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AERODYNAMIC DESIGN OF ENGINE AIR INTAKES FOR IMPROVED PERFORMANCE

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ABSTRACT :

For reasons of aircraft architecture, engines on medium or small size helicopters are located behind the rotor head which makes air intake very difficult. This is more particularly the case of the AS 350 ASTAR, AS 355 TWINSTAR and the SA 365 DAUPHIN equipped with new generation engines.

Suction into these engines can be either axial or annular depending on whether the reduction gear box is located on the jet pipe side or the compressor side. An in-depth study of air intake, right from the project phase can make it possible to design them with a minimum of negative effects on the power delivered by the engines (pressure drop, power loss through reingestion of hot gases, through distortion and fluctuation of pressure before the compressor), on the aircraft drag and on the risks of surge.

Therefore, such a study may well reduce substantially the time and therefore the cost for in-flight tuning. This presentation summarizes the methods used at Aerospatiale and the results obtained in flight on various aircraft.

NOTATION

A = area

V = velocity

P = static pressure

P_T = total pressure

ρ = density

DC60 = distortion index

$$= \frac{(\overline{P_{T2}} \text{ ON A } 60^\circ \text{ SECTOR}) \text{MINIMUM} - \overline{P_{T2}}}{\frac{1}{2}\rho_2 V_2^2}$$

SUBSCRIPTS

$\overline{}$ = mean value

0 = free stream

1 = inlet

2 = compressor

4-5 = venturi

6 = exhaust

1 – INTRODUCTION

Through a large part of the altitude - temperature envelope, twin-engined helicopter performance is limited by the engine power available rather than by the capacity of the transmission components.

In particular, for helicopters subject to FAR 29 Category A, engine failure upon take-off is very penalizing ; to take the twin-engined DAUPHIN SA 365 for example, a 5 % variation in engine power represents 180 kg of take-off weight.

The 5 % figure is typical of the installation loss of power on helicopters for which there has been no detailed investigation of the aerodynamic interface between engine and fuselage, and especially the air intakes.

This paper describes the problems involved in designing engine air intakes :

- aerodynamic behaviour throughout the flight envelope, power losses, increases in consumption, reduction in the engine surge margin, airstream separation on the fuselage causing additional drag,
- environmental protection of engines against foreign bodies, sand and ice,
- ease of installation in the airframe and in-service maintenance.

The methods employed at Aerospatiale in Marignane, and the results, have been improved by a systematic approach to this problem on various recent helicopters such as the DAUPHINS SA 365N and SA 366G (Coast Guard version), the TWINSTAR AS 355 and the SUPER PUMA AS 332.

2 – HELICOPTER AIR INTAKE PROBLEMS

2.1 – Aerodynamic behaviour

Power losses on installation

These are defined as the variations in power observed between the test stand and flight conditions, with the gas generator operating at the same low speed. Such losses are frequent and may result :

- from the reingestion of hot air from the oil cooler, the recycling of exhaust gases by the main rotor or directly from the engine exhaust pipes in tailwind configurations. It should be remembered that a 1°C rise in intake air temperature costs about 0.8 % of power,

- from pressure drops or disturbance in the average intake airflow ; on average, a 1 % (or 10 mb) loss of total pressure will mean a loss of at least 2 % in available power. The effects of pressure distortion and turbulence are not fully known, but these may be the cause of losses that cannot be explained by reductions in compressor efficiency.

Losses on fuel consumption

These losses may be large. They are due to a deterioration in the engine's thermodynamical cycle.

They may result :

- from a rise in the average compressor intake temperature
- from a deterioration in compressor efficiency due to pressure distortion.

Increase in aircraft drag

An unsuitable air intake surface and lip design may cause airstream separation on the cowling, leading to an increase of about 10 % in the overall aircraft drag.

Problems with surging, in-flight tuning

These are the trickiest problems because they make contact necessary between the engine and the airframe manufacturers while, since there are no specific criteria and measurements, it is not possible to clearly establish their respective responsibilities.

Surge problems in tailwind conditions have often made it necessary to perform a difficult in-flight adjustment which generally leads to modifications to the exhaust nozzle.

All these points have a major effect on aircraft performance, fuel consumption, operating range, maximum take-off weights, maximum speed and development costs.

