PROBLEMS FACED DURING INTEGRATED TESTING OF FLUSH AIR DATA SYSTEM (FADS) AND ITS SOLUTIONS

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Abstract

FADS provides air data parameters of an aerospace vehicle such as angle of attack, angle of sideslip, Mach number, etc for use by the flight control and guidance system. It essentially makes use of surface pressure measurements, from mostly the nose cap of the vehicle for deriving these air data parameters. Flush Air Data System (FADS) was indigenously developed and flown successfully in the RLV-TD HEX-01 mission. Before carrying out flight testing of FADS, testing with a full scale model was carried out initially at national wind tunnel facility, Indian Institute of Technology, Kanpur. This paper highlights some of the problems encountered during the integration and testing of FADS at IIT, Kanpur. The corrective steps taken for overcoming these problems encountered is discussed. With the corrections implemented the full scale wind tunnel test was repeated and it was observed that the design objectives of FADS are met by the system.

Keywords: *FADS, Subsonic, Angle of Attack, Wind Tunnel, MEMS*

Introduction

Flight control of aerospace vehicles like aircrafts and re-entry vehicles require knowledge of air data parameters like angle of attack, angle of sideslip, dynamic pressure, Mach number, and free stream static pressure with sufficient accuracy in real time. These parameters are used by the flight control system for generating the appropriate commands for the different control surfaces to keep the vehicle trajectory within the desired envelope. This also ensures that the vehicle loads are limited to the desired values and the thermal environment of the re-entry vehicle is maintained within limits.

Several types of air data systems like laser velocity meter systems, onboard Inertial Measurement Unit (IMU) based systems and intrusive boom type instruments like Pitot tube and mechanical vanes are available. Due to the high energy nature of the flow, most of the above systems cannot be implemented for re-entry vehicles. Hence, hypersonic flying vehicles essentially adopt the concept of Flush Air Data sensing System (FADS). One benefit of FADS is that it senses more pressures than are minimally needed to determine the angles of attack so as to alleviate the detrimental effect of pressure measurement error in the estimated values of aerodynamic state. In FADS, the air data parameters are estimated using pressure measurements from orifices flushed with the surface of the vehicle. Normally, static pressures measured from the blunt nose cap of the vehicle using a matrix of pressure orifices located in and around the nose cap are used for computing the air data parameters [1-6]. To perform this estimation, air data states are related to the surface pressure by an aerodynamic model that is valid over a large Mach number range from hypersonic to subsonic. FADS system has been developed for the space shuttle [7], and has also been demonstrated through a number of flight tests [8, 9].

FADS Configuration in HEX-01 Mission

The Flush Air Data System (FADS) makes use of an algorithm which makes use of surface pressure measurements from suitably located flush orifices on the nose cap of the vehicle. The measured pressures are a function of four parameters, free stream static pressure, impact dynamic pressure, local angle of attack and side slip. In addition there is a calibration parameter to be estimated. Since there are four air data states and a calibration parameter to be estimated, at least five independent pressure measurements must be available to derive the entire air data state. This puts the minimum number of pressure ports as five. In RLV-TD FADS, the pressure ports are arranged in a crucifix fashion. Even though the minimum number of pressure ports required is five total of nine ports were selected. This is done so as to provide redundancy to facilitate computation of air data parameters after failure of a pressure sensor or blockage of a pressure port. As mentioned previously, the pressure ports are arranged in a crucifix fashion with five pressure ports in the vertical meridian and remaining four ports in the horizontal meridian. Two horizontal ports are provided on either side of the vertical meridian.

Each pressure port is identified by two angles known as the clock angle and cone angle of the vehicle. The cone angle (λ) is the total angle the normal to the surface of the port location makes with respect to the longitudinal axis of the nose cap and the clock angle (ϕ) is the clockwise angle looking aft around the axis of symmetry starting at the bottom of the fuselage (Fig.1).

RLV-TD blunt nose body is of complex shape and the pressure variation in the region of stagnation point can be slightly different from that of a sphere. The RLV-TD nose body consists of an inclined spherically blunted conical body attached to the forward part of fuselage. The nose body is inclined to the fuselage by 13.35 deg as shown in Fig.1. The geometric angles from nose cap axis are shown in Fig.1.

