CFD BASED POSITIONING AND CALIBRATION OF HELICOPTER AIR DATA SYSTEM

Murat Şenipek, murat.senipek@tai.com.tr, Aerodynamics Chief Engineer,
Arın Göksan, arin.goksan@tai.com.tr, Aerodynamics Design Engineer,
Alper Ezertaş, aezertas@tai.com.tr, Manager of Aeronautical Sciences
Turkish Aerospace Inc. Helicopter Vice Presidency (Turkey)

Abstract

This paper presents air data system positioning and calibration activities of T625 Gökbey helicopter via computational fluid dynamics analyses. Air data boom and pitot static probe placement is performed by exploring the critical flight conditions including the effect of main rotor downwash and fuselage aerodynamic characteristics. CFD analyses are performed for all possible conditions covering certification flight envelope and feasible locations are defined for all probes. Main rotor downwash is modeled by using actuator disk model in Siemens STAR CCM+ and ANSYS Fluent together with fuselage. Pressure error correction (PEC) flight tests are performed and flight data is compared with CFD.

1. INTRODUCTION

Correct measurement of air velocity and altitude is vital in flying vehicles. For airplanes, correct measurement of airspeed at low speed flights is crucial not to stall the aircraft. Similarly, for helicopters it is important to know the airspeed to stay in the design envelope in terms of never-exceed speed and low speed height-velocity diagram. Category-A take-off and landing procedures require accurate altitude and velocity measurement. Therefore, calibration of the measurement systems must be done so that error in indicated airspeed and altitude values stays in the certification tolerances.

Figure 1 T625 Gökbey Helicopter with air data boom

In helicopters, air data systems consist of one or more pitot or pitot-static probes, air data computer connected to the probes and other sensors if required. Pitot-static probes are mounted at the helicopter where the disturbances due to rotor and fuselage are minimum. There are mainly two stages for an accurate pitot-static system; which are, pitot-static positioning and calibration.

Pitot static system measures the static pressure and total pressure. Dynamic pressure is calculated by subtracting the static pressure from the total pressure. Then this dynamic pressure value is converted into the airspeed by using the relationship between airspeed and dynamic pressure. From the static pressure measurements combined with air temperature, pressure altitude is obtained.

At low airspeeds such as 20-30 knots, pitot static system interacts with the rotor downwash and static port measurements are not accurate since they may remain in stagnation side or suction side. Therefore, calculated airspeed may be negative or positive according to the static port readings. This error in measuring static pressure should be corrected by using calibration methodologies.

Civil certification requirements (CS-29) of air data system calibration are as follows [1]:

- For Category-A helicopter, indication must allow consistent definition of take-off decision point (TDP).
- The calibration must be determined in level flight at speeds of 20 knots and greater, and over an appropriate range of speeds for flight conditions of climb and autorotation.
- The system error, excluding the airspeed instrument calibration error, may not exceed-
- 3% or (5 knots), whichever is greater, in level flight at speeds above 80% of take-off safety speed (V_{TOSS}); and

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- 10 knots in climb at speeds from 10 knots below take-off safety speed (V_{TOSS}) to 10 knots above V_Y.

Each system must be designed and installed so that an error in indicated pressure altitude, at sea-level, with a standard atmosphere, excluding instrument error of more than ±30 ft per 100 knots speed. However, the error need not be less than ±30 ft.

Civil certification requires a means of calibration in level flight starting at speeds 20 knots up to V_{NE} as well as feasible range of climb and autorotation. This calibration is performed in two phases. Firstly, air data system is calibrated in air data computer (ADC) during the development and certification flight tests by using an appropriate methodology. Secondly, any remaining deviation from the correct airspeed is summarized with a single or multiple chart in rotorcraft flight manual (RFM). Afterwards, civil certification investigates the total system error as described above for 3% or 5 knots in level flight at speeds above 80% of V_{TOSS}, and 10 knots in climb speeds within the described airspeed values. Furthermore, static pressure measurements are critical in terms of altitude instrument error margin.

In order to calibrate the pitot-static system, additional methods such as air data boom, trailing bomb, or airspeed course are required at the initial phase of the flight tests. These systems measure the reference airspeed without being affecting the fuselage and rotor induced flowfield. Therefore, accurate flight speed is obtained and can be used to calibrate the pitot static system.

