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NUMERICAL INVESTIGATION OF ROTORCRAFT PRESSURE ERROR CORRECTION BY UTILIZATION OF AIR DAMS

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Abstract

Pitot Static System is a traditional rotorcraft system, utilized to provide flight data parameters. According to aviation standards, the system must be capable of operating during all flight phases of the rotorcraft. However, especially during climb and descent maneuvers, the unsteady phases of the flight, the Pitot Static System struggles to provide adequate data. Generally, this phenomenon is caused by the interaction between the rotorcraft downwash, rotorcraft body and the static sensing ports of the system. To achieve satisfying readings during steady and unsteady flight conditions, static ports must be able to read uninterrupted free stream data. Installation of small barriers called air dams around static ports can help the system to achieve accurate airspeed readings during flight maneuvers. The application of different air dam geometries is investigated using computational fluid dynamics (CFD).

Keywords: CFD; Pitot-Static; Air Dam; Pressure Coefficient; Static Pressure

1. Introduction

Pitot Static System is a traditional system in aviation, utilized to provide flight data parameters such as airspeed, altitude and vertical speed to flight control systems and pilot monitor devices. The system consists of pitot probes, static ports and connecting hoses. Pitot probe and static ports can also be placed on the same equipment which is also called pitot static probe. Pitot probe allows the reading of total pressure. Static port is utilized to measure the static pressure in the undisturbed free flow around the aircraft. Additionally, Pitot Probes (or Pitot Static Probes) and Static Ports are equipped with internal heaters to avoid any accumulation of icing on the surface of the equipment.

Accurate airspeed measurements are required to avoid loss of control and to prevent collision from terrain obstacles. According to EASA Large Rotorcraft Certification Standard CS-29 [1], certified helicopters' Pitot Static System must be designed as fully redundant and capable of providing accurate data between the 10 knots below take-off safety speed to 10 knots above best rate of climb speed of the helicopter.

Providing accurate data is a challenge for Pitot Static System. System suffers from both lag, position and instrument errors. Lag error is caused by unsteady flight maneuvers and routing lengths. With the advancements in sensing technology, instrument errors are becoming negligible. For Pitot Static System, the main source of error is considered as position error. Position error can be briefly described as the disturbance in the free flow, which is caused by rotorcraft body effects. Since static ports are installed on the airframe surface, it can be said that almost always local static pressure is different than freestream static pressure. In this study, only the position error is considered for investigations. Yang H. and Yang S. [2] reported the effects of airframe surface static port installation on static source error.

Gracey W. [3] showed that the installation of static ports has great impact on static pressure measurement capability of the system. Hearing Edward A. [4] demonstrated the subsonic static pressure distribution variation on the aircraft body. Local static pressure can change rapidly in short distances depending on the aircraft structure. Wu et al. [5] brought out that during design phase, an effort must be realized to successfully read undisturbed freestream static pressure. Generally, this effort is actualized with the determination of the location of pitot probe and static ports on the helicopter. Ellingson et al. [6] investigated the effects of probe placement on static pressure measurement.

After determining location of pitot probe and static ports, flight tests must be conducted to verify the readings of the pitot static system. Many recommended practices [7], [8] and papers [9], [10] tackled the flight test methods and procedures of the pitot static system.

Following the completion of flight tests, if pitot static system fails to satisfy the airspeed reading needs according to flight test data, extra steps must be taken to eliminate airspeed reading errors. As stated in [11] air dams can be utilized in many different alignment and orientation to minimize the error during different flight maneuvers.

Unfortunately, there is a shortage of information about the air dam design and installation on the aircrafts and the applications which aim to influence static pressure variation on certain bodies are also little. Especially in vehicles, front air dams are utilized and their effects on static pressure variation are referred in [12], [13].

In this paper, different air dam designs are investigated. The different designs are obtained by changing the orientation, alignment and/or the angle of air dams. The effects of such variations of air dams on the accuracy of static pressure readings are addressed. As shown in the coming sections, different designs can result in different outcomes for different flight maneuverers. Thus, each helicopter must have its own air dam design in order to achieve the most useful result.

2. Pitot Static System Basics

Pitot Static System captures the total and static pressure values which are required to indicate navigational data such as altitude, airspeed and vertical speed. Generally, Pitot Static System is composed of pitot probe, static ports, drain ports and connecting tubing. In this paper we will study the separate pitot probe and static port combination.

Air data computers located at the end of pitot and static lines sense pressure values to generate navigational data. Number of pitot probe, static port and connected air data computers can vary according to design considerations of the aircraft. An example of Pitot Static System architecture is given in Figure 1.

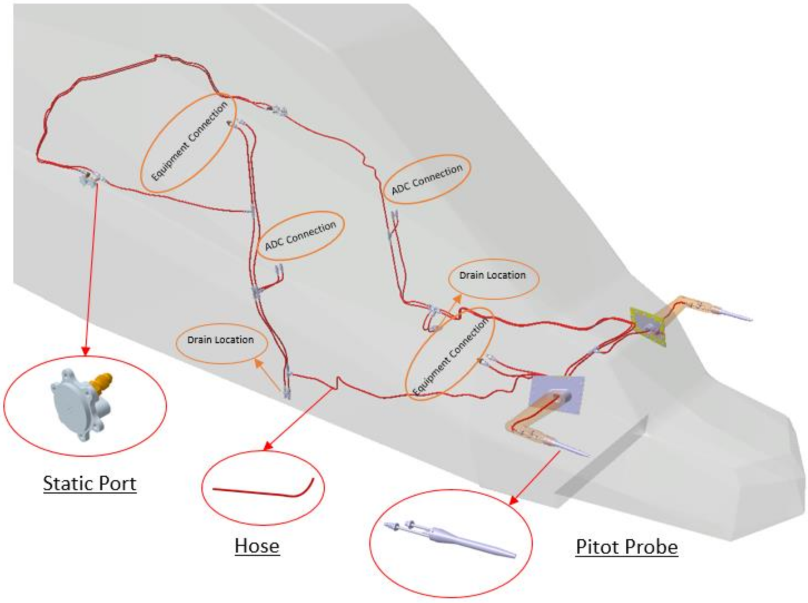

Figure 1 – An Example Pitot Static System Architecture

Captured total and static pressure is transmitted to air data computers via connecting tubing. Total pressure is transmitted from pitot probe to air data computers. Similarly, static pressure is transmitted from static port to air data computers. Airspeed is then calculated by air data computer. Air data computer has its own pressure transducer to sense the pressure transmitted through the tubing.

