NAVIER - STOKES CALCULATION:

AN INDUSTRIAL TOOL FOR AIR INTAKE OPTIMIZATION

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The methodology applied to define and optimize the engine air intakes are presented with concrete examples.

Defining and optimizing helicopter engine air intakes is a complex problem where severe requirements are to be met. The advances in engine design impose increasingly tight operating criteria at the interface that call for very high quality flow. Furthermore, the contractual or regulatory helicopter performance requirements impose that the installation losses and the air intake losses, in particular, be drastically reduced.

Aerodynamicists must then have every necessary tool at their disposal to meet those engine installation criteria and requirements.

Models have been tested in the wind tunnel for quite some time now. These help to measure pressure drops as well as pressure and rotation deviations in the interface plane. Similarity rules can then be applied to evaluate losses induced by engine installation at the helicopter scale.

Calculation codes capable of solving Navier-Stokes equations have recently come into use that improve flow prediction. Today, those codes are invaluable tools that help emphasize local flow characteristics, identify potential problems and reduce configuration number ahead of tests. These tests are then performed with a higher level of confidence, their duration (and, consequently, their costs) are reduced and the best solutions can then be fully optimized.

The calculation code used that helps solve the Navier-Stokes equations coupled to a turbulence model (k, ε) based on a finite elements methods shall first be described.

The testing tool and the type of measurements made on the helicopter models are also described.

Once the criteria related to engine installation and the optimization parameters have been explained, the different calculations undertaken within the framework of this study are discussed:

- preliminary 2D calculations that allow characterizing, quickly and at a low cost, the global flow structure while locating major problems

- 3D calculations with concrete configurations that allow optimizing the design

Finally, the calculations / tests correlation evidence that calculations allow demonstrating the operating and performance criteria satisfactorily at the engine interface plane.

1- PROBLEMS RAISED BY HELICOPTER AIR INTAKES

Engine performances are measured on the engine bench in helicopter ground run conditions (total inlet pressure equal to static ambient pressure) with the intake recording almost ideal pressure distributions.

Once the engine is installed, however, the total pressure field is never uniform ahead of the compressor. The deviations from the mean total pressure are characterised by a distortion index (DC60) and a fluctuation or turbulence rate with respect to the mean flow.

Those flow imperfections generate two types of fundamental problems. On the one hand, the distortions can have a dramatic impact on engine behaviour possibly up to compressor surge; on the other hand, the flow degradation compared to ideal conditions will cause performance losses that can also be unacceptable in given helicopter operating conditions.

1.1- ENGINE MANUFACTURER CRITERIA

Interface criteria must thus be defined between engine and helicopter to supply the engine satisfactorily, thus ensuring its satisfactory operation and performances.

The purpose of this first paragraph is to consider engine installation both from the engine manufacturer and helicopter/engine interface standpoint.

1.1.1- TANGENTIAL DEVIATION

Local speed can be defined with two angles:

- Radial deviation: the angle between the engine centreline and the projection of the local speed in a radial plane
- Tangential deviation: the angle between the speed vector and its projection in the radial plane

Tangential deviation, also known as preswirl, generates (local or average) variations of incidence on the blades of the first stage compressor. This is thus an essential angle as regards engine installation in the helicopter.

The mean preswirl modifies the adaptation point of the compressor air intake and can enhance or reduce engine performances (Fig. 1).