The pressure ports are located on the C-C nose cap which encounters very high temperature during reentry. The pressure ports are connected to the pressure sensors through pneumatic tubing. The tube length is selected such that the temperature at the sensor location is always < 40°C. Further, the tube dimensions (length and diameter) should result in a frequency > 10 Hz for the estimated parameters. The sensor configuration selected consists of three one bar pressure sensors at a pressure port. Thus there are a total of 27 pressure sensors in the system. It was found through simulations that the maximum pressure encountered by the system is 130 kPa. Hence, the full scale of the sensor was selected as 140 kPa. Absolute transducer 3 x 140 kPa is thus used as it meets accuracy requirement, facilitates transducer fault detection using TMR logic and allows redundancy with simple pneumatic plumbing. The magnitude of the pressure to be sensed at the nine pressure ports for the case of nominal trajectory are given in Fig.2.

FADS Algorithm

For carrying out air data estimation, the air-data states must be related to the surface pressure by an aerodynamic model that captures the salient features of the flow, and is valid over a large Mach number range. The complex flow scenario must be described with a model simple enough to be inverted in real time for air data parameter extraction. For this purpose, the aerodynamic model is postulated as a compromise between a simple potential flow model on a sphere, and modified Newtonian flow theory for blunt objects in hypersonic flow. Both potential flow and modified Newtonian flow describe the measured pressure coefficient in terms of the local surface incident angle. To blend the two solutions different schemes are employed. One method uses a calibration parameter ε. The concept of air data parameter estimation is shown in Fig.3.

The pressure at i^{th} port is defined by

$$P_i = q_c \left[\cos^2 \theta_i + \varepsilon \sin^2 \theta_i \right] + P_\infty \quad (1)$$

Here, in Eq.1, θ_i is the flow incidence angle between the surface normal at the i^{th} port and the velocity vector. The incidence angle is related to the local (or effective) angle of attack, (α_e) and angle of sideslip, (β_e) by

$$\cos \theta_i = \cos \alpha_e \cos \beta_e \cos \lambda_i + \sin \beta_e \sin \phi_i \sin \lambda_i + \sin \alpha_e \cos \beta_e \cos \phi_i \sin \lambda_i \quad (2)$$

Where, in Eq.2, the cone angle (λ) is the total angle the normal to the surface makes with respect to the longitudinal axis of the nose cap and the clock angle (ϕ) is the clockwise angle looking aft around the axis of symmetry starting at the bottom of the fuselage (Fig.2). The other parameters in equation 1 are impact pressure (q_c) and the free stream static pressure (P_∞). These are the basic equations from which the air data parameters are extracted. An indigenously developed algorithm was used to derive the air data parameters from the sensed pressures.

Problems Encountered During Integrated Testing of FADS and Corrective Steps Taken

The FADS in tunnel test is a final confirmatory test undertaken as part of its development and provides end to end evaluation of the system in a wind tunnel facility. It can be considered as hardware in loop simulation carried out on a full scale model of the nose cone of the vehicle with pressure sensors, pneumatic tubing and electronics as in flight configuration. The estimated output of FADS is compared with the wind tunnel set conditions.

The above test with 1:1 full scale model of FADS was conducted at National Wind Tunnel Facility, Indian Institute of Technology, Kanpur, during January 30-February 3, 2012. The tunnel used for the test is a closed-return, continuous, atmospheric wind tunnel, with a 2.25m high, 3m wide and 8.75m long test section. Air speed up to 80 m/s maximum can be produced in the test section by a single-stage 12 bladed axial flow fan powered by a 1000kW variable speed motor. This test was done for a fixed Mach of 0.2. The angle of attack is varied from -4° to 20° in steps of 1°. The angle of sideslip is varied from -20° to +20° in steps of 5°. During angle of attack sweep, for each run, angle of sideslip is set at one value and angle of attack is varied. Wind is blown at fixed speed of 0.2 Mach (65m/s). Each angle of attack is kept for 30 seconds before changing to the next value. The angle of attack (α), angle of sideslip (β) and Mach number (M) estimated by FADS algorithm during each wind tunnel run is compared against the set conditions. The problems observed during this full scale testing of FADS and the corrective steps taken are highlighted in this section.