The airspeed calculation is done by utilizing Bernouilli's equation for incompressible flow. Total pressure (p_t) and static pressure (p_s) is sensed by pressure transducer and are used to calculate the airspeed.

$$p_t = p_s + \frac{1}{2}\rho V_{true}^2 \tag{1}$$

$$p_t - p_s = q = \frac{1}{2}\rho V_{true}^2 \tag{2}$$

Difference between total pressure and static pressure yields the dynamic pressure (q). To calculate the true airspeed, density of the air must be known. On the other hand, for low Mach number flights, if the density value of air (ρ) is assumed to be the sea level value, instead of true airspeed, indicated airspeed can be calculated. However, this indicated airspeed value also contains the errors, which can be caused by lag, position or instrument errors. As mentioned before, lag and instrument errors are neglected in this paper. Thus, the error contained in airspeed reading is considered to be only caused by position error.

3. Position Error

Position error or installation error, is the deviation of local pressure values on sensing probe/port from the free air stream. It can be caused by the shape, location or orientation of the port. Both total pressure and static pressure readings may lack accuracy due to position errors. The position error limits for airspeed readings of rotorcrafts which are applicable to the requirements of EASA CS-29 Category A rotorcraft, are given in Figure 2.

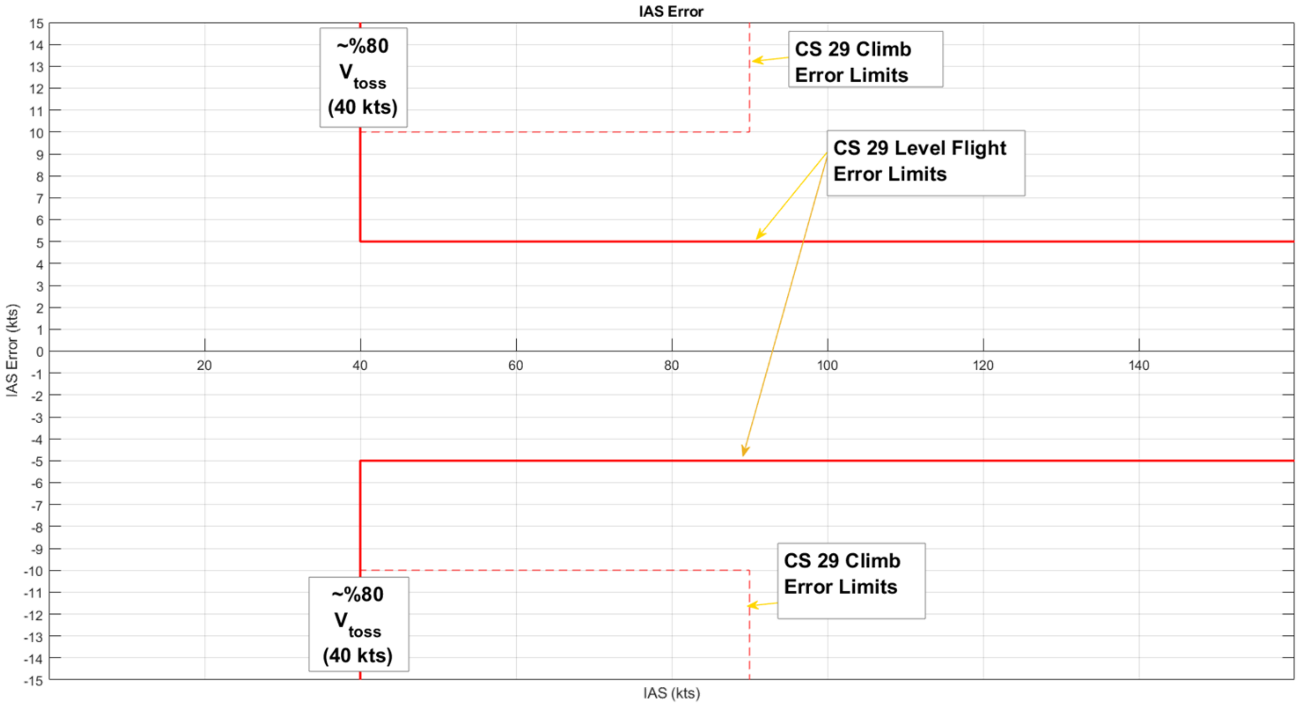

Figure 2 – CS-29 Airspeed Measurement Error Limits

The pitot static system position error of a rotorcraft shall not exceed the error limits given in Figure 2 in order to successfully get an EASA certification and permit to flight. Rotorcraft manufacturers must conduct flight test campaigns to validate the airspeed readings of rotorcrafts. At the end of the flight test campaigns, if the error calculated yields result that is hard or even impossible to calibrate, design process of pitot static system might have to go back to scratch, which highly impacts the cost and schedule of the project. Therefore, to minimize the position error beforehand the flight test campaign, aerodynamic placement analysis is conducted by rotorcraft manufacturers to place the pitot probe and static ports to adequate locations to minimize the position error.

As mentioned before, for the preliminary positioning of the pitot probe and static port, rotorcraft manufacturers conduct flow field analyses to find suitable locations to place pitot probe and static port on rotorcraft. The aim of the analysis is to attain a location where static pressure variation is minimum (pressure coefficient (c_p) = 0). It is possible to find $c_p = 0$ condition on helicopter surface, however it is not necessary to achieve the placement on $c_p = 0$ locations. Instead, CS 29 limits should be aimed to be achieved to loosen the placement restraint. Otherwise, the locations that pitot probe and static port can be placed will be very limited. Additionally, with the utilization of airspeed calibration process, also called as position error correction, even with high c_p values, the CS 29 limits can still be satisfied. So, main consideration should be having c_p values which can be calibrated by airspeed calibration methods. Error limits given as knots in the Figure 2 can be translated into c_p values. c_p limits according to CS 29, are given in Figure 3.