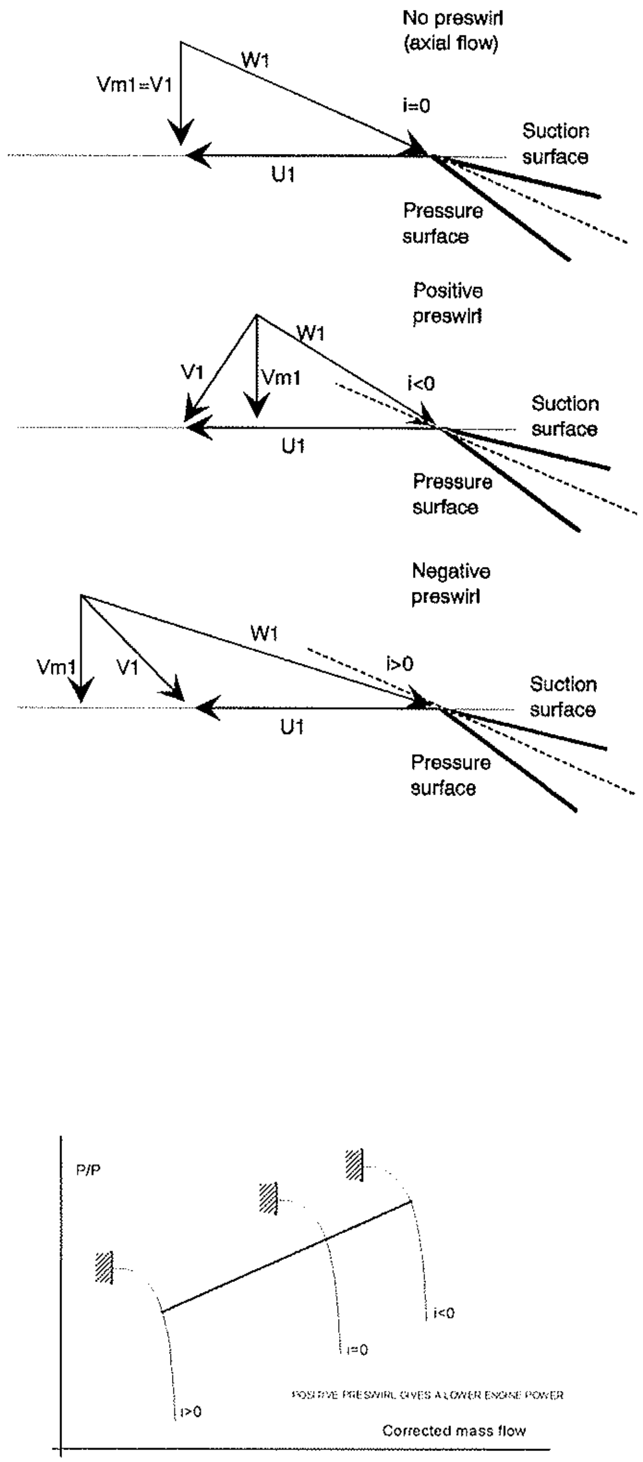


Figure 1 : Preswirl influence on speed components and power

In a symmetrical installation the preswirl is theoretically opposed on the RH and LH side of the helicopter, thus inducing different installation losses on each side. In twin engine operation the adaptation variations on both engines are likely to compensate each other, which is not the case with one engine inoperative (OEI).

The engine manufacturer requirements are:

- the mean preswirl must be as close as possible to the adaptation angle (generally 0°)
- the local preswirl must be comprised between the minimum and maximum values set for each engine.

1.1.2- PRESSURE DISTORTION

The pressure distortions, and to a lesser extent the preswirl, have a direct influence on the engine surge line. The margins are thus reduced whenever distortions occur (Fig. 2). Furthermore, these distortions can have an impact on the dynamic behaviour of the engine as well as the life of rotary parts.

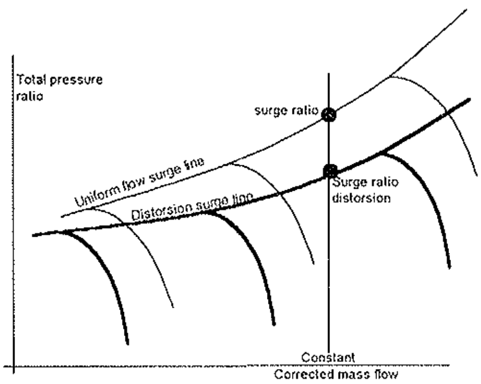


Figure 2: Influence of distortions on engine surge line

1.1.2.1- DC60

DC60 is defined with $\frac{P60min - P_i}{q}$

where:

P60min is the mean value in the air intake of the total pressure mean over any 60° angular sector

Pi is the mean total pressure in the air intake.

q is the mean dynamic pressure in the air intake.

This value is negative and the engine manufacturers demand values higher than a set DC60min.

1.1.2.2- Min/max local pressure distortion

This is the minimum (or maximum) local pressure distortion with respect to the mean total pressure.

DELTAP=P(r,psi)-Pi

P(r,psi) is the total local pressure
Pi is the mean total pressure

This local pressure distortion is to be comprised between set minimum and maximum values.

1.2 - HELICOPTER REQUIREMENTS

The engine manufacturers will guarantee a satisfactory powerplant operation provided a number of criteria are observed upon installation.

The helicopter itself is subjected to severe constraints that are mainly performance related.

Helicopter performances are limited over a large section of the altitude/temperature envelope by the power available rather than the capabilities of the transmission components.

As shown in Fig. 3 and 4, the regulatory or "commercial" performance requirements impose a power breakdown as economical as possible and, in particular:

- Take-off weight

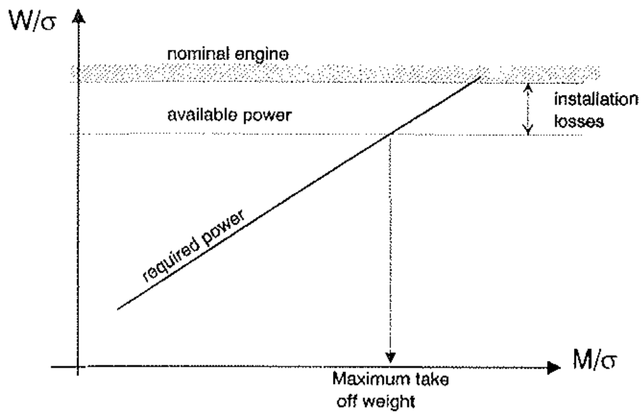


Figure 3: Influence of engine losses on performances in hover

- Engine failure on take-off for FAR 29 Cat. A aircraft (a very severe regulatory requirement) - The take-off weight reduction is directly proportional to the engine installation loss.

- Maximum speed of the helicopter in level flight.

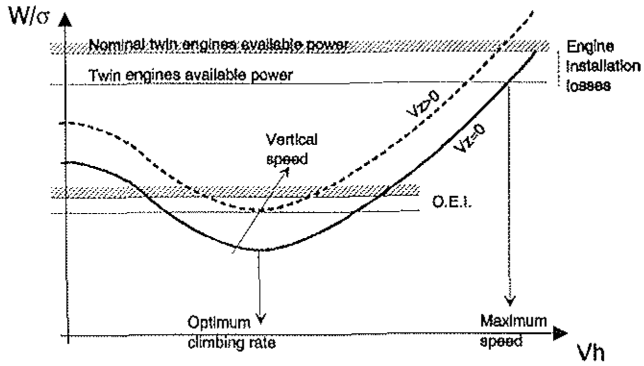


Figure 4: Influence of engine losses in level flight and climb

- Range - Proportional to the fuel consumption/km of the installed engine and thus very closely linked to engine installation and power polar as a function of speed.