Error Due to Extended Length of Sting

The 1:1 model of FADS is mounted inside the wind tunnel using a sting. A nose body structure with the FADS (Flush Air Data System) mounted to it was used for the wind tunnel test. The structure contains nose cap shell, conical shell, end plate and a sting. The structure was mounted on 1.3 m long and 50mm dia. solid shaft. The structure is connected to the shaft through 300mm tubular section of the sting. The sting used for mounting the model is shown in Fig.4. Due to large length of 'sting' (~1.8m horizontal rod on which the model is fixed) the model was vibrating during the test and it resulted in visible variations in alpha and beta. These visible vibrations caused 2 to 3 degrees error in angle of attack and side slip which was not acceptable.

As oscillations with large displacements were observed, the existing interface of nose cap structure and sting was modified. The modifications are, existing interface diameter was increased to 170 mm (OD) from 60 mm, the interface length reduced to 250 mm from 300 mm and thickness of the interface increased to 10 mm from 5 mm. The nose body structure was subsequently mounted on 500 mm long shaft with outer diameter of 150 mm and inner diameter 100 mm which is connected to wind tunnel shaft carrier/pipe.

Dynamic analysis of the test set up with above modifications was carried out. It was observed that the natural frequencies of the structure are 5.812 Hz, 5.814 Hz, 22.689 Hz, 23.303 Hz, 26.523 Hz, 81.139 Hz and 165.81 Hz for normal and lateral I modes, normal and lateral II modes, I torsion mode, I axial mode and combined III lateral mode with local mode respectively.

Structural analysis was also carried out for load due to 1g in the lateral direction and structural pressure, derived from the supplied Cp values with its corresponding dynamic pressure of 2.864 kPa applied on the nose structure. From the structural analysis it was found that the minimum and maximum Margin of Safety (MS) of the structure are 0.99 and 5.3 respectively. The maximum deformation in the nose tip is 10.32 mm.

The 1:1 model of nosecone mounted inside the tunnel with the modified sting is shown in Fig.5. The test was subsequently repeated after modification of the sting. It was observed that the visible vibrations were significantly reduced with the modified sting.

Improvements in Pressure Sensors and Introduction of Split Range Calibration

The pressures measured by the FADS pressure sensors were compared with that provided in parallel by the wind tunnel instrumentation team. The wind tunnel sensor being differential pressure sensors are much accurate than that used in FADS. It was found that there was significant difference between the pressure sensor reading of FADS and wind tunnel sensors. Fig.6 shows the typical pressure difference between FADS sensor and wind tunnel sensor for 0° sideslip angle. The figure shows that maximum pressure difference is 250 to 300 Pa while in some other sideslip cases this difference goes upto 500 Pa.

Each pressure port in FADS is connected to a three in one absolute pressure transducer. The difference between any two pressure port is expected to be of the order of 250 Pa. This was found to be much higher (550 Pa). The maximum error contribution due to this was assessed through simulations to be 1.5 deg in angle of attack and sideslip. To improve the accuracy of the pressure sensors screened components were used in the transducers used for the subsequent wind tunnel test. In addition, the MEMS cells having near identical characteristics were used in the same three in one transducer at a pressure port.

Split range calibration in three ranges was used in the transducers used for the first wind tunnel test. The three ranges were (0 to 20000, 20000 to 50,000 and 50,000 to 1, 40000). With this, it was found that the error in each sensor was 167 Pa. Hence split range calibration in four ranges was adopted for the revised configuration for the second wind tunnel test. The four split ranges used are,

0<=P<=40000 (Range 1)
40000<P<=80000 (Range 2)
80000<P<=110000 (Range 3)
110000<P<=140000 (Range 4)

It was found that the error in a sensor improved to 56 Pa from the earlier value. With the above two modifications, the accuracy of the pressure sensors improved to the desired value of 250 Pa between any two sensors in a pressure port.