Measuring the correct airspeed plays a crucial role for helicopter operations besides the certification requirements. The error in the airspeed and position measurement system may cause fatalities during the operations. Indicating the correct airspeed and altitude at lower forward velocities is important for CAT-A Take-off and landings to check the TDP and LDP, moreover it is important for the pilot to know whether the helicopter operates inside the H-V diagram or not. Besides, high forward speeds are also crucial to operate the helicopter at the most efficient forward speed such as best endurance and best range speeds and to operate below the never exceed speed (V_{NE}). Therefore, the reasons outlined above require a detailed work to measure the correct airspeed when considered the complexity of the flowfield around the helicopter.

The purpose of this work is to determine the placement of air data boom and pitot-static probes by CFD to minimize the risks of air data system calibration.

2. METHOD

In order to obtain a reference airspeed and altitude indication with different angle of attack and sideslip values, air data boom is used prior to pitot-static system calibration. Although air data boom provides good measurement, it is required to be identified and characterized due to the effects of fuselage and rotor downwash on the airspeed and static pressure measurements. In calibration procedure, air data boom is located to a point with CFD analyses where rotor and fuselage interactional effects are minimum. Then, additional flight test methods such as trailing bomb, pacer aircraft and GPS based methods are used to determine the measurement error of the air data boom [2] [3] [4] [5]. After these tests, total and static pressure calibration is applied to air data boom to minimize the interactional effects. Then, only calibrated air data boom is used to calibrate the pitot-static system for different altitude, airspeed, temperature, GW and center of gravity settings.

In this paper, CFD based calibration activities will be summarized during the initial placement of air data boom and pitot-static systems. Commercial solvers and in-house developed methods are used to calibrate the airspeed system by analysis. In-house developed Fluent UDF based CFD Embedded Rotor Model (CeRM) is used together with STAR CCM+ Virtual Blade Model [6]. Both tools include blade element based actuator disk models and helicopter fuselage details.

2.1. Flowfield Analyses

Analyses are performed for both ADB and Pitot-Static Probe placement and calibration. Therefore, two different analyses campaign are performed. In the first campaign air data boom and pitot-static probe locations are investigated. Possible air data boom locations are assumed as a straight line extending from the nose of the helicopter. Flowfield information for a 10-meters line is extracted for different flight conditions to observe the pressure changes to place the air data boom as illustrated in Figure 2.

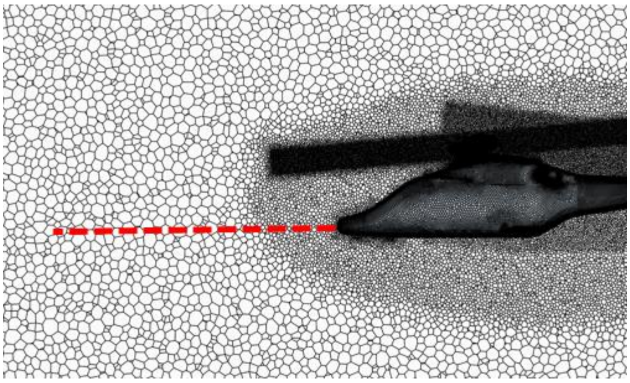

Figure 2 Air-data boom data extraction line

Sample angle of attack and forward airspeed envelope is illustrated in Figure 3. Marked points are analyzed with CFD. For all airspeeds and angle of attack values main rotor thrust trim is achieved for given gross weight by using actuator disk model.

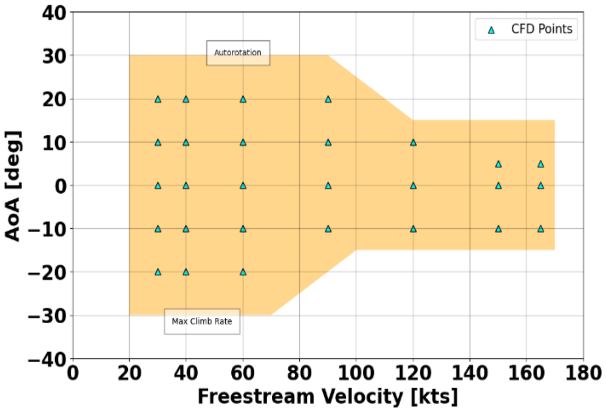

Figure 3 Analyzed angle of attack and indicated airspeed

Together with these analyses, the possible locations for left and right pitot-static probes are investigated. Flowfield data is extracted for several points to observe the pressure field changes for pitot-static probe positioning. As illustrated in Figure 4, CFD analyses are performed to locate the pitot-static probes.

