Master Thesis

CFD Validation of the Engine Air Intake wind tests

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Abstract - The main objective of this study carried on within the Aerodynamics department of Airbus Helicopters Marignane was to validate the Engine Air Intake tests with a CFD model of the helicopter including the whole wind tunnel building. The quantities which have been validated were aerodynamic criteria presented in the below parts. This study was done in order to improve the method and tools of the Airbus Helicopters Aerodynamic Department. The modeling has been improved during this study in order to make the computations results closer to the wind tunnel tests results.

Nomenclature

AI Air Intake -
AIP Aerodynamic Interface Plane -
BC Boundary Conditions -
DC60 Pressure distortion -
DP/P Pressure loss %
DP/Qmax Maximum Local Variation of Pressure
DP/Qmin Minimum Local Variation of Pressure
IGV Inlet Guide Vane -
ISA International Standard Atmosphere -
MGB Main Gear Box -
OAT Outside Air Temperature °K
Pdyn Dynamic Pressure Pa
Pref Reference of total pressure Pa
Ps Static Pressure Pa
Ps0 Upstream static pressure Pa
Pt Total Pressure Pa
Q Mass-flow rate kg/s
V Wind tunnel velocity m/s
Vhc Helicopter Velocity m/s
WT Wind Tunnel -
WTT Wind Tunnel Tests -
α Swirl deg
ρ Air density kg.m⁻³

For the sake of confidentiality, no helicopter name will be mentioned in this paper and every result will be non-dimensional.

Moreover, no pictures of any air intake will be shown.

The use of this paper is strictly limited to exam needs.

Introduction

The main purpose of Engine Air Intake wind tests is to check if the air intake duct of the helicopter is compliant to the engine manufacturer installation manual aerodynamic criteria.

The main function of a helicopter air intake is to supply air to the turboshafts in the helicopter’s performance envelope. The supplying quality has a direct consequence on the operation and the engines performances (power losses, increase of the consumption, reduction of the surge margin) and thus on the helicopter performances.

The supplying quality is characterized by the airflow properties in the air intake (compressor plane):

- Pressure drop
- Pressure and temperature homogeneity
- Swirl
• Temperature with respect to the OAT

From the external aerodynamics perspective, the addition of an air intake on a smooth fuselage leads to an increase of the global drag of the helicopter. This one can be minimized by optimizing the air intake design (sizing, lips, bailers, fairings…)

In addition to its first function, an air intake must be able to protect the engine against the sand, the foreign objects as well as different kinds of atmospheric humidity (icing, snow, rain) that the engine cannot absorb. The constraints in terms of maintainability and noise must be integrated too.

It is good to know that there are in addition to the engine air intake, other helicopter intakes not dedicated to the supply of the turboshfts. The most widespread ones are the cooling air intakes which allow the supply of heat exchangers, cooling fluids such as the engine and MGB oils and the air conditioning coolants.

**Figure 1 : Arrano Turbomeca Turboprop**

For all of these air intakes, one uses the sizing rules described in this document. The size and the function do not mostly require the strict application of the classical aerodynamic criteria.

1. **Helicopter Dynamic Air Intake**

The diversity of the flight cases performed by a helicopter (hover, forward flight, and climb/descent flight) does not allow defining an globally optimized AI shape. There are many types of AI design: one will not go through every of them. For these tests, the AI is a dynamic one. With this type of AI, the helicopter can recover a part of its kinetic energy in the form of dynamic pressure. These AIs have optimized performances for forward flight cases.

It is composed of an AI duct which allows the airflow intake, a plenum which is a settling chamber and allows an uniform airflow supply to the first stage of the compressor.

![Dynamic AI sketch](image)

**Figure 2 : Dynamic AI sketch**

In the WTT and CFD model, the engine is replaced by a simple duct, only the radial AI is modeled where the AIP is located (figure 2).

2. **Aerodynamic criteria of the air intake**

The current part of this paper is a summary of the Air Intake Design Guide written by P.A. from the Aerodynamics Department of Airbus Helicopters. [1]

The engines specs given by the engine manufacturer are established with the tests for ideal supply and ejection conditions. After the installation of the turboshfts on the helicopter, a degradation of the performances appears due to the supply and ejection conditions which are no longer optimal and vary with respect to the flight conditions.

