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NEW AERODYNAMIC DESIGN OF THE FENESTRON FOR IMPROVED PERFORMANCE

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Aerospatiale PANTHER prototype equipped with the fenestron

ABSTRACT

Since the first Gazelle flight in 1968, Aerospatiale has developed the fenestron as an alternate solution to the conventional tail rotor for light or medium helicopters weighing less than 6 tons. This concept has widely evidenced its advantages on about 1100 Gazelle and 235 Dauphin helicopters equipped with this fenestron and totalizing more than 2 million flight hours, without any major accident. The paper first recalls the general definition of the fenestron and its advantages for civil or military applications.

Recent research has shown new opportunities for improving the aerodynamic efficiency of this fenestron. A detailed airflow analysis through the fenestron has recently been achieved with extensive model and full scale tests on the tail rotor bench in hover. The research program was sponsored by the French Government Agencies DRET and STPA. This paper surveys the experimental technique and the flow measurements. It also presents the correlations that have been made with blade element theory as well as a more advanced analysis developed by METRAFLU and derived from a radial equilibrium code in use for compressors.

The tests have authorized more thorough flow investigations which have shown potential benefits in recuperating the rotational energy. This has led to design stator blades located behind the rotor, inside the diffuser. Tests of this device have shown large improvements in the fenestron's figure of merit and maximum thrust, for a given rotor blade solidity. Furthermore, improving the diffuser's performance, the stator blades permit reducing the diffuser's length and thus the fenestron's width with drag savings as a final result. Specifications were drawn up for ONERA to design a set of specially adapted, high cambered airfoils in view to further increase the maximum thrust.

Tests of the fenestron equipped with stator blades and new sections are presented and their influence on fenestron sizing is discussed.

These various results will further enhance the fenestron performance which has already proven quite advantageous compared to the conventional tail rotor for several decisive points such as safety, reliability, performance and cost for civil applications as well as detectability and vulnerability for military applications.

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1.0 INTRODUCTION

The qualities requested for present and future helicopters from an operator view point, are essentially:

- better efficiency
- improved security and reliability
- excellent cost effectiveness

The civil operator will normally be well satisfied if the manufacturer could prove that his helicopter is indeed outstanding on the above qualities. At the utmost, he may also request a high level of availability, but this fourth request is more or less embedded in the previous three.

The military operators have their own special requests depending on the type of missions that they have to fulfill and so they have to accept various types of trade-off. They will at least request low vulnerability and good crashworthiness behaviour.

In this general context, one can ask if it is worth spending time and money to try to develop better tail rotors.

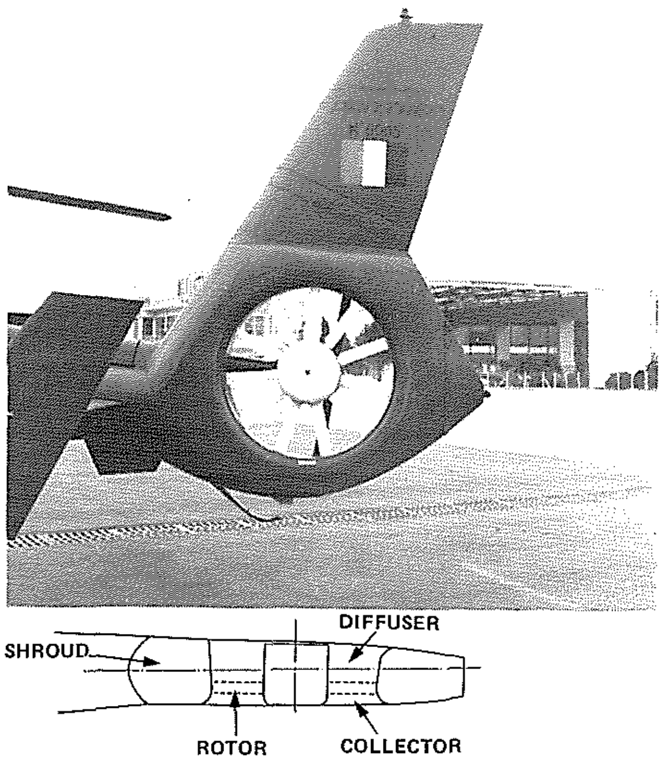

Fig.-1- AS 365 M PANTHER fenestron

A brief set of data can easily illustrate that the answer is yes:

a) The number of helicopters crashed due to failed or impacted tail rotors is about 0.15 per 10,000 hrs of flight in the accident log book, as compared to a registered overall number of accident of 0.71 per 10,000 hrs of flight.

b) Tail rotor noise can represent a significant part of the helicopter acoustic signature at least in one flight path of the ICAO procedures retained for noise certification: the take-off (see ref.[1]). Furthermore on an acoustic detectability standpoint, conventional tail rotors with high acoustic energy content at low frequencies, can be the dominant noise source at large distances.

c) Tail rotors of improved design can on a given aircraft reduce the power needed for maximum tail rotor thrust, improve the maximum thrust capability and reduce the component weight to thrust ratio. When no other constraints are encountered (available power, gear box limitation, structural strength of the helicopter), tail rotor improvement can allow for an increase of the helicopter payload or of the helicopter flight envelope.

Aerospatiale has studied several tail rotors on various helicopters, ref.[2], and has developed an original tail rotor concept the "fenestron", to overcome the major drawbacks of conventional tail rotors.

On the fenestron, the rotor is housed in a shroud which protects it naturally against most of the agressions, reduces the radiated noise and provides several advantages in operation which will be quickly recalled. This paper will then concentrate on the fenestron aerodynamic development in hover, for which recent research has given new opportunities for improving its performance.