2.2 – Suitability to flight conditions

To obtain certification of an aircraft, the airframe manufacturer must demonstrate that the engine runs correctly throughout the flight envelope. To this end, he must conduct tests involving contact with foreign bodies (birds, hailstones, etc...) and also icing tests.

On the latest helicopters, adequate protection is provided by a screen (wire section 0.8 mm – mesh 5.5 mm) installed in front of the air intake and sometimes fitted with stiffeners. This system is detrimental to performance,especially in forward flight, because it causes a pressure loss and a large amount of drag at high speeds.

Some operating conditions even require the use of a sand filter consisting of a large number of vortex tubes which separate off the solid particles by centrifugal force. The loss of power and of take-off weight due to this accessory can be very high.

The noise spectrum of the engine intakes merges into the general spectrum and has not been systematically investigated.

2.3 – Installation on the airframe

The method chosen may depend on the following criteria :

- ease of maintenance beneath the cowlings,
- light weight,
- aesthetic appearance, especially for the civilian market, on which the simple PITOT - type air intakes are not easily accepted.

Design of the air ducts is particularly complicated when the engines are mounted behind the rotor head ; it is impossible to avoid having bends or a great length of duct. The need to prevent leakage from the ducts, which can cause serious power loss through the reingestion of hot gas, may make it necessary to fit removable seals so that the cowling can be opened for access to the transmission assemblies.

3 – FLIGHT TEST EQUIPMENT

Flight tests for air intakes are very difficult to analyze and to interpret unless the installation can be fitted with a rake containing a sufficient number of total pressure probes, located in front of the compressor, so that it is possible to take measurements simultaneously from all the probes during the same flight.

The system currently used has about twelve conventional differential transducers connected to the probes by a given length of tube.

A system for taking unsteady measurements is being designed.

Intake temperatures are measured by thermocouple bulbs.

4 – WIND-TUNNEL TEST FACILITIES

These are basically tools for verifying the design assumptions, by detailed airstream analysis and quantification of the air intake performance.

Fig. 1 shows the general arrangement of a half-scale model originally built for testing the air intakes of the twin-engined Dauphin SA 365C.

By adjusting the wind-tunnel airspeed, the attitude of the mock-up and the air flow of the internal suction fans, the functioning of the engine air intake can be simulated through practically the whole flight envelope defined by the parameters of speed, angle of attack, side-slip, density height and engine mass airflow.

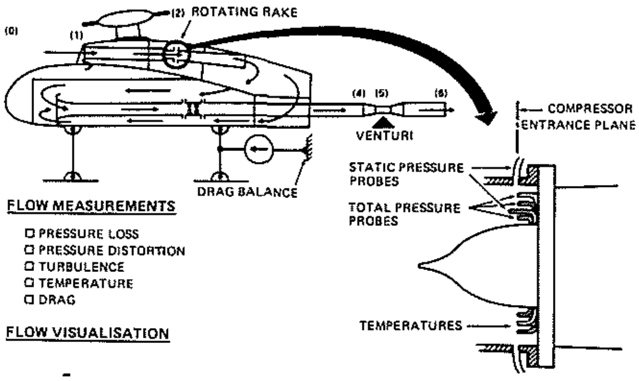


Figure 1 : *GENERAL ARRANGEMENT OF SA 365C DAUPHIN HALF-SCALE MODEL TESTED IN MARIGNANE WIND-TUNNEL*

Study of internal airflow

For each simulated flight configuration, a set of measurements are taken by the rotating rake equipped with total pressure probes and by static pressure probes located on the wall. These give :

- the average pressure loss,
- the distortion index.

The pressure transducers are mounted after a scanivalve connected to the pressure probes by a length of pipe. With the measurement unit used so far, this system does not permit accurate unsteady measurements, but the short-term amplitude of the signal gives an indication of the level of turbulence in the engine intake airflow and makes it possible to classify mock-up configurations using this criterion.

Temperature measurements can be taken using thermocouple bulbs placed on the measurement rake ; by simulating a hot air flow on the mock-up, the sets of temperature readings indicate the amount of hot air ingested.

Drag measurement

The half-scale model sucks in and blows the simulated engine gas airflow within the wind-tunnel and the whole unit is weighed to give comparative drag measurements. The arrangement is as shown in Fig. 1.