In order to ensure functioning, the engine manufacturer defines aerodynamic criteria to be respected at the Aerodynamic Interface.
Plane (AIP) which is the interface between the helicopter manufacturer and the engine manufacturer responsibilities.

The non-respect of these criteria may lead to important surge phenomena. The values of these criteria are related to the power losses induced by the engine installation. Therefore the goal of the helicopter manufacturer is to minimize these quantities by assuring airflow as homogenous as possible.

The number and the definition of these criteria may depend on the engine manufacturer but they generally describe the same physical phenomena.

2.1. Pressure distortion
Most of the time, this phenomenon is quantified with the DC60 coefficient.

This coefficient allows evaluating the homogeneity of the total pressure field at the engine intake. It is computed by using the total pressure averaged on a 60° section.

The DC60 is established as follows:

\[ \text{DC60} = \frac{\overline{P_t_{60^\circ}} - \overline{P_t}}{\overline{P_{dy}}} \]

with:

- \( \overline{P_t_{60^\circ}} \): The minimum value of the average total pressure on a 60° sector of the Air intake measurement plan
- \( \overline{P_t} \): The average total pressure on the air intake measurement plan
- \( \overline{P_{dy}} \): Averaged dynamique pressure at the AIP

Important pressure distortion may have an impact on the lifecycle of the compressor vanes and on the dynamic behavior of the engine (surge).

2.2. Local variation of pressure
This coefficient characterizes the pressure distortion too. It takes into account of the local pressure but not the pressure averaged on a sector.

\[ \frac{DP}{Q} = \frac{P_t(r, \theta) - \overline{P_t}}{\overline{P_{dy}}} \]

The good operation of the engine is guaranteed for values in a range defined by the manufacturer.

2.3. Swirl
For a cylindrical frame whose the origin is the center of the AIP, swirl is defined as the angle between the axial component (engine axis) and the tangential component (angular) of the speed.

Swirl leads to a variation of local incidence on the first stage vanes. The tangential speed component is added/removed to the one created by the rotation of the compressor. Consequently, this phenomenon leads to the difference of power loss between the left engine and the right engine (due to the symmetric airflow and the fact that the engines are identical). One should respect a mean value as well as a minimum and a maximum value for this quantity.

2.4. Pressure loss
The pressure loss is computed by using the following formula:

\[ \frac{\Delta P}{P} = \frac{\overline{P_t}}{\overline{P_{s0}}} \]

with:

- \( \overline{P_t} \): The average total pressure on the air intake measurement plan (relative pressure)
- \( \overline{P_{s0}} \): The upstream static pressure

This quantity quantifies the energy loss of the AIP upstream airflow and is directly related to the power delivered by the engine.
definition of Pref may vary with the manufacturer (Pt upstream, Ps upstream). According to the supplier, 1% (or 10mb) of pressure loss corresponds to a power loss around 2%.

3. Presentation of the WTT
3.1. Wind Tunnel tests

The most used way to estimate the influences of the engine installation are the tests. The wind tunnel tests allow estimating the aerodynamic criteria. The flight tests allow verifying the values of these criteria and estimating the installation losses.

Most of the Airbus Helicopters aircraft types (prototypes and produced ones) had been tested in wind tunnel in order to aerodynamically evaluate their air intakes.

The mock-ups used for the air intake tests have a more important scale than the ones used for the tests concerning the external aerodynamics. The instrumentation used to measure AIP aerodynamic criteria requires a minimum size of the measurement surface. Most of the time, the scale used at Airbus Helicopters is equal to ½.

The mock-up must be representative of the superior cowling which contains the air intakes and the front part of the fuselage. Concerning the after part fuselage, the mock-up does not need to be representative. The presence of the rotor-head is necessary only if it is located at the upstream edge of the air intake. Due to this reason and financial matters this one is not represented in the model.

The principles of these tests are to simulate the movement of the helicopter in the airflow (with the possibility to vary incidence and sideslip) whilst at the same time a fan located at the AIP downstream blows air from the air intake.

