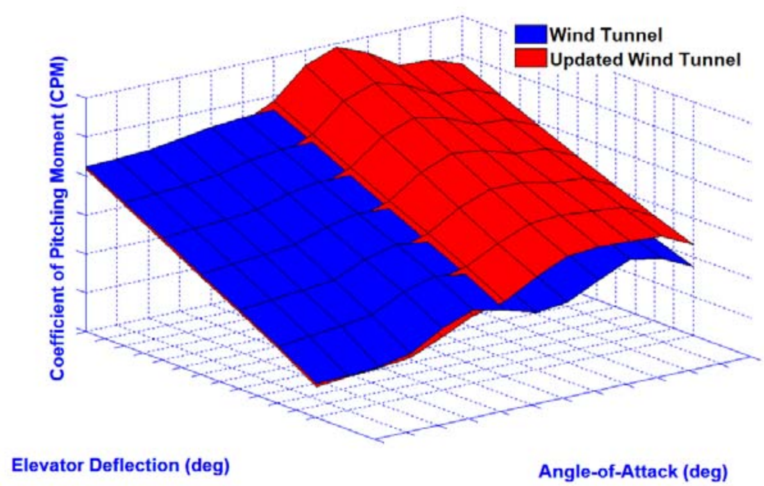

Figure 5. Comparison of Baseline ADS and Updated ADS using Coefficient Level Matching

2.5 Model Validation

The accuracies of the estimated parameters are checked using statistical properties such as cost function, Cramer-Rao bounds, etc. [1]. However, final validation of the identified incremental error model is carried out by comparing the flight trajectories with the simulated response from a 6-DoF simulation environment for a complementary dataset [3]. Canned pilot inputs are fed to the simulation with CLAW (control laws) closing the loop, and generate aircraft trajectories. These simulated trajectories are then compared with the measured flight parameters to validate the flight updates. A typical model validation plot for a pitch maneuver is shown in Figure 6.

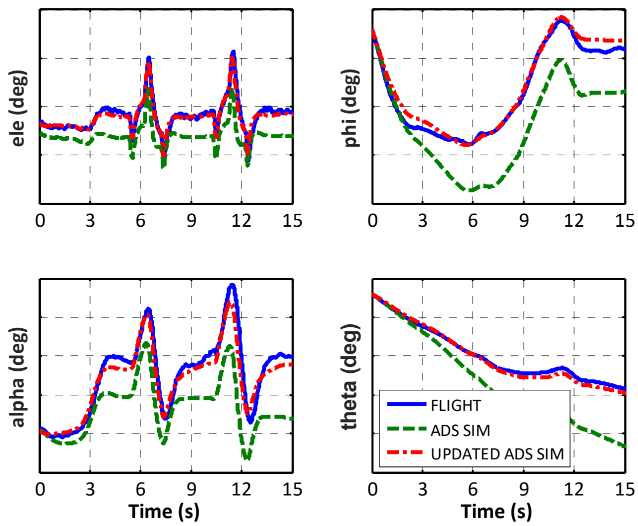

Figure 6. Model Validation for a short period pitch maneuver

3. MAJOR CHALLENGES

This section details the key challenges faced during the flight testing and data analysis phases and how these challenges were overcome are discussed in the following subsections:

3.1 Input execution at higher angles-of-attack and test-point monitoring

Earlier, pull-up trim maneuvers were used extensively to gather data at higher angles-of-attack. This maneuver is good to cover a range of angles-of-attack, but the time window available to execute an input while maintaining the trimmed flight condition is very small. A large variation in trimmed flight states (Mach & AoA) were observed in the data. Therefore, wind-up turns were executed to get a larger time window for input execution while maintaining the trimmed flight states at higher angles-of-attack. However, execution of manual inputs by the pilot at these test conditions resulted in larger excursions of the flight parameters than anticipated. To mitigate this issue, a Flight Test Unit panel (FTU) was developed and On-board Flight Program (OFP) was modified to cater for the computer-generated inputs. The excitations were sent directly to the control surface through Digital Flight Control Computer (DFCC), and the pilot needs to maintain the trimmed condition through sticks/trim tabs. Moreover, these FTUs have embedded abort criteria for flight safety for reducing the pilot effort in the overall procedure of data gathering.