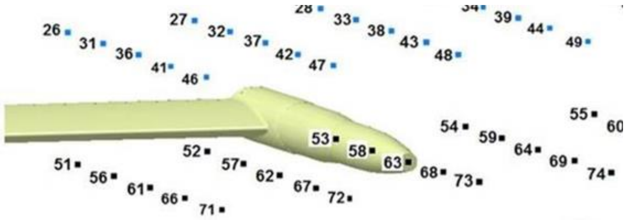

Figure 4 Data extraction points for pitot-static probes

Helicopter fuselage is modeled together with main rotor actuator disk as illustrated in Figure 5. In order to simulate correct downwash effects, main rotor thrust is trimmed to helicopter weight and required incidence is provided via shaft tilt angle to simulate tip path plane effects for different flight conditions such as maximum climb and autorotation.

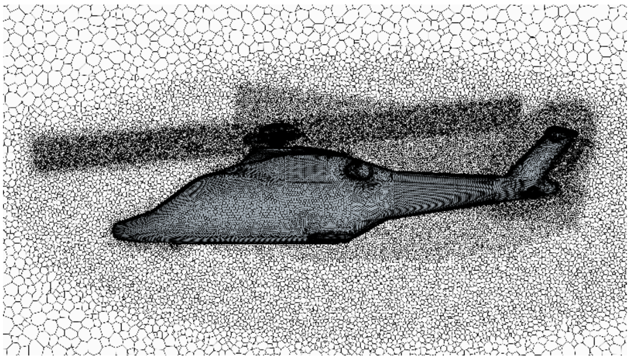

Figure 5 Volume mesh cross-section

The surface and volume mesh is prepared with polyhedral elements by Star-CCM+ software. Analyses are performed under sea level atmospheric conditions with rotor interactions. To simulate the main rotor downwash effect actuator disk (steady) and actuator line (unsteady) models are used. Steady actuator disk models provide quick and sufficient insight for the interactions between main rotor downwash and fuselage. On the other hand, unsteady simulations are useful to identify the main rotor blade passage effects on the ADB and Pitot-static system. Nearly 3 million polyhedral cells are used to discretize the physical domain. Boundary layer is built according to wall function approach with 5 layers. Probe points are placed in the domain to their original coordinates as shown in Figure 6. Velocity and total/static pressure data is obtained from the probe points.

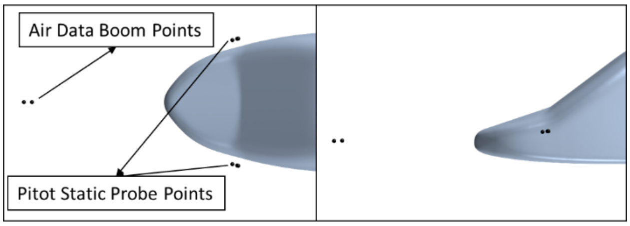

Figure 6 ADB and Pitot-Static Probe Points

Extracted (velocity being read directly from the probe) and calculated velocity (with formula below) are compared. Since in unsteady simulations pressure and velocity data oscillates, an averaging is done for 1 revolution and in the graphs these averaged data is used.

$$V_{Calc} = \sqrt{(P_t - P_s)/(\frac{1}{2} * \rho)}$$

It is aimed to find a location that provides consistent deviation from the freestream having the shortest arm to minimize the structural and vibrational issues due to the length of the air data boom.

There are two main requirements for a feasible point that are:

- Static pressure deviation should be minimum and possible to be calibrated for altitude error,
- Total pressure deviation should be minimum and possible to be calibrated for velocity error.

After determining the feasible points for ADB and Pitot Static Probes, new set of analyses are performed to obtain the required calibration data for wide range of airspeed. Pitot-static and air data boom are physically modeled and system error margins are compared with the test data.

3.2. Air Data Calibration

After obtaining required data from CFD calibration following calibration methodology that is called as static source error calibration (SSEC) can be implemented over the total and static pressure to provide corrected total and static pressure values. Two tables will be required that includes total and static pressure correction coefficients for different dynamic pressure values.

$$pc_t = pi_t + Kt$$
$$pc_s = pi_s + Ks$$

Where

$$Kt = f(Q_{dyn}, Kt)$$
$$Ks = f(Q_{dyn}, Ks)$$

Above equations states that there will be a correction factor for both total and static pressure measurements. Static measurement calibration mainly corrects the indicated altitude, and together with total measurement calibration, airspeed is calibrated. These coefficients will be determined with the calibration flight tests. In addition, direct calibration of airspeed is also possible by providing a correction curve directly to measured airspeed to correct Indicated airspeed for placement errors. Furthermore, some specific methods are existed to calibrate the low speed measurements to estimate a non-zero airspeed of the aircraft as a function of the measured negative impact pressure.