Power losses upon installation are defined by the power deviations between bench and flight with a same reduced generator RPM. This engine behaviour degradation also generates fuel consumption losses at a given power level.

These losses are unavoidable and may be induced by:

- pressure drops - a 1% total pressure loss corresponds, in average, to a 2% available power loss approximately.

- hot air re-ingestion (mean temperature rise and temperature distortion that are also part of the operating criteria). A 1° mean temperature increase corresponds, in average, to a 0.8% loss approximately of the power available.

- mean flow disturbances in the air intake - Here we are at the helicopter/engine interface because, installation losses excepted, these disturbances have an impact on engine operation that can sometimes be serious. The effect of pressure distortions and turbulence is not clear but generates losses by deterioration of compressor operation.

Power losses related to engine installation can amount to 5 to 10% in those helicopters where the aerodynamic engine/fuselage and the air intakes interface, in particular, has not been extensively studied.

2- AIR INTAKES OPTIMIZATION PARAMETERS

2.1-OPERATION

2.1.1- HOVER

The engine draws air from the space around the air intake but this suction effect is very rapidly reduced proportionally to distance. The power needed by the engine imposes the mass flow and speed V1 of the flow drawn at the air intake (Fig. 5).

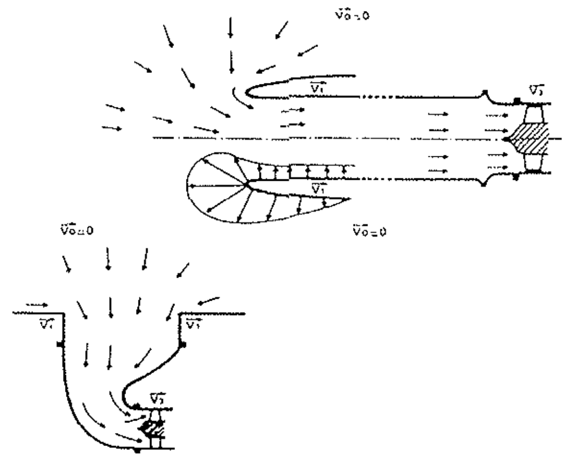


Figure 5: Air intake behaviour in hover

2.1.2- FORWARD FLIGHT

The space can be divided into two areas (Fig. 6):

- the first drawn by the engine defining a surface flow S0 infinite upstream and evolving as a function of the local speed imposed to airstream.

- The other possibly deflected but not drawn.

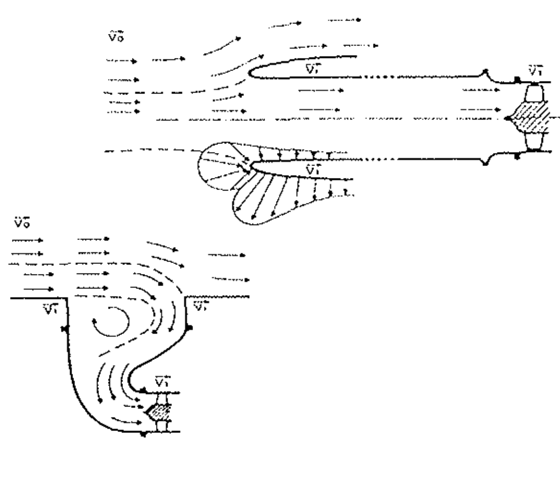


Figure 6: Air intake behaviour in forward flight

The air intake definition must offer the best compromise between two radically different operating conditions. Optimizing the engine installation also imposes dealing with geometrical parameters associated to flight parameters including:

- the influence of forward speed

- the influence of vertical speed

- the influence of sideslip

- the influence of atmospheric conditions (altitude, temperature)

2.2- OPTIMIZATION PARAMETERS

The essential design parameters conditioning efficiency and satisfactory operation are:

- the selection of the air intake plane position on the fuselage

- the surface of the air intake

- the design of protection devices (FOD, de-icing, snow, sand)

- the relative thickness of the lips

- the design of the air intake duct

- the shape of the lips

The aerodynamic design and optimization of an engine air intake calls for a large number of parameters and constraints. The wind tunnel was, until recently, the tool used at ECF to optimize air intakes.

3- WIND TUNNEL TESTS

The purpose of these tests is to evaluate pressure drops, pressure distortions and the related fluctuations, as well as preswirl and the related fluctuations, at the aerodynamic interface plane of a given aircraft, and also to suggest and test improvements.

3.1- TEST EQUIPMENT

The basic part of the mock-up installed in the wind tunnel is a streamlined body intended to reproduce the deflections and overspeeds generated by the fuselage and cowlings.

On this fuselage are installed:

- the rotor head

- the engine and MGB cowlings

- the air intakes

- protection grids in some cases

The air intakes are activated by fans installed in the fuselage and connected to conventional venturi tubes measuring air flow (Fig. 7).

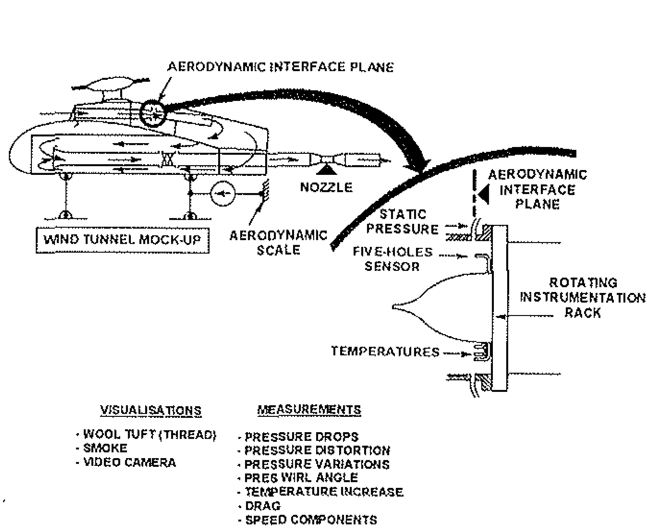


Figure 7: Wind tunnel mock-up for air intake studies

Some similarity rules must naturally be observed (Reynolds and Mach number) regarding airflow.