Proximity of Processing Electronics to the Sensors

As mentioned earlier, there are nine pressure ports used in FADS. Each of these pressure ports has three absolute pressure sensors measuring the same pressure at the port. The output of these pressure sensors are analog voltages in the range 0.25 V to 4.25 V. These analog voltages are then digitized in another module using sigma delta converters. During the first wind tunnel test, the 1:1 model of nose cone which houses the pressure sensors is kept inside the wind tunnel while the digitization module was kept outside the tunnel. The length of the cable from the sensor to the acquisition electronics was 20 m. Running the analog output and ground lines of all the 27 sensors caused degradation of the accuracy of the system. Hence, it was decided to keep the acquisition electronics also inside the wind tunnel. To prevent blockage, the acquisition electronics was kept inside the sting used for mounting the 1:1 model as shown in Fig.7. This approach further enhanced the accuracy of the overall FADS system.

Singularity in Angle of Sideslip Computation

During the first wind tunnel test it was observed that there was large error generated in side slip angle for some of the test conditions as shown in Fig.8. The flight conditions which encountered large errors were $\alpha = 16°$ and 17° and $\beta = 15°$ and 20°. Detailed analysis was carried out on this observation. In FADS algorithm, the solution for side slip angle is obtained by solving a quadratic equation. Both vertical port and horizontal port pressures were used for estimating the side slip angle. There was a singularity related issue while solving the quadratic equation that manifested as large errors in sideslip angle.

The problem was resolved by considering the horizontal ports alone for side slip angle estimation. The side slip angle computation algorithm was modified considering pressures from only the horizontal ports. The second wind tunnel tests were conducted with this modification. It is found that the errors in side slip angle were within the targeted specification of 1 degree as shown in Fig.9.

CP Variation from 1:1 (Nose Cap) Model to 1:8 Model of RLV-TD

During FADS development a 1:8 scale model was used for carrying out wind tunnel tests. The data generated from these wind tunnel tests were used for generating calibration data for use by the FADS algorithm. During the first full scale model wind tunnel test, the Cp data obtained was compared with that obtained during wind tunnel tests with 1:8 scale model.

It was observed that there is significant CP difference between 1:1 (nose cap) models to 1:8 model of RLV-TD. Since the 1:8 model data is used for calibration data generation which is used in FADS algorithm, the difference in data will lead to error in estimation of air data parameters. Fig.10 and 11 shows the typical CP variation between 1:1 (nose cap) models to 1:8 model of RLV-TD. Maximum CP difference observed is 0.22 which is equivalent to 550 Pa.

This difference in Cp manifested as an error in the computed angle of attack and sideslip angles. Fig.12 shows the error in angle of attack between the FADS generated values and that computed offline using 1:8 scale pressure data. From the figure it is found that the maximum difference in angle of attack is within 0.5 degrees.

This difference between the Cp value is mainly due to the difference in the models used for generating the data. The 1:1 model realized consisted only of the nose cone part of the vehicle whereas for wind tunnel tests with 1:8 scale model, truncated model up to wing strake cconsisting of 3 parts was used. This 1:8 scale model is more close to the flight condition and hence error contribution from this was not expected in flight.

Conclusion

This paper addressed some of the problems observed during the wind tunnel test with 1:1 model of nose cone containing the end to end FADS system. The corrective steps taken to alleviate these problems were also explained. With the corrections incorporated, Viz. sensors with improved accuracy, modified side slip computation algorithm and modified sting for model mounting the 2nd test of FADS was successfully completed at Indian Institute of Technology, Kanpur during July 9-12, 2013.

References

1. Whitmore, S. A., Cobleigh, B. R. and Haering,. E. A., "Design and Calibration of the X-33 Flush Air Data Sensing (FADS) System", NASA/TM-1998-206540, Research Engineering, NASA Dryden Flight Research Centre, January 1998, pp.1-32.

2. Ellsworth, J. C. and Whitmore, S. A., "Re-entry Air Data System for a Suborbital Spacecraft Based on X-34 Design", AIAA Paper 2007-1200.

3. Ellsworth, J. C. and Whitmore, S. A., "Simulation of a Flush Air Data System for Transatmospheric Vehicles", Journal of Spacecraft and Rockets, Vol. 45, No. 4, July-August, 2008.

4. Larson, T. J. and Siemers, P. M., "Use of Nose Cap and Fuselage Pressure Orifices for Determination of Air Data for Space Shuttle Orbiter Below Supersonic Speeds", NASA TP-1643, 1980.