The pressure variation measured by the venturi between sections 4 and 5 gives the airflow.

The thrust due to the suction fan, taken along the centreline of the model, is by definition the difference between the input and output dynalpic flows $\vec{G} = P\vec{A} + \rho V^2\vec{A}$ along the axis $T = G_6 - G_0$ which can be written $T = (G_6 - G_1) + (G_1 - G_0)$.

The term $G_6 - G_1$ represents the resultant of the air stream actions between sections (1) and (6) on the area comprising the internal ducting, fans and exhaust pipes.

The term $G_1 - G_0$ represents the theoretical external thrust generated by the suction on the fairing.

The external drag of the air intake is the difference between this theoretical thrust and the effective thrust T_c which this fairing can exert when the sign is changed.

$$Tox = - [(G_1 - G_0) - T_c]$$

To compare two air intakes, at the same engine mass flow so as to keep the same air flow rate for the simulated flight configuration, the same output dynalpics must be made :

$$G_6 = P_6 A_6 + \rho_6 A_6 V_6^2$$

The condition $\rho_6 V_6^2 A_6$ is achieved by maintaining

$2\Delta p$ venturi $= \rho_5 V_5^2 - \rho_4 V_4^2$ constant.

The condition $P_6 A_6$ = constant cannot be achieved simultaneously and accurately with the fans used, and so a slight correction is required. In practical terms, the drag characteristics are established relative to the mass flow rate by maintaining a constant measured pressure differential at the calibrated venturi and by varying the wind speed. The flow pressure is corrected at each point.

Study of outside airflow

The study of hot air recycled by the main rotor is possible only at a much smaller scale, I : 7 or I : 10 depending on the aircraft involved. This type of testing is used to analyse the path of hot gases in critical flight configurations, as in **Fig. 2** which applies to the SUPER PUMA AS 332.

The size of the models makes it very difficult to simulate the temperature field directly. The hot exhausts are simulated cold by injecting carbon dioxide. The local concentrations are measured and a concentration-to-temperature correlation law is applied to estimate the amount of hot air reingested by the engine air intakes for example. This process has revealed phenomena similar to those mentioned by Boeing during the UTTAS design programme (ref. 4).

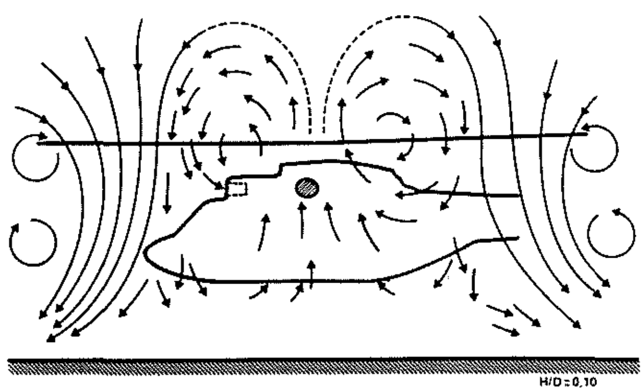


Figure 2 : *FLOW VISUALIZATION AROUND A SUPER-PUMA AS 332 IN HOVER FLIGHT (I.G.E.)*

5 – RESEARCH METHODOLOGY

Fig. 3 summarizes the key air intake functioning parameters that can be adjusted at the design stage.

Whatever the design chosen, actual engine performance in flight depends basically, for a given exhaust nozzle :

- on the average total pressure before the compressor,
- on the average total temperature before the compressor.

Engine performance is measured by the builder on the test stand in the helicopter's ground run conditions (total pressure at input = static ambient pressure) with intake lips giving near ideal distribution.

In practice, the total pressure field is never uniform before the compressor ; variations from the average total pressure are described by means of a distortion index (variations in space) such as DC60 and by the level of fluctuation and turbulence relative to the average flow (variations in time).