3. RESULTS

Analysis results for air data boom positioning for a 10 meters line starting from the nose of the helicopter is obtained. Air velocity deviation for hover and different forward flight conditions are obtained and illustrated in Figure 7 and Figure 8. In hover case after 2 meters from the nose, velocity deviation becomes less than 4 knots.

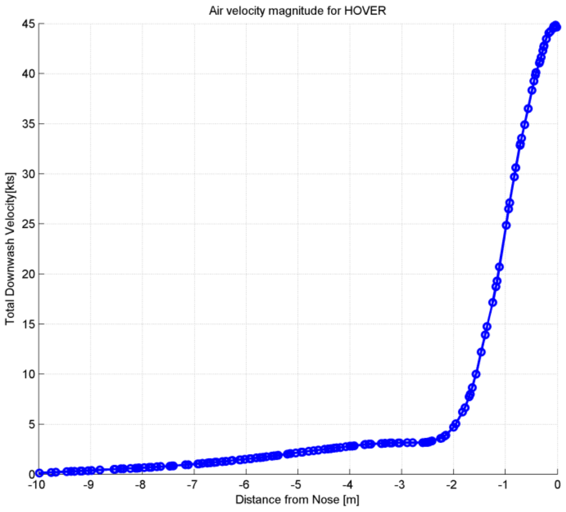

Figure 7 Main rotor downwash effect on possible air data boom locations

Velocity deviation from 40 knots to 120 knots level flight conditions are illustrated in Figure 8. There is a high main rotor interference below two meters from the nose of helicopter. However, almost zero deviation for forward velocity is possible for an air data boom having 8m length.

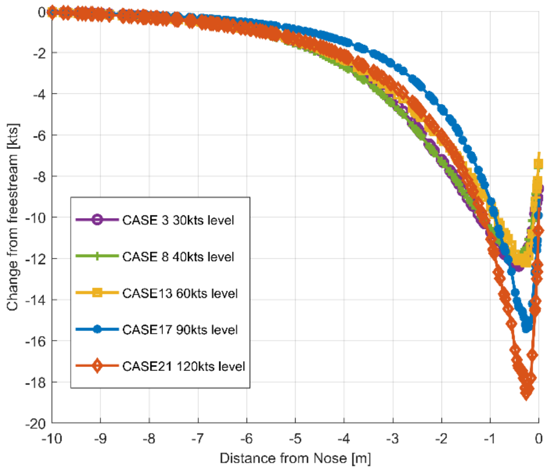

Figure 8 Velocity deviation from freestream in level flight

It is not a feasible result when structural and vibrational complexities are considered. Therefore, a location having a consistent bias from the freestream velocity will be more feasible. If the bias does not vary significantly for different flight conditions, calibration of air data boom will be more straightforward. It is observed that a location after 1.5 or 2.0 meters seem to be feasible in terms of consistency and calibration.

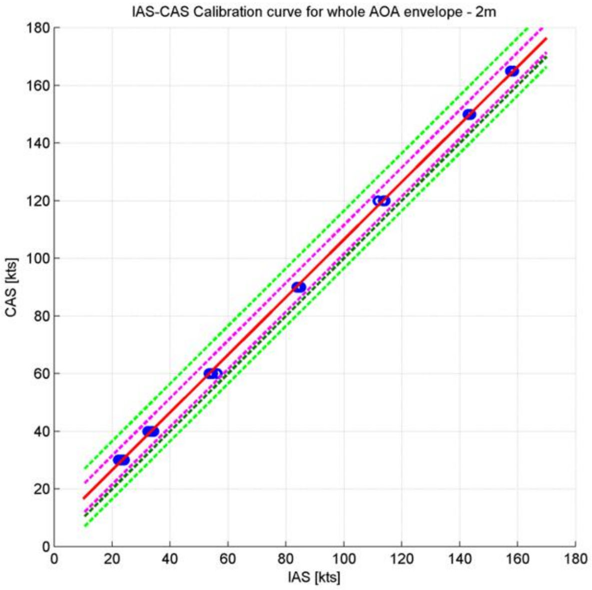

Figure 9 Linear calibration curve for ADB

In Figure 9 sample linear calibration is applied to air data boom velocity as $CAS = A \times IAS + B$ for 2 meter location is given and maximum difference for the highest angle of attack values are around ~1 knot. Velocity error margins from CS29 are plotted as dashed lines that are simply 5 knots for level flight and

10 knots for climb and descent conditions. Therefore, linear calibration of air data boom after 2 meters is predicted to be possible by CFD analysis.