3.2- SIMILARITY RULES

3.2.1- Reynolds number similarity

The Reynolds number cannot be applied in a wind tunnel for such tests. The pressure drops should thus be higher on the mock-up than on the aircraft. In fact, those deviations are not generally recorded when the Reynolds number is changed in the wind tunnel or when the results of mock-up and flight tests are compared. There are numerous reasons for these findings all linked to turbulence effects:

- the turbulence rate can be particularly high in the wind tunnel

- the surface condition of the mock-ups is not ideal.

- most of the tests are performed with protection grids generating additional turbulence.

Those points tend to create a "turbulence level" close to that encountered in flight and finally compensate for the non observance of the Reynolds number similarity.

3.2.2- Mach number similarity

As far as specific air intake tests are concerned, compressibility has almost no role in the field under study, except in the immediate vicinity of the compressor where the flow is accelerated rapidly. The phenomena studied (separations, vortices, pressure drops, turbulence) all arise in the incompressible area where the Mach number has no significant influence.

However, compressibility corrections must be made on the static pressure measured in the compressor plane with isentropic flow equations.

3.1.2.3- Airflow similarity

In hover the mock-up airflow is proportional to the square of the scale.

Qm(mock-up)=Qm(helicopter).(1/K2)

In forward flight the main similarity parameter for air intake studies is the airflow coefficient ε determining the borderline of the flow entering the air intake:

ε = Qm / (rho0 . V0 . S0)

Where Qm is the mass flow and S0 an arbitrary reference surface.

Knowing that flight speed is simulated, the values to be observed in the wind tunnel are easy to determine while checking that they are compatible with the test equipment available.

3.3-TESTS PERFORMANCE AND PROCESSING

3.3.1 - Measurements

Pressure, the speed components and deviation angles are measured at the aerodynamic helicopter/engine interface plane. The influence of the air intake on the aerodynamics of the engine compressor inlet is thus characterized as accurately as possible.

3.3.2- Test envelope

The test envelope is that accessible in the wind tunnel. Tests can begin in the airflow similarity mode in hover and at low speeds and proceed to the airflow coefficient similarity mode as speed increases. Equivalent operating modes are thus obtained at the maximum helicopter speed up to 300 - 370 km/hr.

The ruggedness of the power plant is checked with respect to mock-up sideslip and attitude in the envelope that is accessible without any significant wind tunnel blockage effect.

3.3.3- Measurements processing

Measurements are processed in such a way that the results are reset to the helicopter scale and standard pressure / temperature conditions.

The results obtained are also reset to a reference airflow (usually the maximum airflow for level flight at Vmax and hover) and the engine airflow variations must be taken into account during flight at intermediate i.e. delivery power.

The results are processed as pressure or local preswirl cartographies indicating those areas of the compressor that will possibly be attacked by a degraded flow (Fig. 8).

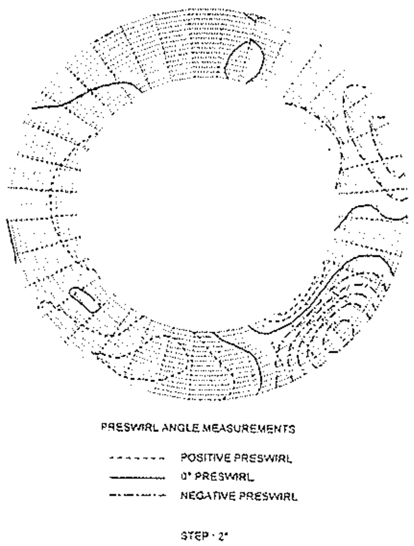


Figure 8: Preswirl cartography

Results are also processed in such a way as to provide pressure drop and distortion. Figure 9 show the excellent correlation observed between flight and wind tunnel measurement.

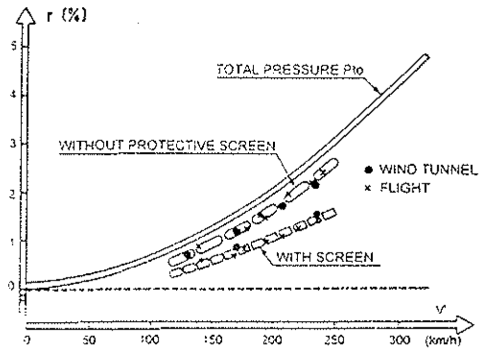


Figure 9: Wind tunnel/flight correlations - Mean total pressure

3.4- CONCLUSION

The tests help to quantify the performances of a given design as well as introduce improvements once the measurements have been analyzed.

- The main advantage of those tests is to give direct access to the measurements of these parameters that are of interest for the engine and the airframe manufacturer. The wind tunnel tests evaluate the ability to perform a large number of influence studies (airflow, speed, sideslip, attitude...) on a well known definition. This methodology is reliable and helps avoid unpleasant surprises in flight. The definition is as close as possible to the full scale one including grids, main rotor head etc. Furthermore, one can define and evaluate modification kits that will allow for faster development in flight. It is a very effective tool to qualify the performances of a given definition.