From the flight test safety point of view at the extreme pockets of the envelope, the designed control inputs are simulated with the nominal aerodynamic database and with tolerances on the ADS. This procedure generates an acceptable boundary on the excursion of flight parameters from the trimmed state during the maneuver, known as Parameter Excursion Boundaries (PEBs). The PEBs were uploaded to the flight telemetry station and were used to monitor the critical flight parameters in real-time to ensure flight safety, as shown in Figure 7. This shows the real-time monitoring of a test case during flight testing for different parameters. If any critical parameter falls beyond the PEBs, the test may be aborted, and cases will be examined appropriately.

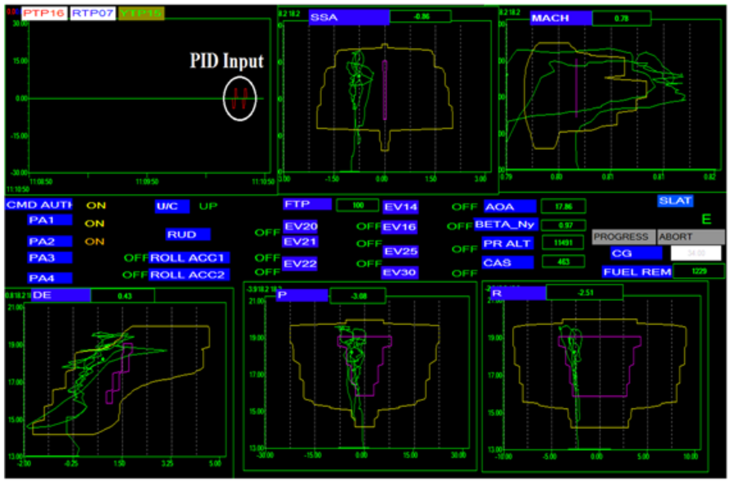

Figure 7. Real Time Monitoring of flight parameters using PEBs

3.2 Sensor Calibration and Wind Estimation

Over a period of time, as the flight testing progressed, the number of aircraft prototypes increased to gather data for different design groups. For accurate model identification, it is always better to perform the flight tests in a calm atmosphere to avoid the uncertainties of additional noise. During the initial stages of flight testing, the test crew at NFTC was used to ensure this condition. However, to expedite data gathering for system identification, less attention was paid to the restriction of performing tests in a calm atmosphere. Many of these flights were flown to gather data at higher angles of attack. Moreover, the flight tests were also carried out at high altitudes, especially in the stratosphere regions with a significant increase in the wind gusts [5].

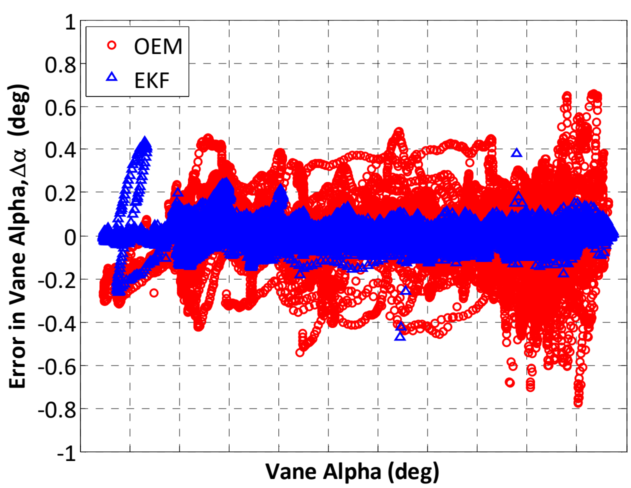

Figure 8. Comparison of estimation vane AoA error between OEM and EKF

Output Error Method (OEM) failed to produce accurate results in the presence of process noise due to atmospheric disturbances for the above-mentioned flight tests (shown in red in Figure 8). This necessitated the implementation of an alternative technique to address this problem and also to cater for the non-linearities at higher angles-of-attack. Extended Kalman Filter (EKF) was then used to carry out FPR to improve the accuracies in the measured flow angles in the presence of process noise. Figure 8 shows the comparison of estimation error for vane AoA sensor from OEM and EKF. It is evident from the figure that the uncertainties induced in the data because of process noise were degrading the estimation accuracies, specifically at higher angles-of-attack. OEM estimated a constant wind for the maneuver, while a time-varying wind is estimated through EKF. With EKF, the wind is estimated for the full flight, as shown in Figure 9. It is also to note that estimation of time-varying wind also helped improve the accuracy of the flow angles, especially at higher altitudes, as shown in Figure 9.