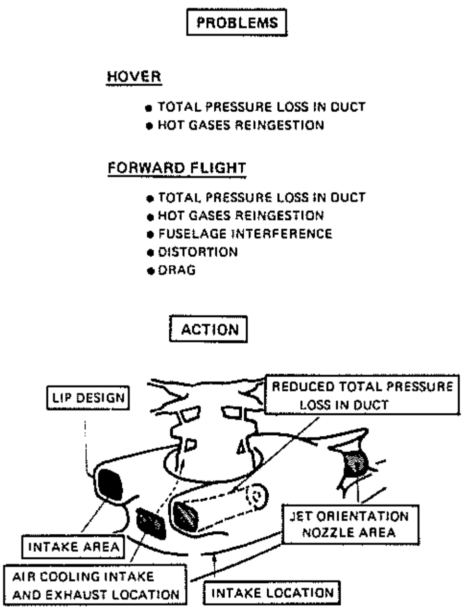


Figure 3 : KEY POINTS OF ENGINE AIR INTAKE DESIGN

Air intake functioning in hover

The engine sucks air in from all around the intake, but the suction effect decreases very rapidly with the increase in distance. The power required of the engine determines the mass airflow qm and the speed V_1 **(cf. fig. 4)**.

The functioning of the intake lips can be explained as follows : the airstream near the lip must flow round the lip and accelerate from 0 to the speed V_1. The curve in the air current will correspond to a negative pressure spread over the lip and with an integral on the outline equal to the suction force.

The thinner the lip, the sharper the pressure peak and the steeper the positive pressure gradient determined by the average low pressure level in the air duct. At the extreme point on this pressure gradient, airstream separation occurs.

The extreme case would be that of an infinitely thin lip ; here, airstream separation is immediate and the pressure loss is roughly equal to the internal dynamic pressure.

Thus, it is primarily the relative lip thickness which determines the pressure loss factor,

$$\frac{\Delta P_T \text{ lips}}{1/2\, \rho_1 V_1^2}$$

and, to a less extent, the lip profile.

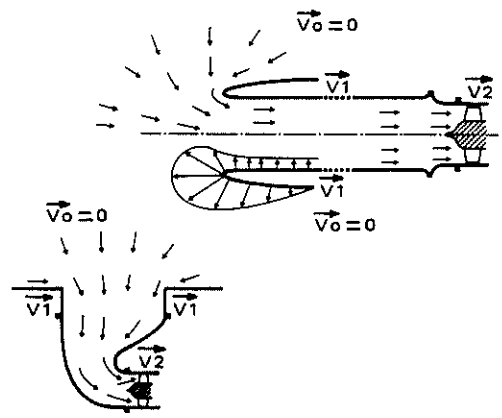


Figure 4 : ENGINE AIR INTAKES FLOW IN HOVER

Air intake functioning in forward flight

The surrounding space can be divided into 2 areas **(see fig. 5)** :

- the first is the air drawn in by the engine, forming a tube-shaped airstream of section area A_0 stretching to the free stream and moving according to the local velocities,
- the other may be deflected but is not drawn in. The airflow follows the outer side of the lip, accelerating from the stagnation point until it reaches a low pressure level determined by the thickness and profile of the lip (suction), then slowing down and merging with the airstream controlled by the overall shape of the fuselage. The more abrupt the deceleration, the sooner airstream separation is likely to occur.

On the inner surface of the lip, the air generally accelerates continuously from zero, and there is no risk of airstream separation inside.

The relation $\epsilon = \dfrac{A_0}{A_1} = \dfrac{\rho_1 V_1}{\rho_0 V_0}$ is called the mass flow rate,

and it indicates the adaptation of the air intake.

The angle of incidence α is the angle between the axis of the stream tube drawn in and the centre-line of the air intake.

The mass flow rate and the angle of incidence determine the amount of airstream separation occurring outside and possibly inside the lips.

The same figure shows the functioning of static air intakes ($\alpha = 90°$) in forward flight. The stream tube drawn in does not take up the whole surface of the air intake, but only a working area ; the remainder being a vortex area which increases in size as the mass flow rate decreases. The vortex is not very stable and it causes fluctuation of the airflow in the air intake, resulting in a high amplitude in the total pressure signals at the compressor, in addition to reductions in the average flow due to airstream separation and friction against the walls.

In forward flight there may be total pressure losses resulting from disruption in the stream tube drawn in, upstream of the air intake, due to friction against a wall or an obstacle.