-The limits of these tests are those inherent to a methodology based on experiment. A design must be available to perform the tests and must be accurate. As a consequence, wind tunnel tests are usually performed late in the development phase. It is difficult to predict the results and decisions to be made ahead of time to improve a design. As a consequence, those elements manufactured for wind tunnel tests must almost always be briefly optimized in the vein. Designs cannot thus always be improved and the risk not to have a full convergence is real.

Moreover, the implementation of those tests, although simple in principle, is heavy, dear and the number of configurations to be tested must often be limited.

4- NAVIER STOKES CALCULATIONS

It is thus clear that the wind tunnel methodology that proved reliable on several occasions is short of calculations and analyses that would help describe complex shapes and flows as design guidelines. These have matured over the last few years to guide aerodynamicists in the design and optimization of air intakes.

The purpose of these calculations is to significantly reduce the costs and lead-times inherent to flight or wind tunnel tests.

4.1- CALCULATION CODE DESCRIPTION

4.1.1- Objectives

The code used (N3S) was initially developed for internal hydrodynamic flows.

This code is a fluid mechanics software package based on the finite element method. It can handle 2D, axi-symmetrical and arbitrary, complex 3D geometries with performance levels (CPU time and memory load) equivalent to those of other industrial software programs based on structured grids. Our applications and the complexity of the geometry to be computed lead to a shape description in local areas and to adapt the grid as well as possible to the reality of the flow. This is why the finite element approach is necessarily coupled in our applications, with unstructured meshes.

This program is currently able to compute non-isothermal incompressible turbulent flows. This code is so far sufficient to compute internal and external aerodynamic shapes as soon as the application meets the assumptions. Further developments will soon model expansible flows with combustion and radiation phenomena. Those developments will be suitable and of great interest for air conditioning topics or hot gazes expansion around the fuselage.

This code and its integrated user-friendly interactive environment is a complete packaged code well designed for use by non-specialists. It is really suitable for the current industrial applications.

4.1.2- Method

N3S solves steady and unsteady Navier-Stokes equations using a velocity/pressure equation coupled with a turbulence model and a thermal equation (Appendix -1-). Advection-diffusion equations with source terms and general boundary conditions can be associated to process extra passive scalar fields.

Time discretization is performed by splitting the operators at first or second order in time. The advection step is solved by a characteristics algorithm introducing a natural upwinding. Finite element space discretization is used for the diffusion and propagation steps. The resulting generalized Stokes problem is solved using a preconditioned Uzawa algorithm. Linear systems are solved by sophisticated conjugate gradient algorithm with sparse matrix storage minimizing computational time and memory load.

An advanced processing of turbulence with algebraic mixing length or two equations k-epsilon models is available for both 2D and 3D problems. It is coupled with wall boundary conditions on velocity and temperature to simulate boundary layers.

Great care was taken to base N3S on robust and at the same time computationally efficient numerical methods:

- The finite element method was selected for its flexibility and the comparatively small number of necessary computation points as well as for the mathematical accuracy and natural incorporation of boundary conditions offered by its formulation,

- state of the art algorithms are used which take advantage of new architectural features of supercomputers (vectorization and parallelism).

4.1.3-Pre processor

The following are standard mesh generators for N3S but they can easily be interfaced with other mesh generators.

SIMAIL (developed and marketed by SSII and SIMULOG) is easy to use and provides powerful reliable algorithms such as the VORONOI free mesh generator which computes a tetrahedron mesh from a highly complex geometry defined by its skin mesh.

SUPERTAB (developed by SDRC,US) is part I-DEAS/CAEDS which also has a geometry modeller.

N3S is pre-processed in the following stages:

- Creation of N3S input files from mesh generator output with appropriate boundary condition data,
- a test for mesh consistency,
- independent selection of P1 or P2 discretization for each variable,

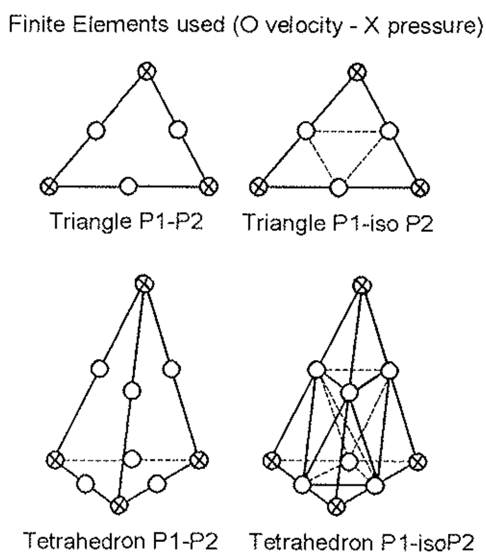


Figure 10: P1 an P2 nodes for unstructured meshes

- definition and modification with user-provided subroutines of some parameters such as body forces, flux boundary conditions and physical characteristics of fluids.

4.2- APPLICATION EXAMPLES

This short description of the calculation method shows that the meshing and calculation tools available in an Engineering Dept. today are ideal to solve the complex problems inherent to the design of an air intake.

CAD tools and meshers help take the accuracy of the geometry into account. Non structured meshes seem most suitable for complex designs, the meshes can be refined at will and the design can be modified locally for optimization purposes.

Numerical tools help solve Navier-Stokes equations for incompressible turbulent viscous flows.

These tools are today indispensable when defining the installation of an engine and designing an air intake.

4.2.1. 2D APPROACH

The intention here is to form a quick and full opinion regarding flows. Fig. 11 provides an application example.