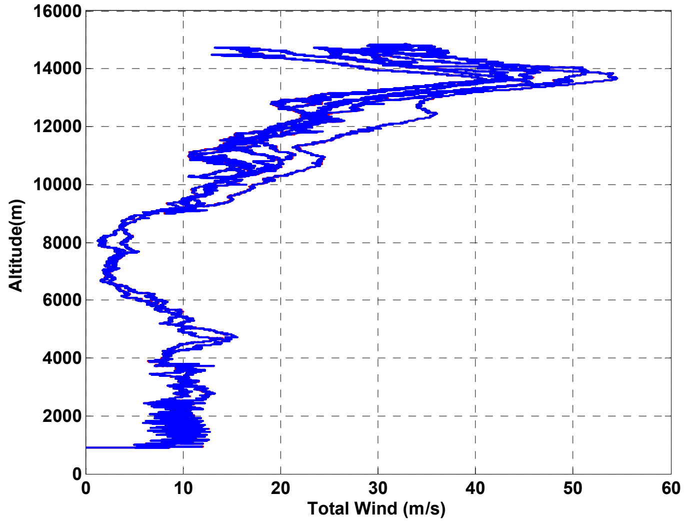

Figure 9. Estimated wind with respect to aircraft altitude

3.3 Aerodynamic Modelling Issues

There were several aerodynamic modelling issues encountered during the process of validation and update of LCA aerodynamic database. A few of them, along with the modelling solutions, are discussed in this subsection.

3.3.1 Pitch-up and Hysteresis Modelling for Naval Variant

While chasing for an optimal landing configuration for the LCA Naval variant, the aircraft was flight tested in several configurations. In one of the configurations, interesting aerodynamic modelling problems were occurred, which are briefly summarised as follows:

- A huge pitch-up at designated landing angle-of-attack,
- Hysteresis in ΔC_m for a range of angles-of-attack, and
- Wing-rocking phenomenon around the landing angle-of-attack.

As discussed in Section 2.4, update of the aerodynamic database using the Coefficient Level Matching approach is a two-step iterative process. Therefore, error in pitching moment $\Delta C_m (= C_{m(FLT)} - C_{m(ADS)})$ was initially plotted with respect to angle-of-attack, and pitch-up was observed as shown in green color in Figure 10(a). This pitch-up was modeled as a function of α, and the residual error is shown in blue color in Figure. 10(a). This residual error showed hysteresis phenomenon with respect to higher frequency flight parameter pitch rate, for certain range of angles-of-attack. Therefore, the residual trend was then modeled as a function of pitch rate, as shown in red in Figure. 10(a), resulting in the reduction of scatter in the residual error. Similarly, the wing-rocking phenomenon was captured in the coefficient of rolling moment as a function of α. Thus, the ADS was updated with the following incremental error model:

$$Cm_{Updated} = Cm_{ADS} + \Delta Cm_0 + \Delta Cm(\alpha) + \Delta Cm_q(\alpha)$$