3.2. Measurement equipment

In addition to internal equipment, other measurement equipment will be implemented:

- A Pitot probe which estimates the WT speed
- A temperature probe at the mass flow measurement device.
- Several static probes on the different parts of the mock-up

The measurement test section is at the AIP (plane before the IGV).

The mass flow rate of the fan is controlled thanks to a Venturi system.

In order to estimate the values of aerodynamic criteria, it is necessary to use a complex measurement tool. This one is named the five-hole probe and it is located at the AIP.

![Figure 3: Five-hole probe used at the AIP](image)

This probe allows measuring the swirl at different locations of the AIP as well as the total pressure.

3.3. Rules of similitude

As the WT speed is limited, one has to use a rule of similitude to simulate the engine functioning for high speeds. This rule is based on the conservation of the mass-flow-rate coefficient. This coefficient is defined by the following formula:

$$\varepsilon = \frac{Q}{\rho_0 V_0 A_1}$$

with:

- $Q$: engine mass-flow rate
- $V_0$: speed of the helicopter/model
In function of these parameters, the correspondence between WT airspeed and engine mass-flow rate with respect to the scale=1 model will be done by using the following formulae:

\[ Q_{WT} = \frac{1}{k^2} \left( \frac{\rho_{WT}}{\rho_{HC}} \right) \left( \frac{V_{WT}}{V_{HC}} \right) \]

\[ V_{HC} = V_{WT} \times \frac{1}{k^2} \left( \frac{\rho_{WT}}{\rho_{HC}} \right) \left( \frac{Q_{HC}}{Q_{WT}} \right) \]

with:

- \( k \): scale of the model
- \( WT \): scale of the model
- \( HC \): scale 1

In practice, when one has reached the maximum WT speed, if one wants to simulate a higher real scale helicopter speed, one has to decrease the engine mass-flow rate. That is why for the last runs, one decreases the mass-flow rate for a constant WT airspeed.

Concerning the similitude in Mach, the capacities of the tests installations do not allow to respect it most of the time. One will ensure to be very close of this similitude when one will define the WT parameters.

Concerning the similitude in Reynolds, this one is not realizable as well for the same reasons. This non-respect leads to an increase of the model boundary layer with respect to the real one. Consequently, one will get more penalizing results.

4. CFD Validation

4.1. Strategy of the FLUENT validation

The CFD validation was done by using the ANSYS CFD software named FLUENT.

To do this study, one must develop a strategy. Firstly, one has decided to fix the geometry of the air intake. The cowling has been fixed for the study. Then, in order to avoid an important waste of time, one has decided to focus only on 10 runs which one are “sure” of the quality of the measurement given by the wind tunnel tests.

For these runs, one extracts the results of the CFD calculations. The results which one focuses on are composed of the AIP aerodynamic criteria quantities such as DC60, DP/P, DP/Qmin, DP/Qmax and swirl but also the values of static pressure probes. A first analysis is done on these quantities.

Then, one compares this results to the ones obtained from the wind tunnel tests.

If the CFD results are not in agreement with the WTT ones, one will vary different parameters of the model such as pressure scheme, turbulent model, turbulent intensity…etc… or one will change the refinement of the mesh.

Furthermore, one will go through a deeper analysis of the AIP total pressure, the probes’ static pressure and standard deviation extracted from the tests in order to understand what happens at the vicinity of the AIP.

4.2. Boundary conditions

To solve a problem in CFD, one has to know how to set the boundary conditions. The first quantity to be set up is the operating pressure which corresponds to the total pressure reference.

Then one assumes that all of the walls are adiabatic.

It has been decided to model the whole wind tunnel except for some particular details such as the entrance corridor, the lab room…etc… because that is not significant for this study. Indeed, computations are longer with respect to the number of cells. Furthermore, one has modeled neither any window nor any furniture for the same reasons.
The entrance surface of the upstream tunnel has been defined as a pressure-inlet where the value of pressure has been set up at 0 Pa (relative pressure).

Concerning the Air Intake mesh, one has decided to mesh the engine duct as a simple duct with an outlet condition at the downstream section. The remaining surfaces are considered as walls. One has decided to model the five-hole probe as well.

In order to simulate as precisely as possible the wind tunnel tests, one has to set up 4 input parameters. The first one is the pressure reference (operating pressure) which is computed with the average of the total pressure at the Pitot probe during the test (the real one).