For pitot-static probes, it is shown that after 40 knots airspeed can be calibrated in level flight by a linear curve fit and the maximum error is around 3 knots for level flight as provided in Figure 10. However, the scattering of airspeed is wide at lower airspeeds due to main rotor downwash interaction.

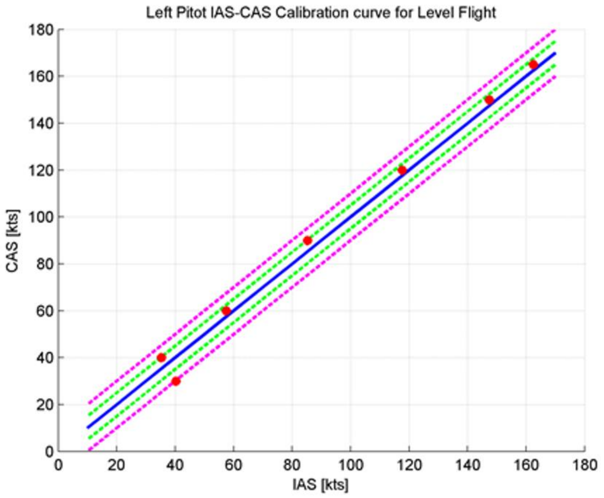

Figure 10 CFD generated pitot-static calibration curves

After finalizing the locations of the ADB and pitot static system. More analyses that are detailed are performed to compare with the available test data. In this paper, only uncalibrated level flight test data is compared with the analysis for both steady and unsteady simulations as given in Figure 11 and Figure 14.

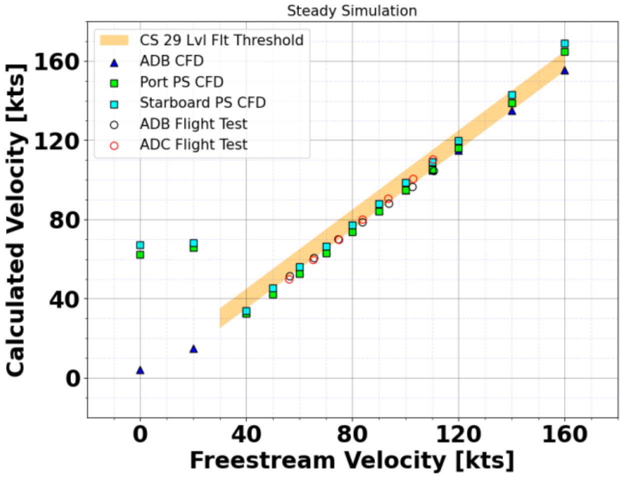

Figure 11 Level flight steady disk simulation results vs. uncalibrated test data

Flight test data of ADB is shifted from the freestream by ~3-4 knots up to 110 KIAS. Identical trend is obtained from the CFD results. For flight test data of ADC (represents pitot static system readings), it is seen that the line is steeper than ideal line. Around 100 knots, velocity reading from ADC is similar to freestream that is consistent with CFD data. Both test and CFD results shows an almost constant deviation in IAS for ADB, and negative to positive error for ADC. The reason will be discussed in the following chapters. This type of constant deviation may be easily calibrated with a constant or linear calibration curve.