$$Cl_{updated} = Cl_{ADS} + \Delta Cl(\alpha)$$

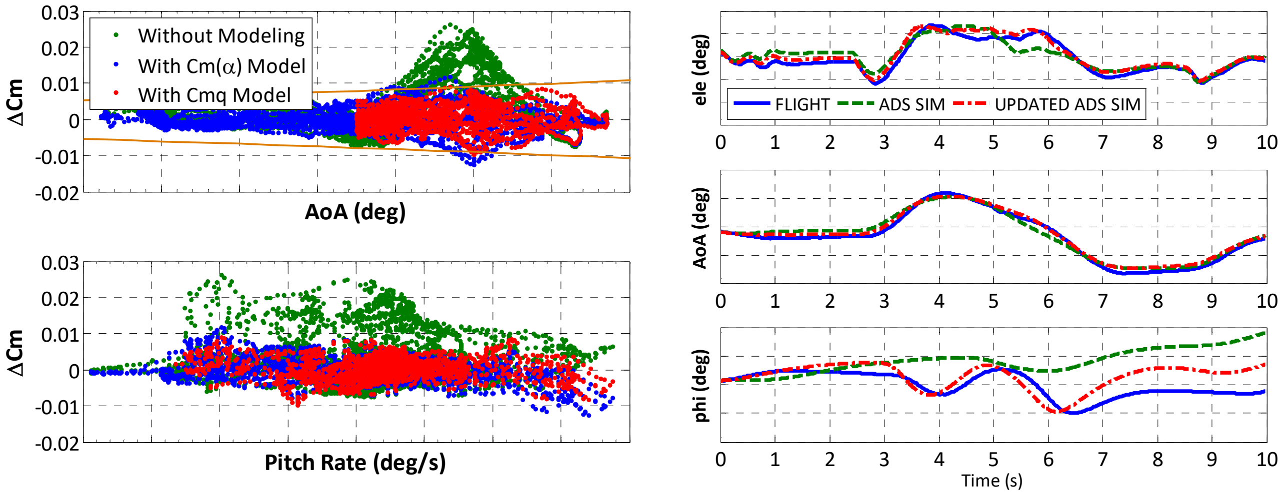

Figure 10. (a) Coefficient Update using CLM approach, (b) Model Validation using simulation

The effect of this update (shown in red) is evident from the model validation plot shown in Figure 10(b). Wing-rock modelling helped in matching the roll angle (phi), while the update in Cm showed a better match with the flight as compared to ADS for AoA and elevator deflection.

3.3.2 Weathercock stability for extended airbrake configuration

At lower Mach number and lower angles-of-sideslip ($\beta \sim 2^{o}$), a reversal in Wind Tunnel predictions were observed in $Cn\beta$, shown in red in Figure 11 for extended airbrake configuration. However, flight data analysis showed that this was not real, and the coefficient of yawing moment was modelled with respect to sideslip (shown in black squares). Based on the flight data analysis discoveries, the Wind Tunnel predictions were reviewed, and a new aerodynamic database was released, as shown in blue in Figure 11.

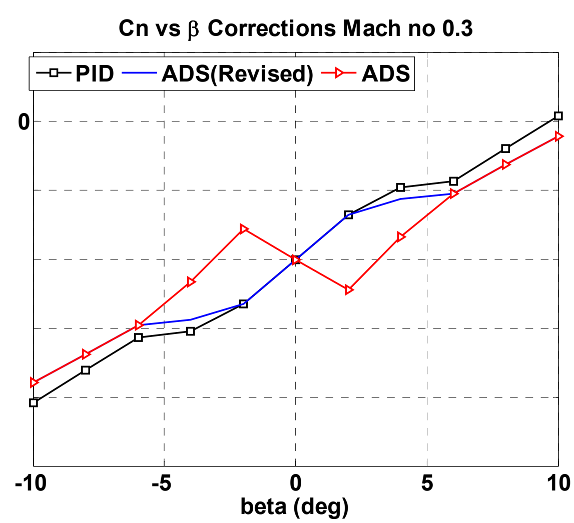

Figure 11. Corrections to weathercock stability parameter

3.3.3 Reduction of tolerance bound

During dynamic wind tunnel testing, large scatter was detected in the estimates of damping derivatives, especially in transonic Mach regions. So large tolerance bounds are apparently used for damping derivatives as a function of Mach number. These larger bounds were creating problems during the control law clearances. As the flight tests progressed, the results from Coefficient Level Matching did not show any necessity of the increased tolerance bounds for damping derivatives at transonic Mach numbers. Therefore, the tolerance bounds were revised and implemented in the simulation and control software. Figure 12 shows the updated and original tolerance bounds for pitch damping derivative (Cm_q) plotted with flight test data against the Mach number.