The second one is the temperature reference which will be applied on every walls of the model.

The third one is the mass-flow-rate created by the ventilation at the downstream AIP, and it is applied on the engine outlet surface of the model. The value that one sets up is the average of the real mass-flow-rate given by the WTT.

The last one, the Pitot Speed or Wind Tunnel Speed is the most complex to set up because of the fact that one knows the speed at the vicinity of one single point (the Pitot probe) but nevertheless that is not physical to apply a boundary condition on a single point. As one knows that the WT type is an Eiffel WT (open return WT) that means that the fan is located at the test section downstream.

As the fan is creating a difference of pressure at the WT downstream, one has decided to apply a pressure-outlet as a boundary condition at the downstream tunnel surface which will lead to a given speed at the Pitot probe. So for a given pressure-outlet and for a fixed temperature, one obtains a value of Pitot speed.

The pressure-inlet corresponding to the upstream tunnel still remains at 0 Pa. Regarding the first Air Intake Plane, this boundary condition has been defined as a wall. Indeed, this one should not have any impact on the Pitot speed. This assumption will be verified when one will compute the tests.

This one is computed by monitoring the total pressure, the static pressure and the air density at the Pitot probe by using the following formula:

\[
V_{WT} = \sqrt{\frac{2 \left( P_t - P_s \right)}{\rho}}
\]

To get these values, one has to create a point located at the real Pitot probe position.

The first computations were for a given temperature of 300°K. This value is approximately the maximum temperature observed during the tests campaign.

The range of pressure-outlet values used for this calibration is the following one: [0 Pa; -X Pa]. These values are obtained with the same formula as the Pitot one by defining a typical speed range of [0 m/s; Y m/s].

Indeed, one has to take into account of the blockage effect due to the important cross-section of the fuselage, thus one has to set up a range of speed wider than the WT speed range.
From the interpolation of this curve (the violet one = 300°K), one gets an equation which correlates the pressure-outlet with the WT speed.

One has also computed this calibration for another value of temperature, which corresponds to the minimum value of temperature obtained for all of the WT tests. The conclusion, one may highlight, is that both curves are proportional to each other with the temperature. That is described by the following formula:

\[ V(X \, ^\circ K) = V(300 \, ^\circ K) \frac{300}{X} \]

This step done, one can start to simulate every test with FLUENT. The following table gives the parameters used as the BCs values (the operating pressure (Pref), the OAT (Tref), the pressure outlet (Pout), and the mass-flow rate (Q) divided by the maximum value of each quantity.

As one can see in the figure 6, the general trend of DP/P is respected and the values are very close to each other. This is due to the low difference between the averaged total pressures in both cases.
Figure 7: DC60 versus $V_{hc}$

The figure 7 shows that one does not get the same trend for the DC60 curve. In fact, this is due to the high difference of local total pressure between FLUENT and WTT at the AIP.

Figure 8: DP/Qmin versus $V_{hc}$

Figure 9: DP/Qmax versus $V_{hc}$

For the same reason as the DC60 case, the local variation of pressure analysis (figure 8 & 9) does not give good results for the validation.

Figure 10: Swirl min versus $V_{hc}$

Figure 11: Swirl max versus $V_{hc}$

Figure 12: Swirl average versus $V_{hc}$

Concerning the swirl, it is not so obvious to understand its behavior because the relation between the 5 pressures given by the probe and the angle is not provided by probe supplier.

One can highlight that the trends of the three swirls (min, max, average) are not so respected. However, as one knows that the standard deviation of the five-hole probe concerning the swirl is around $1^\circ$, it seems that
the computations give results within the precision range. The most significant result is the averaged swirl. Indeed, the difference between FLUENT and WTT is lower than 1°.

As one said in the part 1, the aerodynamic criteria are important for the design of a helicopter AI. Being able to reproduce the WTT results with the FLUENT computations would allow the aerodynamic department to better estimate the AI performances with CFD in the future.

To obtain these graphs, an important number of change had been done in the modeling of the WT. Indeed, different turbulent models had been tested, as well as the pressure scheme, refinement of the mesh, turbulent intensity, adding of the five-hole probe in the mesh.