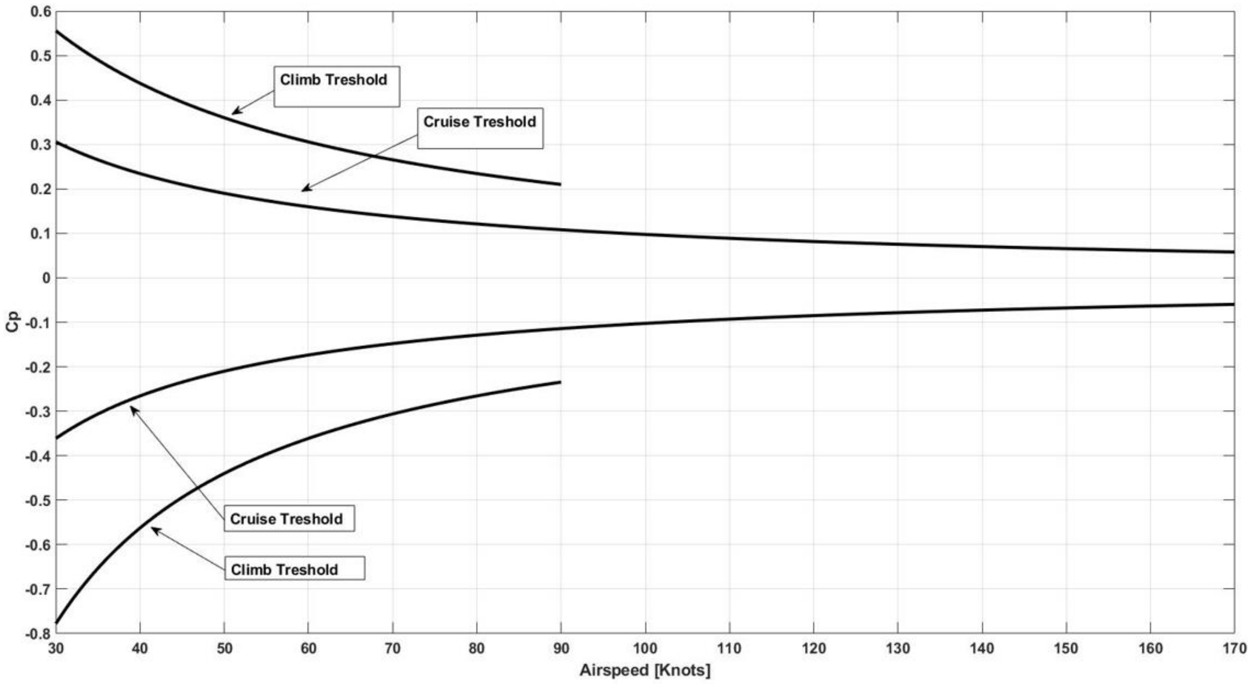

Figure 3 – CS-29 Airspeed Measurement Error Limits Translated to c_p

Generally, because of the restrictions of AS8006A [14], commercially available pitot probes easily give accurate readings up to ± 20° angle of attack. AS8006A is a pitot probe performance standard which strictly restricts the airspeed reading accuracy for pitot probes up to ± 20° angle of attack. It is required to comply to this standard in order to get CS-29 certification. Since the main goal is to pursuit CS-29 certification, if we assume a pitot probe which is applicable AS8006A is utilized for pitot static system under study, we can say that pitot probe can generate healthy total pressure values. Thus, we can specify the static ports as the main source of position error.

4. Pressure Error Correction Process

Since the generated indicated airspeed value contains position errors that has been caused by the considerations which mentioned in the previous section ($c_p \neq 0$), this position error should be minimized in airspeed readings. The elimination of position error consists of comparing the rotorcraft's airspeed readings with a reference airspeed indicator. The reference airspeed indicator can be an equipment which is mounted on the helicopter or it can be a completely different aircraft with a precisely calibrated airspeed indicator to compare the airspeed readings. Following the determination of the error generated by the readings of the air data computer, a calibration curve is created to correct the airspeed readings. In air data computer applications, these curves can be implemented to the readings by the air data computer.

Airspeed calibration can be realized at main flight control computers of the rotorcraft. However, applying these calibration formulas to main flight control computers, increases the safety level of the equipment, thus it is not preferred by many rotorcraft manufacturers. Instead, one of the methods that has been provided by air data computers is selected for airspeed calibration. IAS/CAS conversion is one of the most used calibration methods to eliminate position errors from airspeed readings. IAS/CAS conversion simply shifts the airspeed readings in one direction. An example study conducted as part of this research is given in Figure 4.