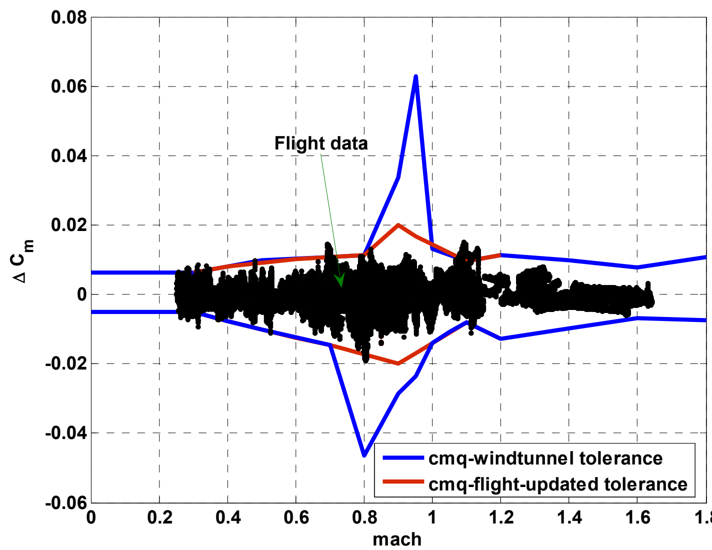

Figure 12. Reduction of Tolerance bound

3.4 Near real-time flight envelope expansion

A traditional way of flight clearance for envelope expansion to higher angles-of-attack is to gather onboard recorded data and analyse it offline, which usually take a few hours to complete. So, to accelerate the clearance process, an in-house tool was developed which processes the telemetry data in near real-time and aids in deciding to go forward with envelope expansion or not. This helped the LCA Navy program in the quick clearance of test points without risking the safety of the aircraft. Figure 13 shows a screenshot of the tool, which generates the error plots of the aerodynamic coefficients with ADS tolerance. Hence, a decision can be taken by analysing these error plots in the near-real time after the execution of a test point whether to go ahead with the next test point or to abort it.

3.5 Store grouping: A tool to optimise flight testing

As the number of store configurations to be flight tested kept increasing during FOC and post FOC, it is really time-consuming and costly to flight test all these configurations for aerodynamic database validation. Aerodynamically similar stores were grouped together to minimise the flight testing effort using system identification. The primary basis for store classification is the aircraft aerodynamic characteristics. The aerodynamic similarity among the store combinations is proven for the entire Mach range. This poses severe challenges in the transonic region, where aerodynamic characteristics are difficult to model and predict. Also, depending upon the size, shape and distance between two stores, one store may suppress or enhance the effect of another store mounted at the adjacent location. Figure 14 shows the store grouping concept from aerodynamic database using Wind Tunnel database and the groups are arrived by relating longitudinal and lateral parameters. A number of stores configurations were selected for grouping, and finally, 5 groups were arrived at based on the similarity-based concept [7]. One representative from each group can be selected for database validation and update of all the configurations in the group.