What it can be said is that the refinement of the tunnels mesh has no influence on the computations. Concerning the turbulent model, K-ω does not bring the computations results closer to the WTT ones. Furthermore, it requires more iterations to converge to its solution. That is why K-ε model remains the model used for the computations because of its stability and its better convergence.

Concerning the pressure scheme, the second order had been chosen because it gives better results at low speeds in term of DP/P than PRESTO!. At high speeds, no improvement has been observed.

6. **Analysis of the total pressure at the AIP**

This study consists in a deeper analysis of what happens at the AIP concerning the total pressure. Indeed the total pressure is the only key which can explain the difference between the FLUENT computations and the WTT results. This physical quantity is the only one used for the calculations of the DP/P and the DC60.

![Figure 13: Frame of the five-hole probe (in red) at the AIP](image)

The study will only be done on two runs which are run 296 (hover flight), run 306 (high speed forward flight). The chosen modeling case is the one with the tunnels refinement, with a turbulent intensity of 1.6, a 2nd order pressure scheme and a turbulent model K-ε. The first position of the five-hole probe is on a (Y+225°) axis, it moves from external annulus to internal annulus, the next rakes are described in a clockwise direction.

![Figure 14: Total pressure at the AIP for different position of the 5-hole probe (run 306)](image)

Concerning the graph shown in figure 12, it shows that the Pt values given by FLUENT at the AIP do not present the variations observed in the WTT results, although the levels are comparable. Nevertheless, one can notice that the trend is respected at each rake as well as the general trend of the total pressure along the move of the five-hole probe.

This analysis has shown that one have a problem at the AIP. In fact, the difference of.
total pressure is high and the consequences of that problem are the bad values of some aerodynamic criteria.

Nevertheless, this study does not explain the behavior of the flow upstream the AIP. As the WTT give values of the static pressure at different locations of the Air Intake, it would be interesting to compare it with the FLUENT results in order to better understand the flow around and in the AI.

7. **Analysis of the static pressure probes**

In this part, one is going to focus on the analysis of the static pressure probe. This analysis can be considered as a third level one. In fact the most important ones remain those concerning the aerodynamic criteria and the AIP total pressure analysis.

In fact, if one sees an important variation of static pressure, this might lead to a difference of total pressure and aerodynamic criteria as well.

This step done, one has created a VBA code in order to analyze the AI sections static pressure by section of each FLUENT test with its corresponding WT test.

As one can see in the following graphs, the FLUENT static pressure remains very close to its corresponding WT one except for the ENG section which is the AIP. So what the static pressure analysis highlights is that the most important discrepancies are indeed observed at the AIP, probably due to the fact that the five-hole probe is not present in the model.

![Figure 15: Difference of static pressure between FLUENT and the WTT](image)

What one can show from this graph is that there is a big gap between the WTT and the FLUENT computations concerning the static pressure at the external radius of the AIP (averaged per zones). This gap is all the more important given to the other difference of static pressure extracted from the other zones of the Air Intake.

![Figure 16: Difference of static pressure between FLUENT and the WTT without AIPext](image)

In this graph, one has removed the ENGext histogram, in order to get a better view of what happens for the other zones. It can be said that AI, cowling and plenum zones computations give good results. Indeed, the maximum difference that one gets is around 300 Pa at the AIP, or around 100 Pa elsewhere.
Another analysis with the display of $P_s$ contours in FLUENT has shown that the trend of this quantity is respected along every parts of the Air Intake duct, the plenum, and the cowling.

**Conclusion**
The CFD validation of the Engine Air Intake WTT has been done by keeping in mind the goal of the study:

- The pressure loss has been validated by the CFD thanks to good results concerning the averaged total pressure at the AIP
- The swirl has been validated as it lies within the precision range of the five-hole probe
- The analysis of the static pressure field has shown good results upstream the AIP
- The local trend and general trend of the total pressure repartition at the AIP are respected
- The general trend of every quantity has been respected along the cowling, the AI and the plenum

Ways of improvement are still numerous: the five-hole probe needs to be represented as well as the movement of the sensor at the AIP in order to get more realistic computations. Moreover, the other runs need to be computed with their respective configurations (new cowling, grid upstream the helicopter AI). That will require meshing new geometries of the model.

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**References**