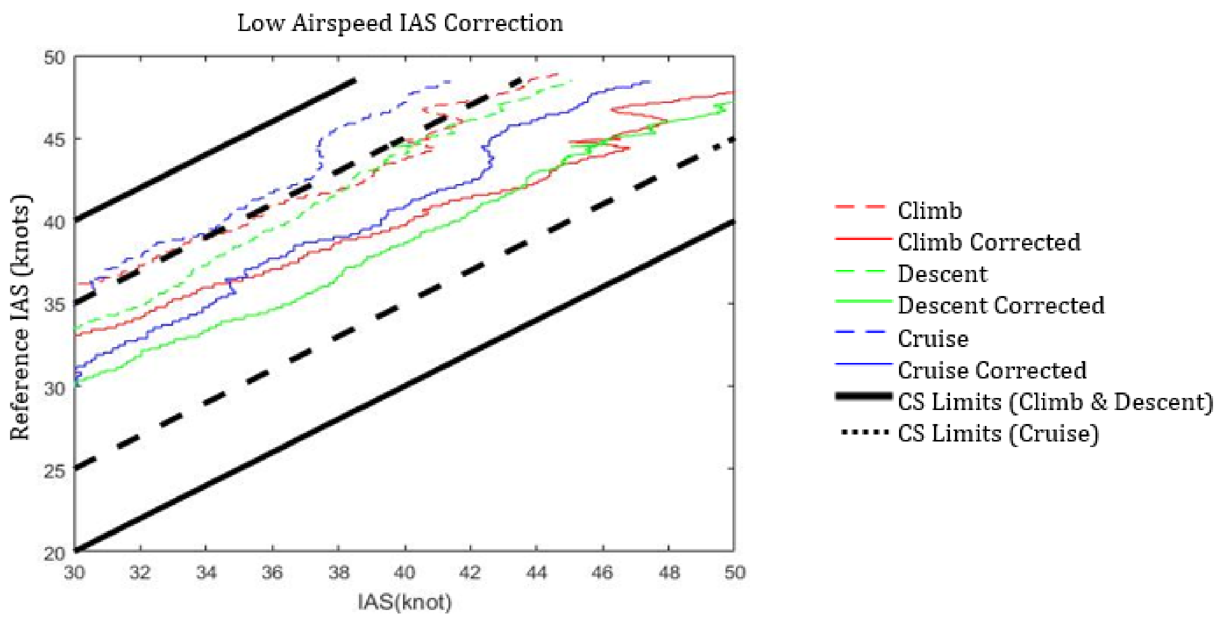

Figure 4 – IAS/CAS Calibration Study

Data utilized in Figure 4 is a virtual rotorcraft which has airspeed error around 5 knots in all flight maneuvers. This virtual rotorcraft has no angle of attack sensor to separate the maneuvers from each other. Therefore, there is no possible way to separate the maneuvers from each other and apply different calibration curves to different maneuvers. The airspeed correction is applied to all maneuvers at once.

The air dam study will be conducted on a rotorcraft with similar features.

- No angle-of-attack sensor is present.
- Corrections applied by air data computer shifts all airspeed data. (Cruise, climb and descent)

5. Air Dam Design Process

For the cases, where calibration by air data computers can not satisfy CS29 limits, a physical intervention to pitot static system is required. It can be done either by changing the location of probes/ports of the system or by manipulating the airflow around this equipment to satisfy the airspeed error limitation needs. The first option is not desired by helicopter manufacturers because the process has very high cost. It impacts the whole qualification and certification process of the system. Many of the test and analysis that has been conducted on pitot static system should be repeated afterwards. However, if one can successfully manipulate the airflow around the probes/ports, there will be no need to repeat any ground tests on pitot-static system. Thus, second option is much more desirable for helicopter manufacturers to save time and money.

As mentioned before, static port can be considered as the main source of the position error. Pitot Probe's nature is much more tolerant to the angle changes of the incoming flow. So, we can decide that, airflow around the static ports should be manipulated. To be able to successfully achieve the required readings from the static ports, the required c_p values must be determined from a placement analysis. For this case study, a generated data from previous calibrations is used. The c_p values gathered around static port placement is given in Figure 5.

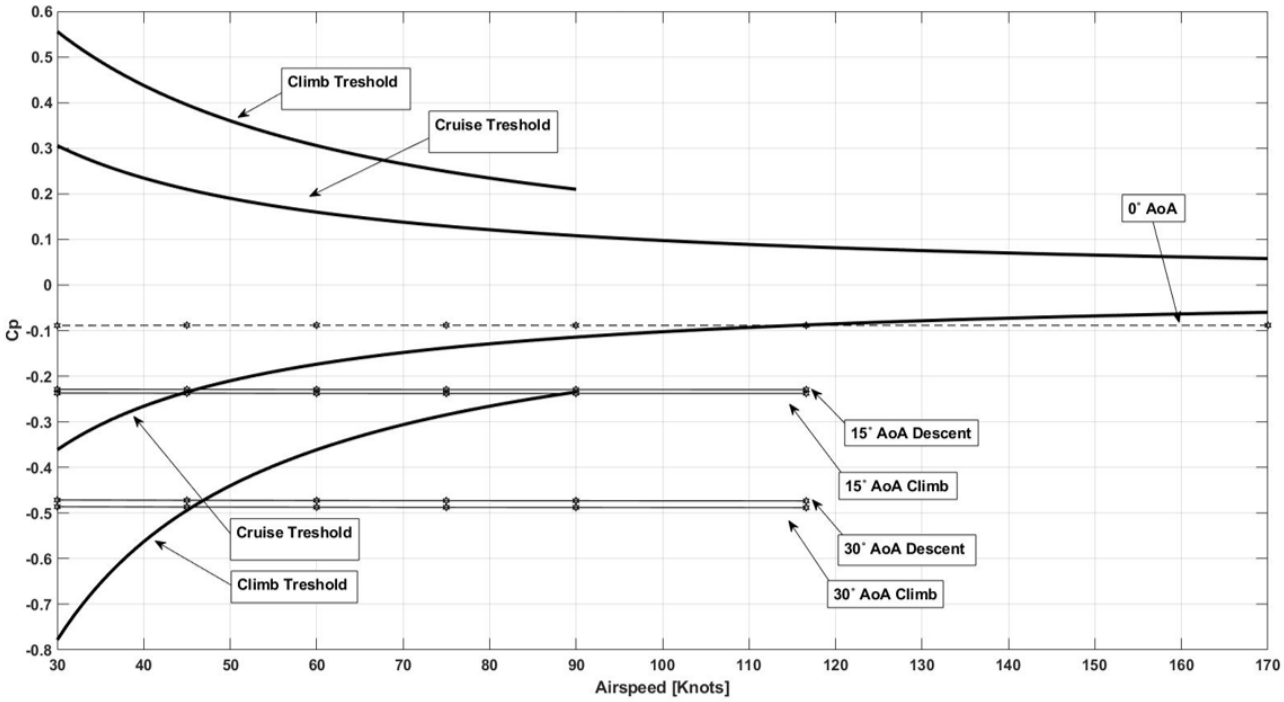

Figure 5 – c_p Values of Static Port Placement Under Study

According to Figure 5, air dams should increase c_p during cruise by around 0.1, while during 15° and 30° climb and descent, c_p increases by around 0.22 and 0.48 respectively. Since descent and climb has similar c_p characteristics, a symmetric air dam configuration is considered.