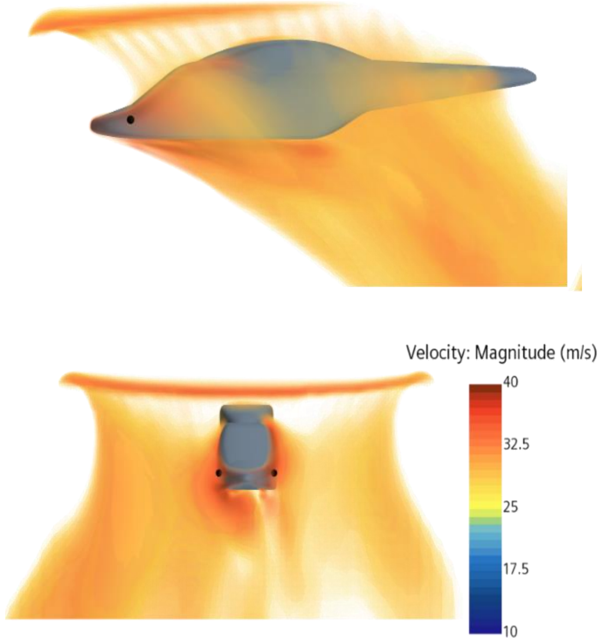

Figure 12 Velocity contours for 20 knots level flight condition

In Figure 12, the effect of the main rotor downwash on the Pitot tubes is visualized. The rotor downwash is directed towards Pitot locations that causes huge deviations in measurements.

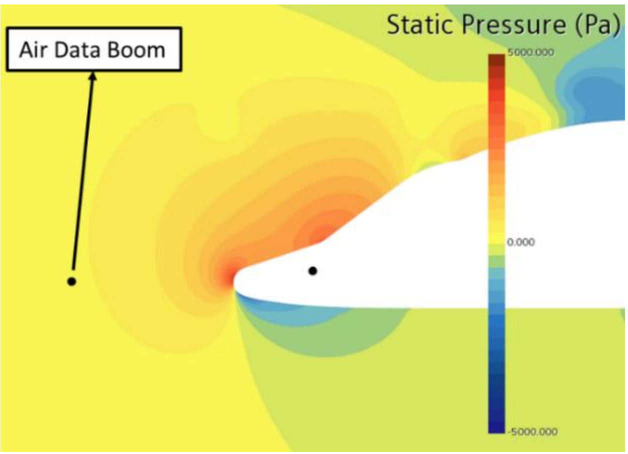

Figure 13 Static pressure contours @160 KIAS, negative α

In Figure 13, static pressure contours from steady simulation are plotted. For 160 KIAS air data boom measures pressure close to freestream that indicates that air data boom measurements are not highly affected by fuselage at high speeds. Slight difference caused by the fuselage due to stagnation of air at the nose of the helicopter.

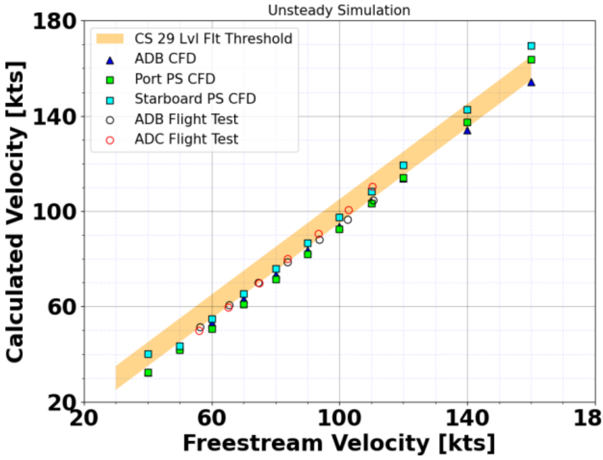

Figure 14 Level flight unsteady disk simulation results vs. uncalibrated test data

In Figure 14, CFD data that is obtained by unsteady actuator line model is compared with the flight test data. Trends are almost identical after 40 knots when compared with the test data for both ABD and ADC. However, for low airspeeds there is not huge measurement errors. It can be concluded that the usage of steady disk increases the main rotor downwash effects on the pitot-static probes.

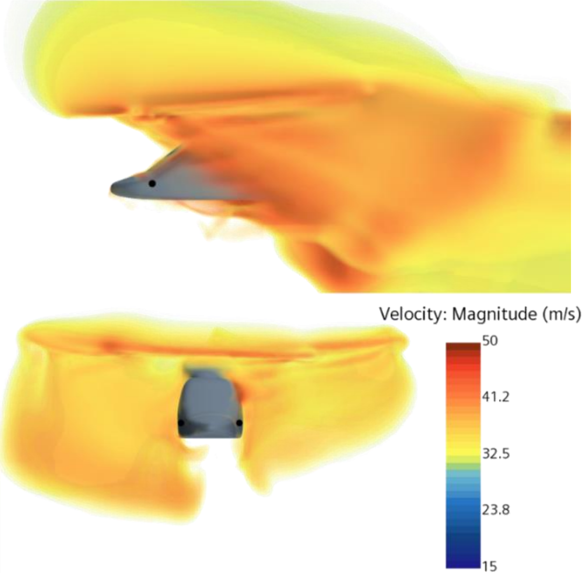

Figure 15 Velocity Contours for 40 KIAS of level flight condition (Unsteady)

In Figure 16, steady simulation is conducted without actuator disk (i.e. without rotor downwash) to observe the effect of fuselage presence on air data boom and Pitot-static system. It is observed that as the airspeed increases, measurements at the location of ADB provide smaller values of airspeed. Presence of the fuselage nose increases the static pressure upstream. On the other hand, Pitot-static system readings separate positively as increasing KIAS due to high velocity region near the front fuselage.