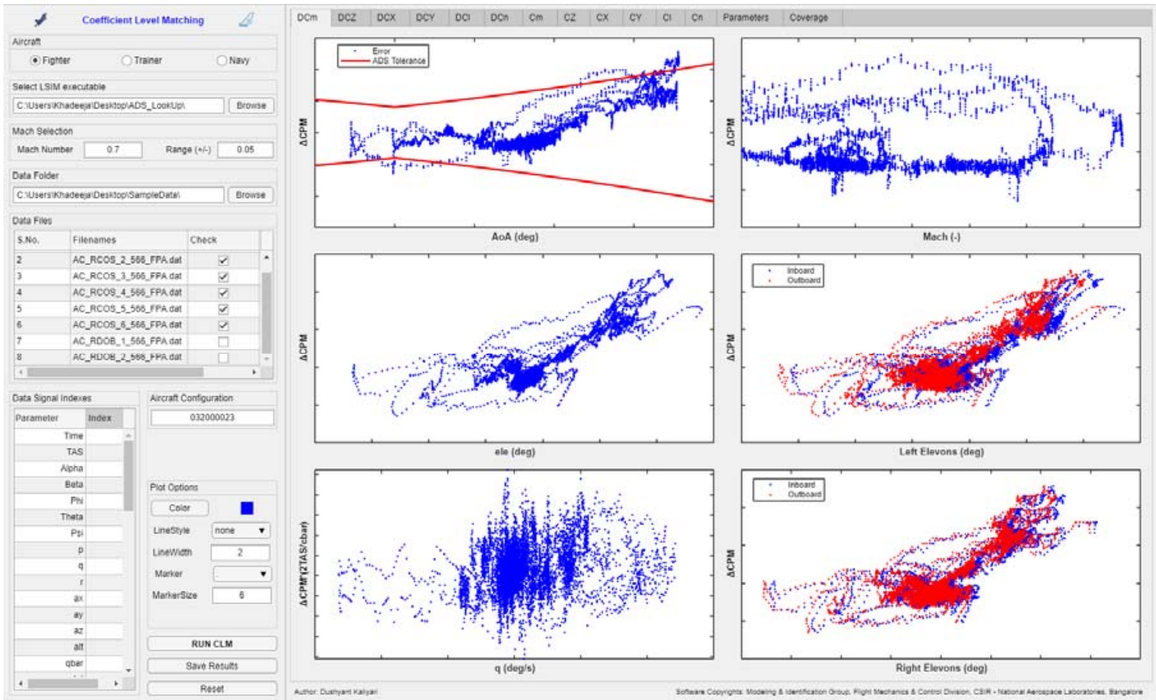

Figure 13. Tool for near-real time flight clearance

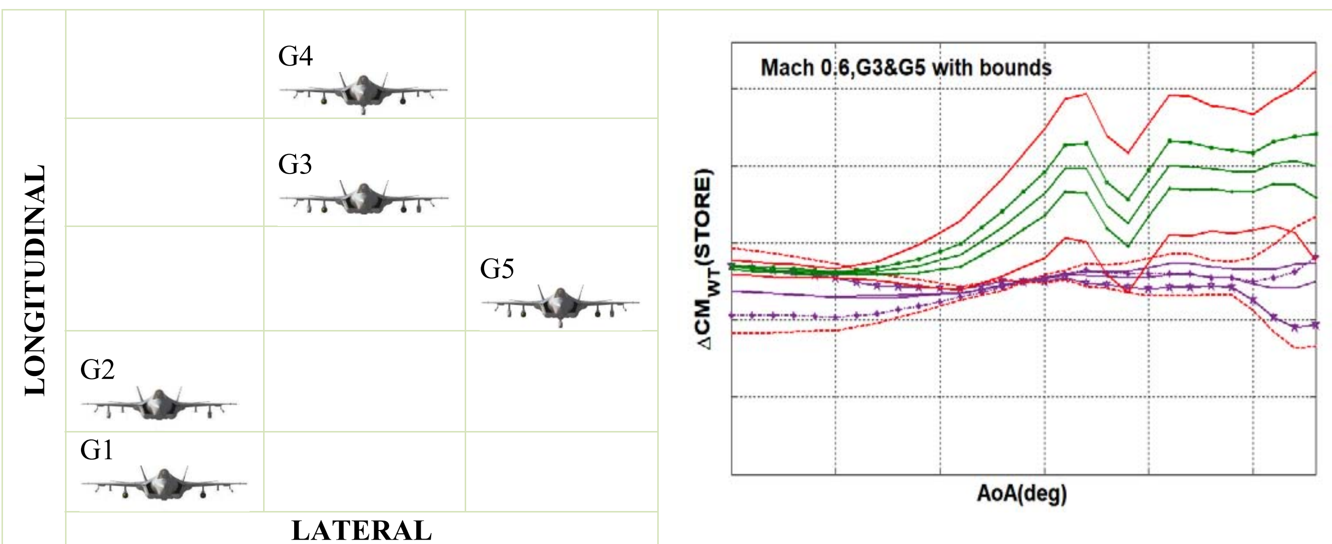

Figure 14. Store Grouping

4. CONCLUSIONS

The validation and update of LCA Tejas aerodynamic database from flight test data amid different challenging problems are discussed in this paper. The updated aerodynamic database is playing an important role in the expansion of the flight test envelope. This procedure is done cautiously and incrementally, particularly at higher angles-of-attack because the characteristics are highly nonlinear and uncertainties are more. The excellent match of aircraft behaviour between simulator and flight has given a lot of confidence to pilots which led to the practice of complicated flight test maneuvers in the simulator prior to actual flight.

5. ACKNOWLEDGEMENT

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