The c_p calculations are conducted by solving the flow field around air dam using the RANS equations. The RANS equations are given in a conservative form as:

$$\frac{\partial}{\partial t}\int_V Q\, dV + \oint_S (\mathbf{F}\cdot\mathbf{n})\, dS - \oint_S (\mathbf{F_\upsilon}\cdot\mathbf{n})\, dS = \int_V s_T\, dV \tag{3}$$

Where,

$$Q = \begin{Bmatrix} \bar{\rho} \\ \bar{\rho}\,\bar{u}_1 \\ \bar{\rho}\,\bar{u}_2 \\ \bar{\rho}\,\bar{u}_3 \\ \bar{\rho}\,\bar{e}_0 + (\overline{\rho' e'} + k) \end{Bmatrix}, \quad F_j = \begin{Bmatrix} \bar{\rho}\,\bar{u}_j + \overline{\rho' u'_j} \\ \bar{\rho}\,\bar{u}_1\bar{u}_j + \bar{p}\delta_{1j} + \overline{u_1}\,\overline{\rho' u'_j} + \overline{\rho' u'_1}\,\bar{u}_j \\ \bar{\rho}\,\bar{u}_2\bar{u}_j + \bar{p}\delta_{2j} + \overline{u_2}\,\overline{\rho' u'_j} + \overline{\rho' u'_2}\,\bar{u}_j \\ \bar{\rho}\,\bar{u}_3\bar{u}_j + \bar{p}\delta_{3j} + \overline{u_3}\,\overline{\rho' u'_j} + \overline{\rho' u'_3}\,\bar{u}_j \\ \bar{\rho}\,\bar{h}_0\bar{u}_j + \bar{e}_0\,\overline{\rho' u'_j} + (\overline{\rho' e'} + k)\,\bar{u}_j \end{Bmatrix} \tag{4}$$

And

$$F_{\upsilon j} = \begin{Bmatrix} 0 \\ \bar{\tau}_{1j} - \tau^T_{1j} \\ \bar{\tau}_{2j} - \tau^T_{2j} \\ \bar{\tau}_{3j} - \tau^T_{3j} \\ \bar{u}_i\bar{\tau}_{ij} - \bar{q}_j + \Theta^T_j \end{Bmatrix} \tag{5}$$

For this purpose, Fluent R2022 commercial computational fluid dynamics software is utilized. Air dam can be configured with many different options. Some of the sample configurations and static port placement are given in Figure 6.

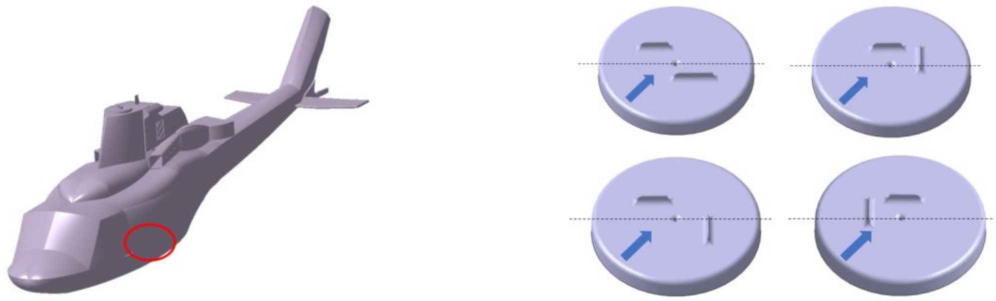

Figure 6 - Static Port Placement on Helicopter Body and Several Variations of Air Dam Alignments

The most suitable dam configuration should be able to achieve to balance c_p values around 0. The data shows that, air dams should increase the c_p values during cruise, climb and descent. However, the rise of the c_p should differ in each case. In cruise, c_p increase should be minimum. On the other hand, during climb, c_p increase should be almost two times larger than cruise to balance the c_p value around 0.

For this purpose, 8 different dam designs are prepared to investigate the effect of dams on c_p values. As mentioned before, dam configuration will be handled as symmetric because of the c_p characteristics of the studied case. A simplified model for air dam configuration is utilized during the analyses. Whole helicopter model is not included to save cost and time. Air dam configuration is placed on a flat plate to observe locally raised surface pressure distribution around the dam. Calculations are realized for 8 different dam designs with different angle of attacks.

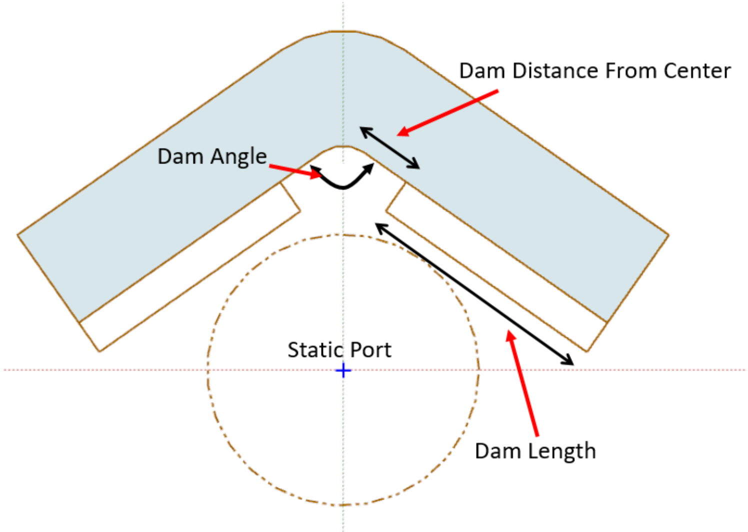

Figure 7 – Static Port Air Dam Design Parameters

Table 1 – Dam Design Points

	D1	D2	D3	D4	D5	D6	D7	D8
Dam Angle (degree)	60	100	120	90	100	120	90	120
Dam Distance(mm)	7.5	7.5	7.5	15	15	15	20	25

First 3 dam designs have constant dam distance while dam angle is variant. Following 3 dam designs, D4, D5 and D6 have constant dam angle while dam distance is variant. D7 and D8 are investigated for even further increased dam angle and dam distance. Static port diameter is set as 38 mm since commercially available products on the market have diameter around 1.5 inches. Thus, dam length of 38 mm is considered as long enough to cover whole static port diameter and utilized as constant. Since sideslip angles are neglected in this study, dam height is considered to have no effect on c_p increase. Dams are encircled with a structural part to provide installation means. This structural part has minimum possible thickness to minimize its effect on c_p increase. Air dam and static port assembly located close to the inlet. Boundary conditions and solver settings are given below.