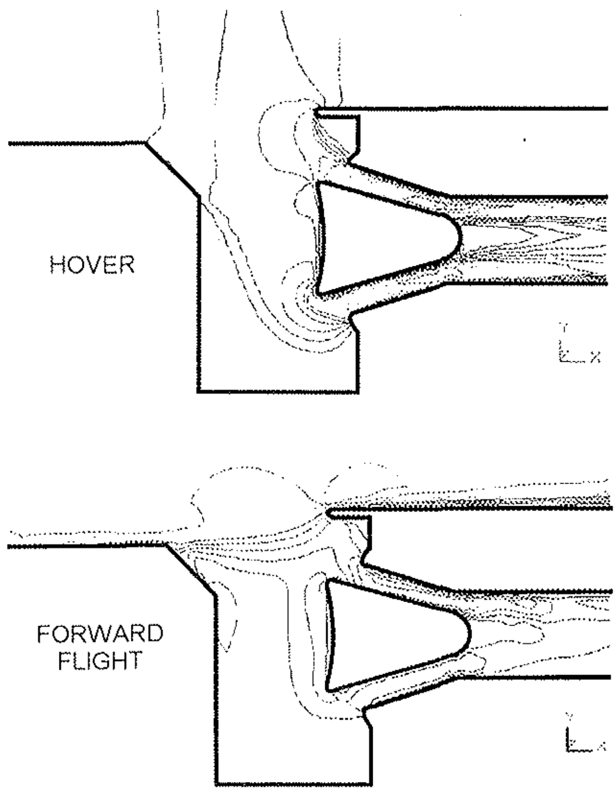


Figure 11: Iso-velocity lines (2D)

The main advantage is the ease and rapidity of those calculations. The designs and flows are plane, possibly simplified, and the meshes are naturally highly simplified. The first main flow structures as well as the first orders of speed magnitude are rapidly accessible. The design can quickly be repeated while some "flight configurations" are rapidly scanned. Fig. 11 illustrates the mode of operation of this air intake concepts for different helicopter speeds.

These calculations naturally represent a first approach only and, with a few exceptions, simplifying the problem down to 2D flow is not sufficient. The switch to 3D is quickly necessary as soon as a finer quantification of the performances is required.

4.2.2. 3D APPROACH

4.2.2.1- CALCULATIONS

The advantages and objectives of 3D calculations are to study flow more accurately. One can then access those flows in true 3D mode and precisely quantify the operation and performance criteria of the designs. These calculations help guide design and tests ahead of time to speed up the design phase.

It becomes possible to access pressure, speed and preswirl cartographies at the aerodynamic interface plane as well as express those parameters anywhere in the calculation envelope.

Fig. 12 shows the speed vector in the air intake symmetry plane.

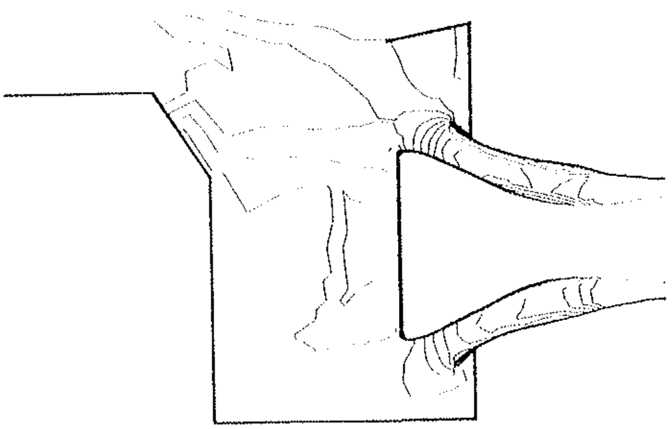


Figure 12: Iso-velocity lines (3D

It can be checked that 2D calculations highlighted the large flow structures and proved that short parametric studies can be undertaken. It is possible as calculation results are analyzed in detail to determine every critical flow area and introduce modifications.

Fig. 13 presents a preswirl cartography at the aerodynamic interface plane and show the consequences of the flow previously examined at the engine intake plane.

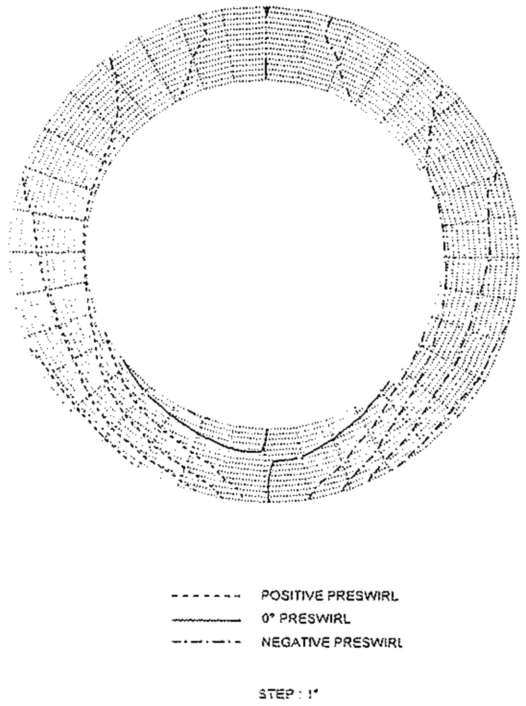


Figure 13: Preswirl cartography at the aerodynamic interface plane

4.2.2 - TESTS/RESULTS CORRELATIONS

Fig. 14 shows that calculations and tests are correlated satisfactorily although there are local differences. These are due to the fact that some excessively complex elements are not taken into account in the calculations at the design level but their impact on the average parameters and performances are of the second order of magnitude. These cartographies represent the impact at the engine level of what is actually occurring upstream in the air intake and its duct.