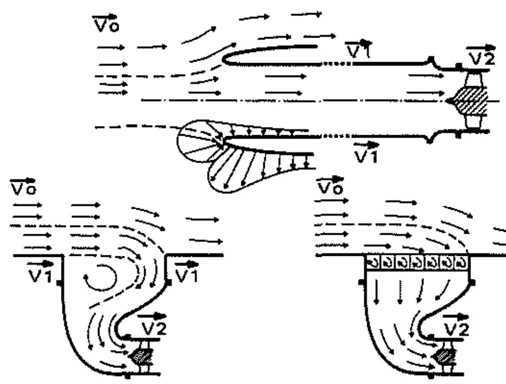


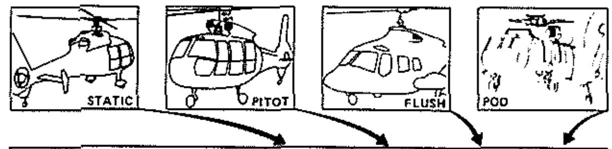
Figure 5 : ENGINE AIR INTAKES FLOW IN FORWARD FLIGHT

6 – EVALUATION OF THE VARIOUS SOLUTIONS COMPATIBLE WITH THE AIRCRAFT'S ARCHITECTURE. POSITIONING OF THE AIR INTAKE SURFACE PLANE

Fig. 6 shows the presumed advantages of the various air intake arrangements developed so far for use on helicopters with engines located behind the rotor head.

This table may provide useful information for the selection of the air intake surface plane position, based on the aircraft's role and on the importance placed on the parameters in the left-hand column.

For light twin-engined helicopters with good speed performance (Bell 222, Sikorsky S76), the flush arrangement of the air intakes seems to predominate at present. It was finally chosen for the Dauphin SA 365N and the Twinstar AS 355, both twins, in preference to the «Pitot» arrangement which gives slightly better performance, mainly with respect to drag, but which poses installation problems and is questionable from the aesthetic viewpoint.



	STATIC	PITOT	FLUSH	POD
HOVER	●			
FORWARD FLIGHT	●	■	▲	■
DRAG	●	■	▲	■
DESIGN	▲	●	■	●
ICE & FOREIGN MATTER PROTECTION	■	▲	▲	▲
SAND FILTERS	■	●	▲	●
WEIGHT	■	●	▲	●
MAINTENANCE	■	●	▲	■

● BAD ▲ ACCEPTABLE ■ GOOD

Figure 6 : COMPARISON OF VARIOUS AIR INLET ARRANGEMENTS

The «pod» arrangement, developed for heavier helicopters such as the UTTAS and the BOEING VERTOL CHINOOK, is very advantageous from the point of view of drag (despite the increase in surface area) and of engine performance since it means that the air intake and the exhaust pipe can be parallel to the aircraft centre-line. This arrangement also simplifies the design of the equipment used to reduce the infra-red signature of the exhaust (military uses, installation of an exhaust gas deflector). On the other hand, it is heavy and unaesthetic.

7 – DIMENSIONING PRINCIPLES – METHODS OF CALCULATION

Air intake section area A_1 and angle of incidence α

The optimum ground run condition is to have a very large intake section area, but this is incompatible with the optimum condition for flight at cruising speed, which corresponds to the adaptation in which :

Surface of stream tube drawn in A_0 = Intake section surface A_1.

The proposed compromise is

$$\frac{A_0}{A_1} = 0.8$$

A_0 being calculated for ground-level cruising flight conditions, where this ratio is almost at its lowest, given the high local airflow speeds due to the shape of the fuselage.

In these conditions, a lip thickness 'e' of about 25 % of the air intake diameter will generally suffice, if the intake is symmetrical about its centre-line and the incidence $\alpha = 0$, to prevent airstream separation and excessive drag.

If the intake is bevel-shaped or against a wall, the relative thickness of the lip becomes less, since the wall becomes the plane of symmetry, and the 25 % of diameter rule becomes inadequate.

Fuselage boundary layer

If the preliminary design favours air intakes merged into the fuselage, a considerable improvement can be made in the recovery of pressure in forward flight and in reducing distortion, by installing a boundary layer bleed.

Lip profile calculation and air duct design

So far only two-dimensional methods are used ; in particular, a semi-empirical method using conformal transformations, which is very fast to run.

Direct computation of the local pressures on a lip is done by the finite difference method using an ONERA programme (reference 6). This programme is also used to compute the internal airflow in the duct.

Three-dimensional methods are being developed for this application at ONERA.