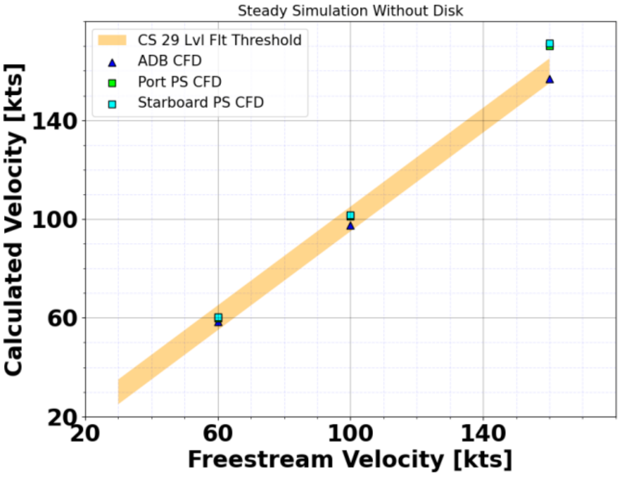

Figure 16 Simulation results with Fuselage only (w/o disk)

In addition to level flight analyses, climb and descent cases are analysed with CFD Actuator Disk. Figure 17 and Figure 18 shows data obtained from descent/climb with steady analyses. In climb cases, the effect of rotor wake is more dominant.

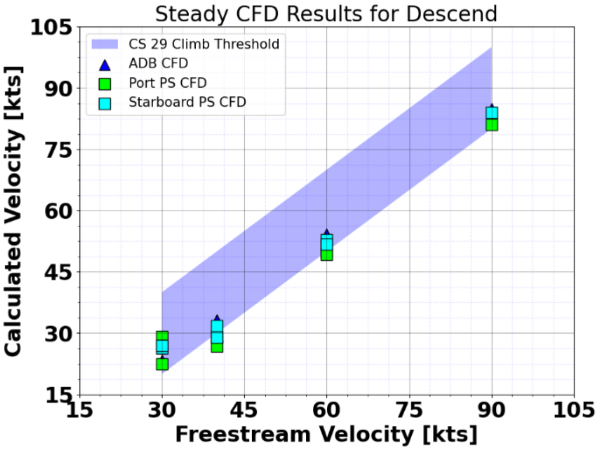

Figure 17: Steady CFD Results for Descend

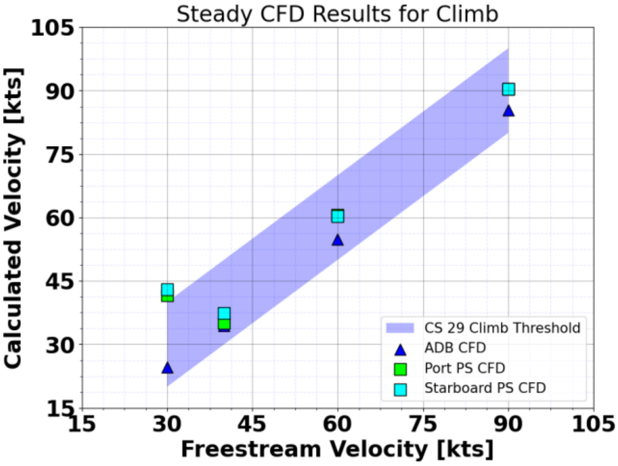

Figure 18: Steady CFD Results for Climb

In descent cases calculated air velocity is within the CS 29 limits, whereas in climb cases freestream is above the CS 29 limits.

In Figure 19, CFD data obtained by using actuator line model (unsteady) for climb cases is presented. Similar behavior is observed with the data obtained using actuator disk model (steady).