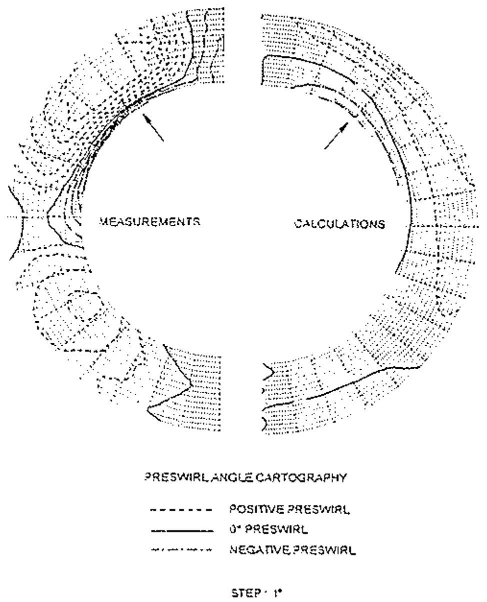


Figure 14: Local tests / results correlations

Fig. 15 shows for the air intake concept illustrated above that the calculation of engine criteria is quite satisfactory compared to tests. One can see that handling the definition with the 3D Navier Stokes calculation produces the same air intake performances increase in terms of engine criteria. The excellent calculations/tests correlation demonstrates the reliability as well as the improvement, of the Navier-Stokes tool in the calculation of flow inside air intakes.

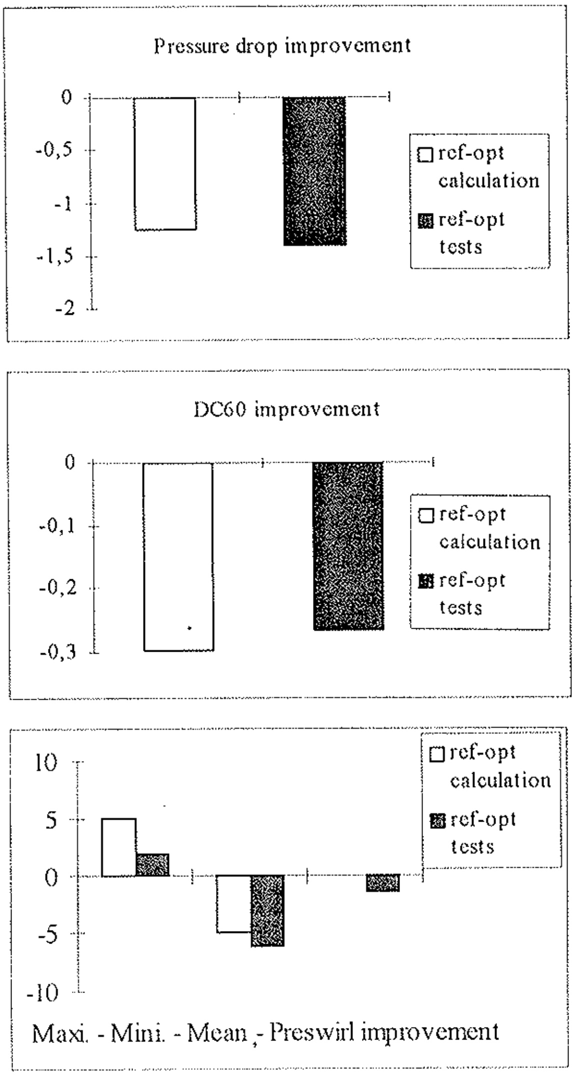


Figure 15: Global tests / results correlations

4.3- CONCLUSION

The calculations provide an extensive understanding of the phenomena of a given design.

The main advantage of this approach is that it can be applied early in the development phase.There is no need for a precise definition taking every constraint into account and the research studies can begin with a preliminary design sketch. The evolution of the definition can be followed with either a simplified (2D) or complicated (3D) application. At this stage, the definition can be changed and largely improved while taking the computational results and knowledge of the aircraft operational constraints into consideration. This early process can help with the design itself and influence the general architecture.

This computational methodology also helps visualize the streamlines in the internal flow and offers a local knowledge of the flow. It is then possible to optimize internal details.

The limits of these computations are the difficulty to qualify over the whole flight envelope the behaviour or the ruggedness of the optimum definition.

Moreover, the external fuselage streamline requires many calculation man/hours. Some unavoidable aspects that are not taken into account here can also have a significant influence. The main rotor is one of those elements along with grids, hoist and other protrusions.