Fig. 7 shows the lines obtained by the hodograph method and used for the AS 365N DAUPHIN.

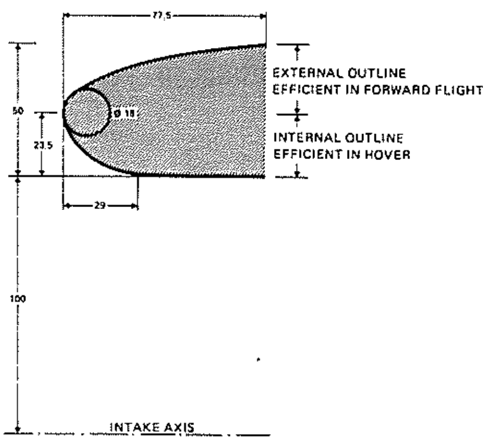


Figure 7 : INLET LIP DESIGN ON SA 365 DAUPHIN (HODOGRAPH METHOD)

Fig. 8 shows a comparison between calculation and testing for the AS 350 Ecureuil air intake in ground run conditions.

The airflow in the duct can be computed provided that there is no airstream separation across the intake section area ; empirical data such as the Data Sheet charts are used to calculate the pressure loss due to the duct alone.

In other cases, especially those with airstream separation, loss calculation can be achieved only by wind-tunnel testing of a model.

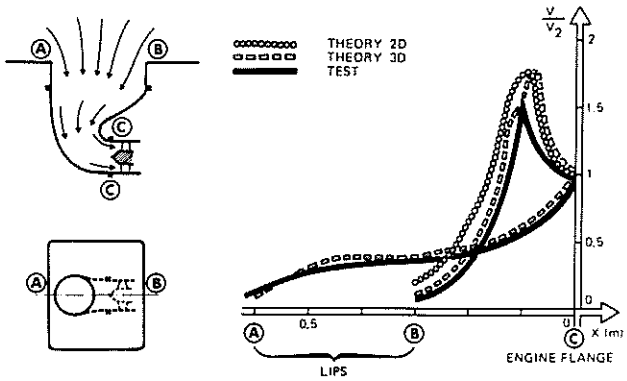


Figure 8 : MEASURED AND PREDICTED INTERNAL VELOCITIES IN HOVER ON ASTAR AIR INTAKE (TURBOMECA ARRIEL)

It should be remembered that in a straight circular duct the pressure loss varies approximately as :

$$\frac{\Delta P_T}{1/2\,\rho_1 V_1^{\,2}} \simeq K \frac{L}{R}$$

V_1 Average speed in the air intake, determined by the engine throughput in the flight configuration considered.

L Length of air duct.

R Average radius.

K Factor of about 0.015 in the case of cylindrical ducts.

The duct length chosen is a compromise, unless it is dictated by a general architectural feature of the aircraft.

- a long duct, about 8 times the compressor diameter, has the advantage of eliminating airstream distortion in the intake ; this is the length required for the large vortex formations that could occur in the air intake to be destroyed,
- a short duct has the advantage of reducing the pressure loss.

We have avoided having a large internal volume serving as a plenum chamber, because the pressure losses are too high.

8 – RESULTS

Two recent helicopters are fitted with static air intakes, the twin-engined DAUPHIN SA365C and the ASTAR AS 350. As we have seen, this type of intake has the advantages of simplicity and of ease of adaptation for protection systems.

At high speed, however, the distortion is very considerably greater (see fig. 9) and performance is less good than with dynamic air intakes (cf. fig. 10). The installation of a filter resembling a coarse honeycomb material in the air intake surface plane considerably reduces distortion and speed fluctuations before the compressor, but does not significantly reduce the pressure loss (cf fig. 5).