5. Larson, T. J., Whitmore, S. A., Ehernberger, L. J., Johnson, J. B. and Siemers, P. M., "Qualitative Evaluation of a Flush Air Data System at Transonic Speeds and High Angles of Attack", NASA TP-2716, 1987.

6. Rajeshkumar, G.V. et al., "Calibration of Air Data Systems Using Numerical Simulation of Supersonic Flow Over Blunt Forebody", 20th National Convention of Aerospace Engineers, October 29-30, 2006, Trivandrum, India.

7. Siemers, P. M., Paul, M., Henry, W. and Martin, W. H., "Shuttle Entry Air Data System (SEADS) Flight Verification of an Advanced Air Data System Concept", AIAA 88-2104, 1988.

8. Whitmore, S. A., Moes, T. R. and Larson, T. J., "Preliminary Results From a Subsonic High of Attack Flush Air Data Sensing (HI-FADS) System Design, Calibration and Flight Test Evaluation", NASA TM-101713, 1990.

9. Whitmore, S. A., Davis, A. R. and Fife, M. J., "Flight Demonstration of a Real Time Flush Air Data Sensing (RT-FADS) System", AIAA Paper 94-3433, August 1995.

10. Rajesh Kumar, G. V., Harish, C. S., Swaminathan, S. and Madan Lal., "Development of a Flush Air Data System for a Winged Body Re-entry Vehicle", 2nd European Conference for Aerospace Sciences (EUCASS), Belgium, France, 2007.

11. Remesh, N., Jayakumar, M., Finitha, K.C., Abhay Kumar., Shyam Mohan, N. and Swaminathan, S., "Pressure Measurement Sensitivity Studies on a Reusable Launch Vehicle (RLV) Flush Air Data Sensing System (FADS)", Proceedings of National Conference on Space Transportation Systems, Opportunites and Challenges (STS), 2011.