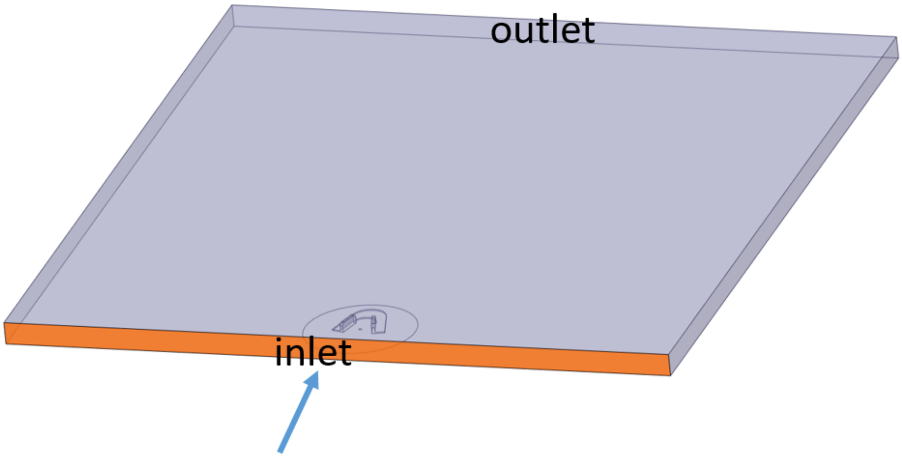

Figure 7 – CFD Model

Table 2 – Boundary Conditions

	Velocity Inlet Boundary Conditions
0 AoA	0.1 Mach magnitude, x:0, y:1
5 AoA	0.1 Mach magnitude, x:sind(5), y:cosd(5)
15 AoA	0.1 Mach magnitude, x:sind(15), y:cosd(15)
30 AoA	0.1 Mach magnitude, x:sind(30), y:cosd(30)
45 AoA	0.1 Mach magnitude, x:sind(45), y:cosd(45)

Solver Settings are set as;

- SST k-omega viscous model
- SIMPLE Pressure-Velocity Coupling Scheme

Mesh structure is constructed for the model shown in Figure 8. Mesh specifications and mesh geometry is given in Figure 8.

Mesh Specifications

- Surface Mesh Size Function: Curvature & Proximity
- Growth Rate: 1.2
- Minimum Size: 2mm
- Maximum Size 60mm
- Polyhedra elements
- Elements: ~ 500 thousand

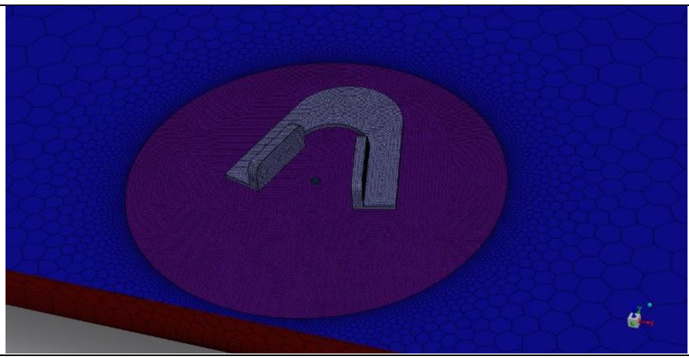

Figure 8 – Mesh Specifications

6. Results and Discussion

Solver is run for 300 iterations. Around 200th iteration, it has been seen that c_p value over the control surface (which is placed at the proximity of static holes) is converged for the cases. The CFD results are presented in Figure 9, Figure 10 and Figure 11. Table 3 includes all results for the all the angle of attack values.