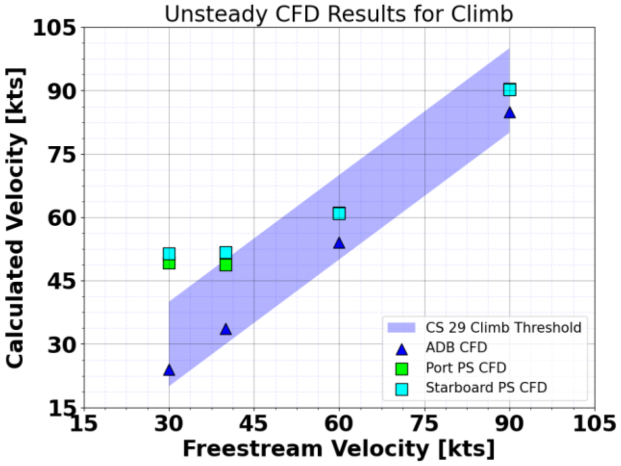

Figure 19: Unsteady CFD Results for Climb

4. CONCLUSION

In low airspeeds, pitot-static probes are influenced by main rotor downwash, especially in climbing flight as illustrated in Figure 20. However, as the forward velocity increases this effect is minimized. At higher airspeeds, apparent airspeeds at the pitot-static probes are high due to aerodynamic shape of helicopter fuselage nose structure.

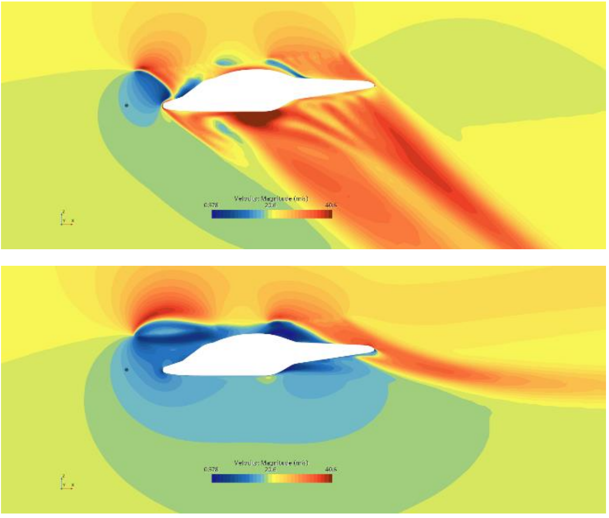

Figure 20 Velocity deviation contours & ADB location for 40 knots climb and descent cases

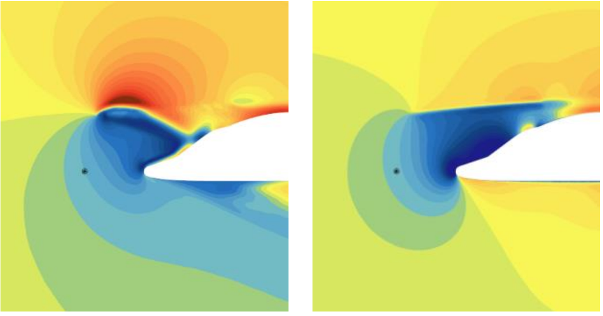

Figure 21 Velocity deviation contours & ADB location for 40 knots and 150 knots level flight

Almost constant velocity deviation of air-data-boom given in is visualized in Figure 11 and Figure 14. It can be observed from the colormap that the location of air-data-boom probe always stays inside the same velocity deviation region.

Finally, finalized air fata boom and pitot static system locations are determined by CFD and CFD analyses are performed including the helicopter flight trim condition to compare the behavior of air-data-boom, port and starboard pitot-static probes since there may be difference due to main rotor swirl and rotor pressure field.

Test data is consistent with the flight data for level flight conditions for both ADB and ADC. In level flight conditions, ADB measures lower airspeed than the actual airspeed mainly due to the presence of the fuselage. ADC measurements are changing with almost a linear pattern around the ADB measurements. Their readings indicate lower airspeed below 100 knots and slightly higher airspeeds above. ADC readings are also consistent with the CFD analyses and the calibration is possible with a single linear calibration line on either pressure values or airspeed values.

CS-29 threshold airspeed values are provided illustratively and will be determined as the V_{TOSS} and V_Y values are identified.

Analyses shows that during the descent cases, both ADB and ADC works well and will not require high effort for calibration since the rotor downwash effects are minimized.

Climb cases show problematic behavior for low airspeeds; however, specific calibration methodologies may be implemented to calibrate the low speed measurement after performing several flight tests.

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