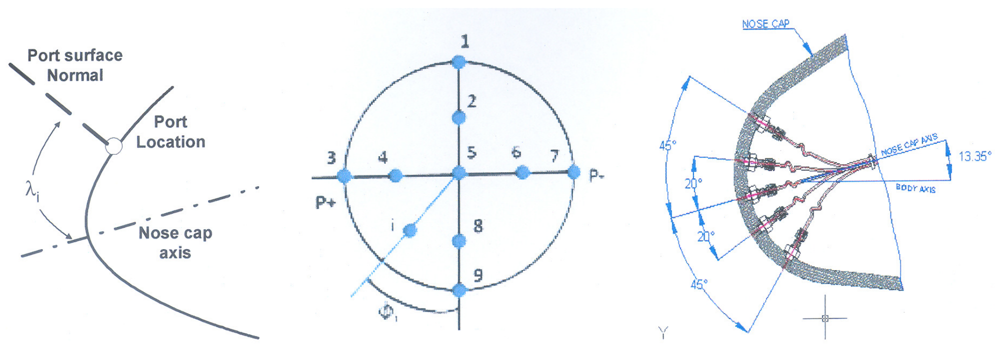

Fig.1 Pressure Port Configuration in FADS

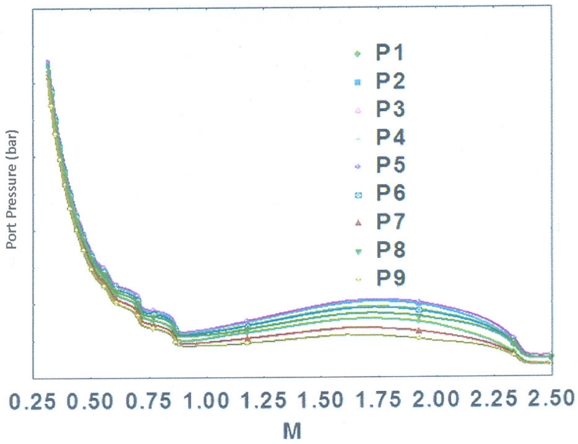

Fig.2 Pressure Variation Among the Nine Pressure Ports

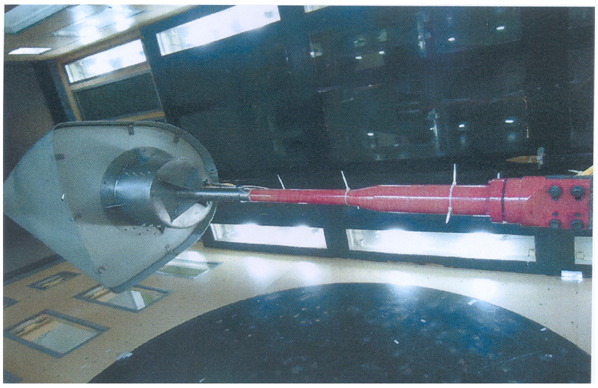

Fig.4 Model Mounted with Sting of Length 1.8 m

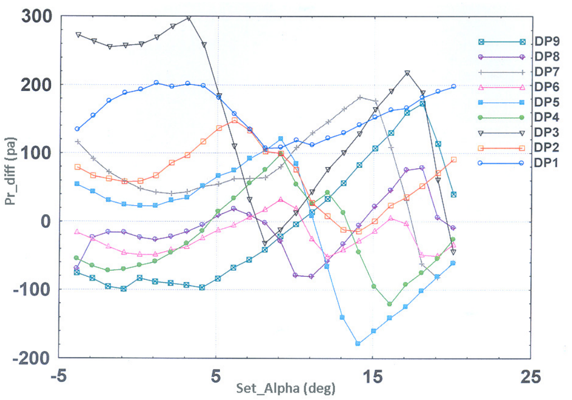

Fig.6 Pressure Difference Between Wind Tunnel Sensor and FADS Sensor (Beta = 0°)