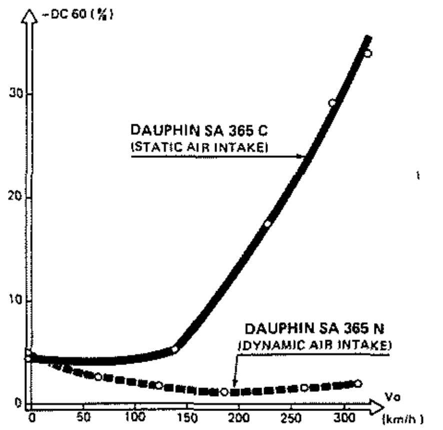


Figure 9 : AIR INTAKE DISTORTION (WIND-TUNNEL TESTS)

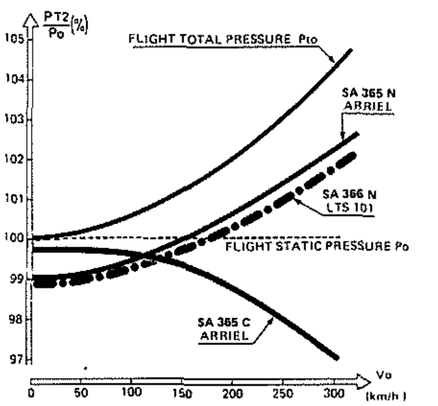


Figure 10 : COMPARISON OF PRESSURE RECOVERY FOR SEVERAL AEROSPATIALE AIR INTAKES (WIND-TUNNEL TESTS, WITH PROTECTION SCREEN)

This modification has been included in the AS 350 (ARRIEL) production standard.

Also, on the SA 365C, vortex generators have been installed on either side of the rotor head to limit the effects of the wake and the ingestion of hot air from the main gearbox well. This device keeps the wake well above the cowlings and keeps a free flow area clear.

Fig. 10 also shows the wind-tunnel results for various air intakes of the DAUPHIN family. Dynamic intakes give far better performance in forward flight, and have been used for the following recent helicopters : DAUPHIN SA 365N, SA 366G (COAST GUARD), TWINSTAR AS 355 and SUPER PUMA AS 332.

Furthermore, for the SA 365N, the air intake plane has been positioned forward of the rotor head in order to avoid hot air recycling.

Despite the complexity due to the engine's annular suction system, the Coast Guard SA 366G's air intake does not show an appreciably greater pressure loss than that of the SA 365N.

On the AS 355 TWINSTAR fitted with ALLISON C20, the cooling air is channelled along the transmission shaft and released to the rear of the engines, and so there has been no problem with hot air recycling in forward flight. It has thus been possible to design shorter air ducts with flush air intakes located beside the rotor head. This design has lead to a very good efficiency on the whole flight envelope.

Fig. 11 shows the gain in total aircraft drag on the SA 365N equipped with the dynamic air intakes as compared with the static air intakes.

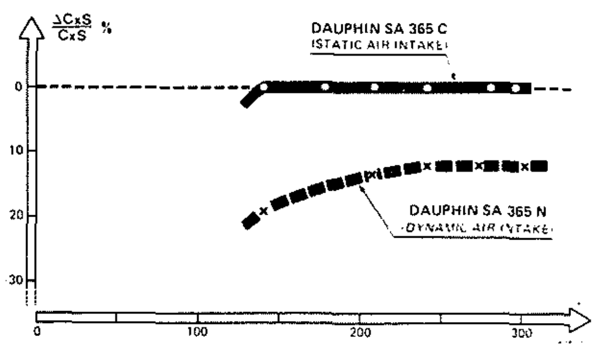


Figure 11 : COMPARISON OF DRAG (WIND-TUNNEL TESTS WITHOUT PROTECTION SCREEN)

On the SUPER PUMA AS 332, special attention was paid to the design of the intake lips and protection screen, resulting in a 6 km/h gain on the aircraft's maximum speed, relative to the initial standard.

9 – CONCLUSIONS AND RECOMMENDATIONS

This paper has described the methods and results of engine air intake design at Aerospatiale Marignane. Thanks to this research it has been possible to reduce significantly the installation power losses and fuel consumption losses which occur on all helicopters, if one compares measurements taken on the engine test stand with those taken in flight. In the same way, it is possible to avoid major airstream separation on the fuselage, which causes large power losses due to drag.

The fundamental design parameters, which determine whether the level of efficiency will be acceptable, are as follows, by order of importance :

- the choice of the air intake plane position on the fuselage,
- the surface area of the intake,
- the angle of incidence,
- the design of the protection systems (against foreign bodies, ice, snow and sand),
- the relative thickness of the lips,
- the air duct design,
- the lip shape.

The potential of the calculation approach is becoming steadily greater, but wind-tunnel testing cannot yet be dispensed with if very high performance is sought.

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