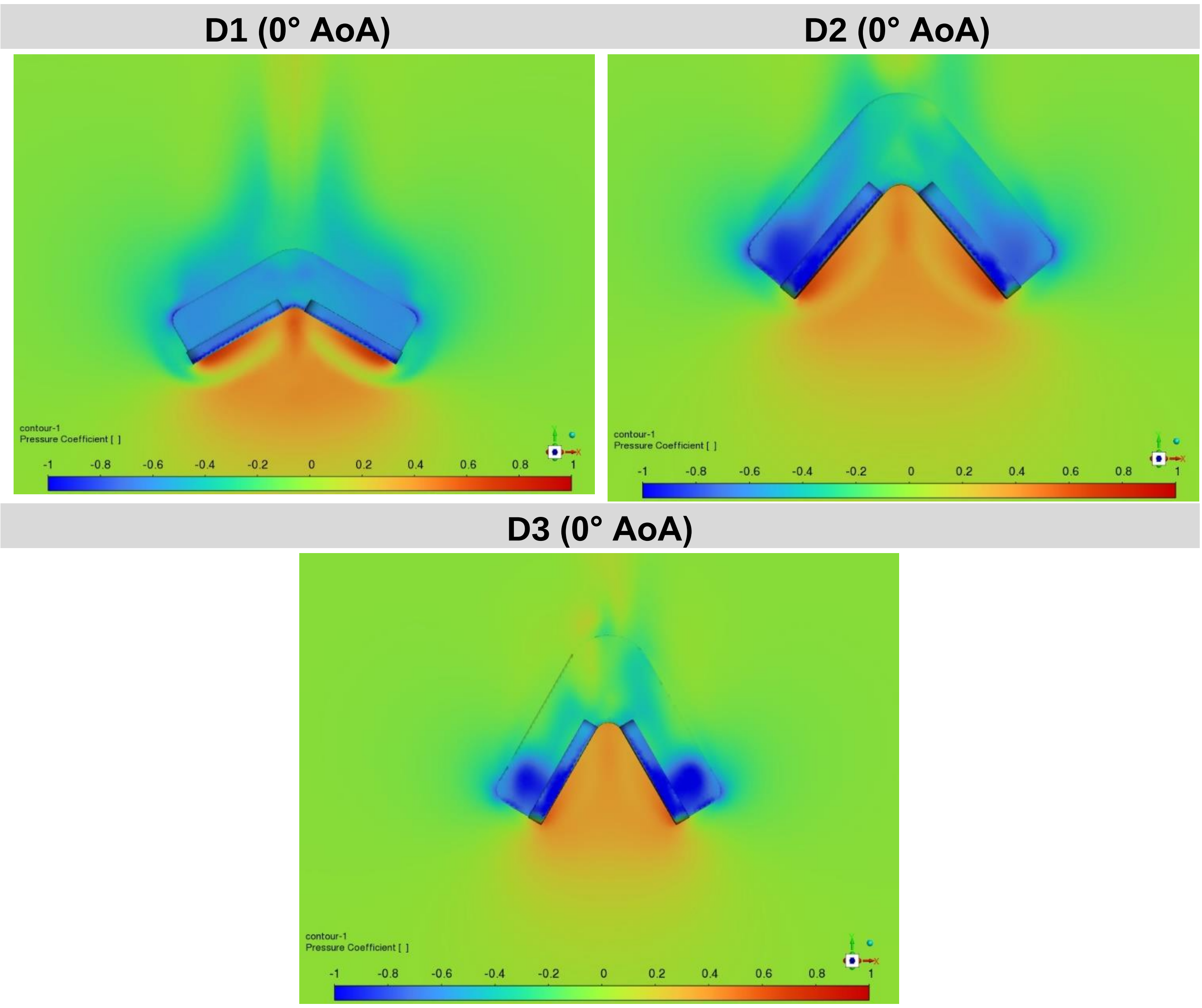

Figure 9 – 0° AoA Results of the D1-D2-D3

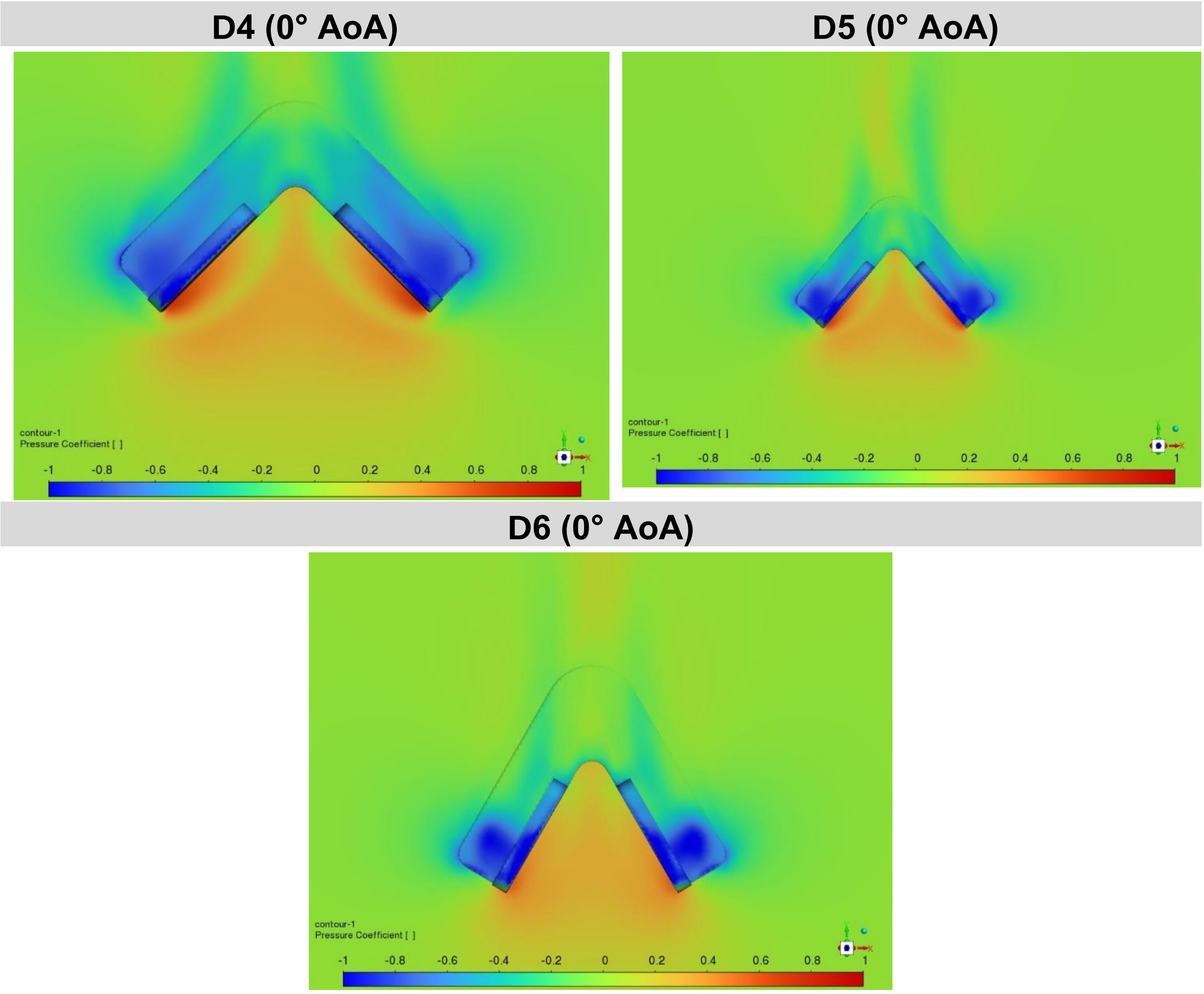

Figure 10 – 0° AoA Results of the D4-D5-D6

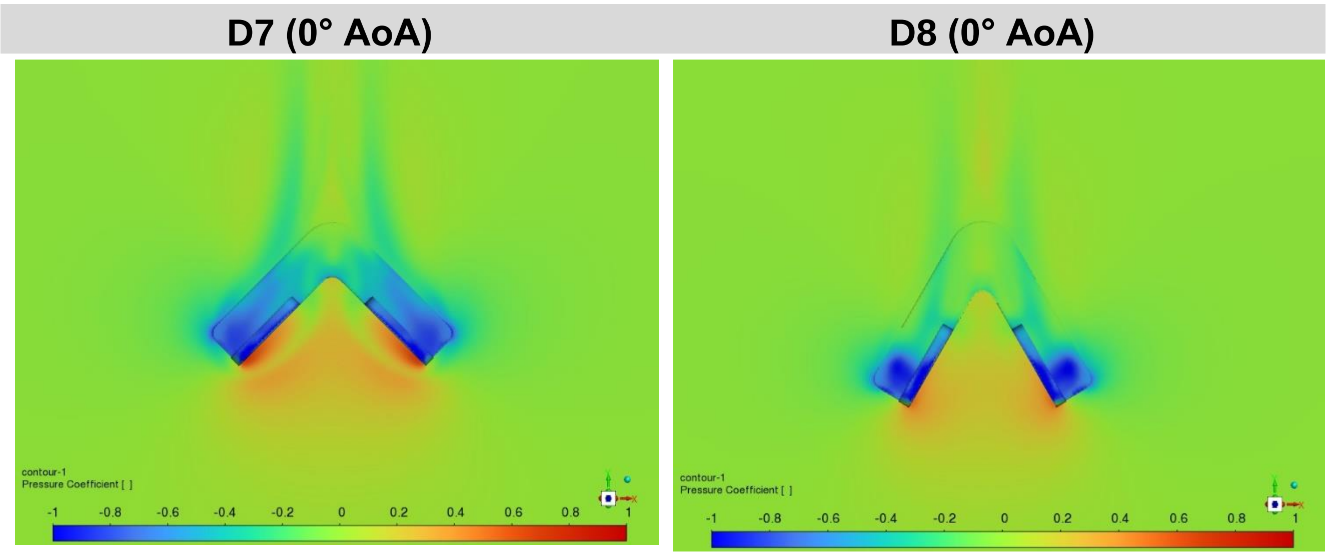

Figure 11 – 0° AoA Results of the D7-D8

Table 3 – c_p Results for 8 Dam Design

	Constant Dam Distance Group			Constant Dam Angle Group				
	D1	**D2**	**D3**	**D4**	**D5**	**D6**	**D7**	**D8**
0° AoA	0.394	0.381	0.358	0.326	0.299	0.285	0.279	0.202
5° AoA	0.405	0.383	0.354	0.325	0.295	0.298	0.282	0.201
15° AoA	0.412	0.370	0.314	0.334	0.285	0.240	0.284	0.197
30° AoA	0.376	0.365	0.236	0.331	0.294	0.194	0.293	0.195
45° AoA	0.332	0.323	0.0873	0.311	0.280	0.0331	0.290	0.114

According to CFD results, none of the designed dam configurations satisfy the required c_p increase. Each dam design increase c_p value with a similar offset for all angle of attack scenarios. Some of the air dam configurations have tendency to show lower c_p increase at high angle attacks. This phenomenon is actually the opposite of what we aim for. We learned from these results, if the dam distance from center increases, c_p increase decreases. Additionally, with the dam angle increase, especially around 120°, at high angle of attack conditions, air dams become obsolete. First 8 designs showed us that if the dam placement is closer to static port, c_p increase at all the angle of attacks become larger.

First set of air dams failed to satisfy the required c_p increase because surveyed angles were too step. We decided to significantly decrease the dam angle. A new design D9 is created. Table 6 contains the design variables for D9.

Table 4 – New Dam Design Data According to Results Acquired from CFD Results

	D9
Dam Angle (degree)	30
Dam Distance(mm)	10

CFD analysis is conducted once more for D9 with different angle of attacks. CFD results are given below.

	D9
0° AoA	0.338
15° AoA	0.393
30° AoA	0.561

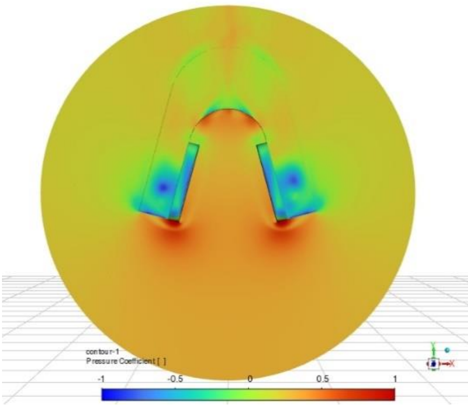

Figure 9 – D9 c_p Results

With the new dam design D9, we achieved to obtain increased c_p values at higher angle of attacks. Even though c_p increase at 0° angle of attack is quite higher than expected, c_p increase starts to rise with high angle of attack values.

7. Conclusion