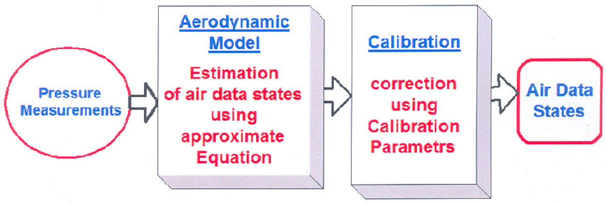

Fig.3 Aerodynamic Model and Calibration Factor

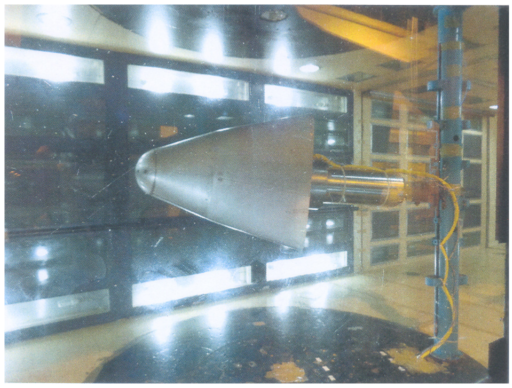

Fig.5 Model Mounted Inside Tunnel Using Modified Sting

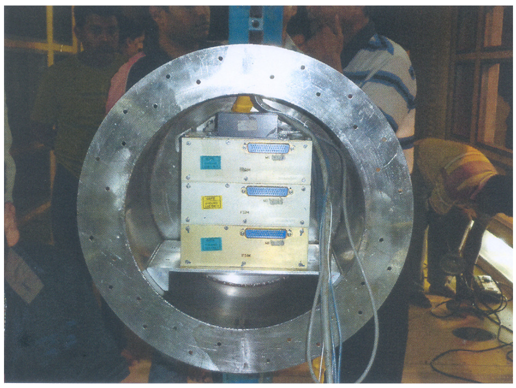

Fig.7 Acquisition Electronics Mounted Inside the Sting

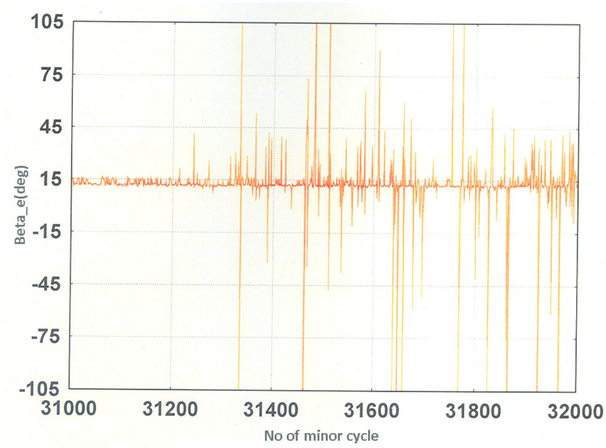

Fig.8 Large Error in Sideslip angle Computation

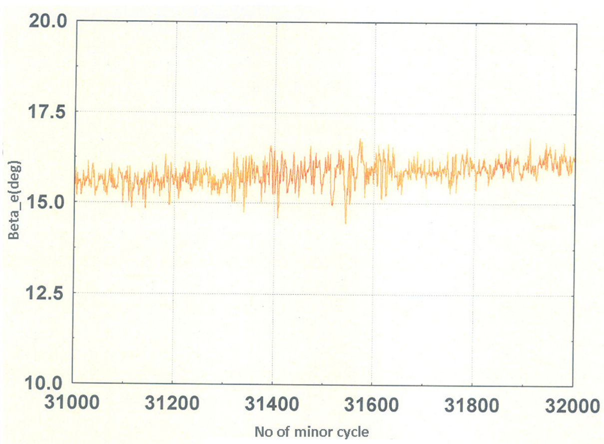

Fig.9 Error in Sideslip Angle with Modified Sideslip Angle Computation Algorithm

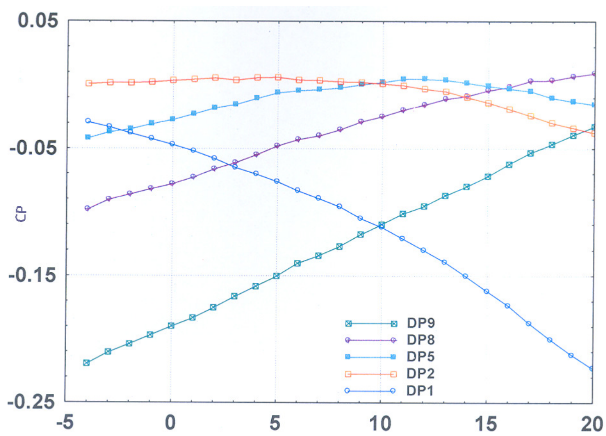

Fig.10 Cp Variation from 1:1 Model to 1:8 Models in Vertical Meridian Port

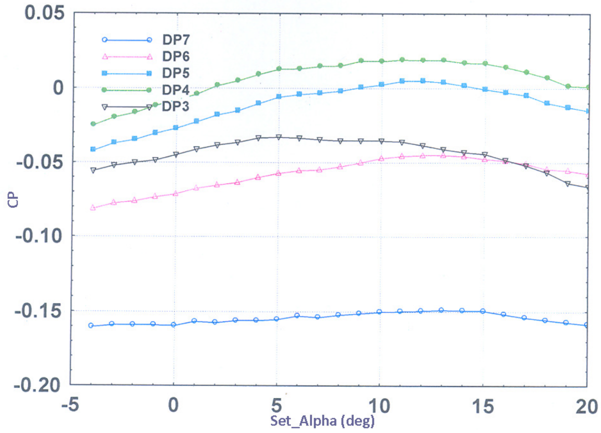

Fig.11 Cp Variation from 1:1 Model to 1:8 Models in Horizontal Meridian Port

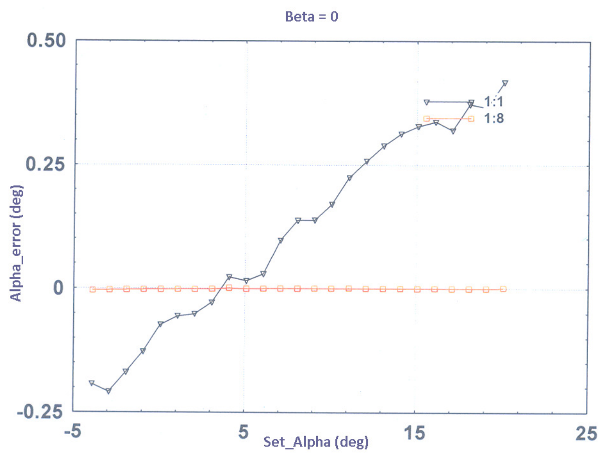

Fig.12 Alpha Error Between 1:1 and 1:8 FADS Model