5- GENERAL CONCLUSION

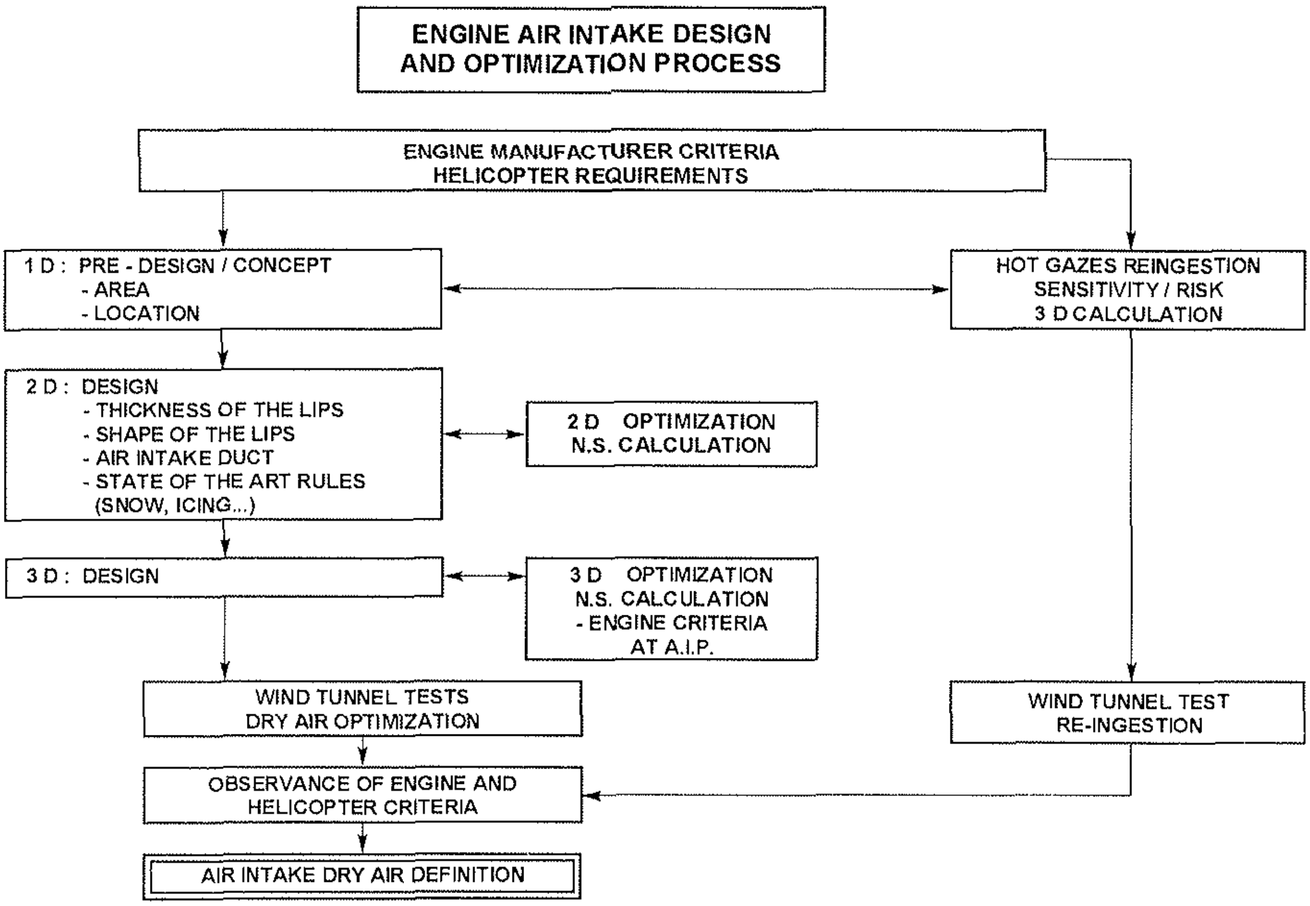
Defining and optimizing helicopter air intakes is a complex problem which imposes tight operating criteria and requirements.

The wind tunnel « tool », and its reliability in terms of qualification, remains mandatory for the air intake design process.

The flexibility and the reliability of the Navier-Stokes calculation tool at a very upstream stage of the project is now demonstrated.

Air intake optimization is now possible at an advance stage of the programme. This optimization must necessarily complete the qualification tool (wind tunnel) with an upstream tool such as Navier-Stokes calculations.

As a result of the combined use of these tools, engine installation is no longer a major problem from the aerodynamic point of view. This methodology is well adapted for dry air and a strong effort is now put forward at ECF to take into account, at a very upstream stage of the design process, every other tasks such as grids, icing and snow.



APPENDIX -1-

Navier Stokes equations

$$\begin{cases} \operatorname{div}(\rho.\overline{V}) = 0 \\ \dfrac{\partial\rho.\overline{V}}{\partial t} + (\overline{V}.\overline{\mathrm{grad}}).\rho.\overline{V} = -\overline{\mathrm{grad}}.p + \operatorname{div}\left[(\mu.\overline{\mathrm{grad}})\overline{V}\right] \end{cases}$$

k-ε model

$$\begin{cases} \dfrac{\partial\rho.k}{\partial t} + (\overline{V}.\overline{\mathrm{grad}}).\rho.k = \operatorname{div}\left[\left(\mu + \dfrac{\mu_t}{\sigma_t}\right).\overline{\mathrm{grad}}.k\right] + P - \rho.\varepsilon \\ \dfrac{\partial\rho.\varepsilon}{\partial t} + (\overline{V}.\overline{\mathrm{grad}}).\rho.\varepsilon = \operatorname{div}\left[\left(\mu + \dfrac{\mu_t}{\sigma_t}\right).\overline{\mathrm{grad}}.\varepsilon\right] + \\ \qquad\qquad C_{\varepsilon 1}.\dfrac{\varepsilon}{k}.P - \rho.C_{\varepsilon 2}.\dfrac{\varepsilon^2}{k} \end{cases}$$

$P = 2.\mu_t.\mathrm{tr}(\underline{\underline{dd}})$, $\quad \mu_t = \rho.C_\mu.\dfrac{k^2}{\varepsilon}$,

$C_{\varepsilon 1}, C_{\varepsilon 2}, C_\mu$ usual constants

Enthalpy equation

$$\frac{\partial\rho.T}{\partial t} + (\overline{V}.\overline{\mathrm{grad}}).\rho.T = \operatorname{div}\left[\left(\mu + \frac{\mu_t}{\sigma_t}\right).\overline{\mathrm{grad}}.T\right]$$

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