Pitot static system pressure error correction is a mandatory process for most of the rotorcrafts to satisfy CS 29 requirement. Since position errors during the static port installation is unavoidable, airspeed reading error will also occur because of the position error. To minimize the position error, pressure correction methods which can be conducted via air data computer software, can be applied to the airspeed readings. However, if the rotorcraft does not have any means to separate the flight maneuvers all the flight maneuvers will receive the same treatment. If one of the maneuvers has distinctive position error than other maneuvers, correction with air data computer software will be unsuccessful. In this case, a physical intervention to pitot static system is required. This can be done by implementing air dams around static ports to manipulate airflow around the static ports. With the help of air dams, locally decreased surface pressure values can be increased. In total, 9 different air dam designs are investigated. Investigation results yields that, if air dams placed closer to the static ports, local surface pressure increase will be higher. Additionally, dams should have small angles between each other. If the angle between dam is increased beyond 30°, with the high angle of attack maneuvers air dams become obsolete which means that the local surface pressure increase becomes almost 0.

As for future work, the study can be conducted with actual c_p values acquired from an actual pitot static system placement analysis. In this way, the dams can be placed on the rotorcraft and placement analysis can be repeated with dams in place. This method will lead us to c_p values before flight test campaigns. After the completion of flight test campaign, data gathered from flight tests can be compared with placement analysis results that has been conducted with air dams in place.

Additionally, to able to choose the best dam configuration, more angle of attacks and dam designs can be surveyed. A parametric study can be conducted to optimize the dam design even further.

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9. Copyright Statement

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