2.0 GENERAL DESIGN AND TECHNOLOGY EVOLUTIONS

FIG.1 shows the outline of the AS 365M PANTHER fenestron. The assembly is composed of a small rotor housed in a shroud and topped with a large vertical fin. The rotor diameter is almost one half the equivalent conventional tail rotor diameter and the rotor solidity is roughly twice. So, the blade area is also reduced to one half.
The shroud includes a small collector with rounded lips, a small cylindrical zone at the blade passage and a conical diffuser accommodating the transmission tube, the gearbox with its support arms and the pitch control system.

The first fenestron was flown on a prototype GAZELLE helicopter in April 1968. The production aircraft fenestron had a 700 mm diameter rotor. The blades were made of forged metal and were linked to the hub through a set of thin stainless steel strips of small torsional rigidity to ensure pitch variations. The hub, which holds the self-lubricating plastic type bearings to cantilever the blades, was machined from a light aluminium alloy stamping. The shroud and the fin also are metallic. Ref.[3] and ref.[4] have provided the main aerodynamic performance, stresses and control loads characteristics of this GAZELLE fenestron.
Ref.[5] surveyed the main features of the SA 360, 365 C and 365N DAUPHIN fenestron equipped with a 900 mm diameter fan (first flight in 1972): the technology is similar and the aerodynamic design is derived from the latest optimized version of the GAZELLE fenestron on which an extensive research test program had been achieved.
In 1980, studies were engaged to develop an advanced technology fan-in-fin concept with 1100 mm diameter rotor to be flight tested on DAUPHIN. So, the shroud, the fin and the blades have been fully redesigned with use of composite materials, ref.[6]. The new moulded plastic blades are cantilevered at two stations on plastic self-lubricating pitch bearings and linked to the hub with a unidirectional Kevlar fiber

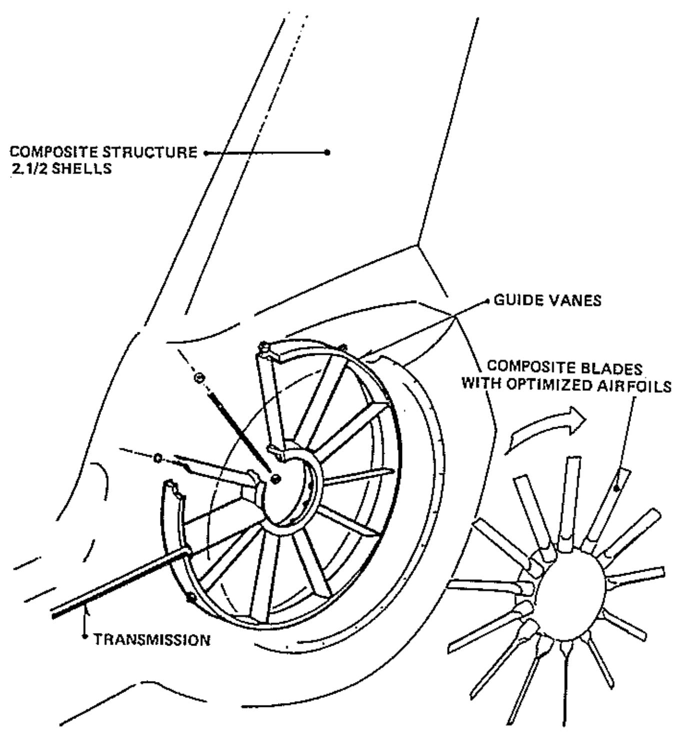

Fig.-2- Light helicopter composite fan in fin

spar providing low torsional rigidity for blade pitch variations.
This new "composite fenestron" is now fitted to the 365N1 DAUPHIN and 366G1 DAUPHIN, COST-GUARD version as well as on the 365M PANTHER prototype.

The most advanced technology is under study for light helicopters and includes new composite blades with optimized airfoils, stator blades in the diffuser replacing the gearbox support arms so as to recuperate the flow rotational energy. The shroud and the fin will consist of two half- shells made of composite structure, FIG.2.

3.0 OPERATIONAL ADVANTAGES

The various advantages of the fenestron have been presented in details in the above mentioned papers and reviewed in ref.[1]. We will simply recall the major points.

3.1 MANOEUVRABILITY, EFFICIENCY

In addition to all the flight tests and the whirl rig tests which have been achieved on the fenestron, more than 1700 hours of testing has been performed in the wind tunnel on 1/2 to 1/8 scaled models in order to get a in-depth understanding of its aerodynamic characteristics.

- HOVER

Due to the complexity of the flow environment of the tail rotor, much disappointment has been encountered in the past by helicopter manufacturers in sizing conventional tail rotors and consequently, by the pilots in using aircraft affected by poor yaw performance and handling. This explains why great efforts have been made to attempt a good understanding of this interactional aerodynamics-related topic, ref.[7] and ref.[8].

In hover with sidewind it is generally considered that in the wind direction-wind intensity map (FIG.3), three zones can be critical on conventional tail rotors:

- zone 1, RH sidewind (main rotor turning counter-clockwise): it is the maximum thrust critical zone which, under the most severe conditions of altitude/temperature including the yaw manoeuvering capability, determines the maximum disc and blade loading required for the tail rotor. In this case, the fin or the transmission fairing interacts the tail rotor creating flow blockage and whatever the selected solution, tractor or pusher tail rotor, there is a loss in the tail rotor net thrust. The fenestron is free of this interference. Furthermore, without intermediate gearbox, its smaller size and its lower position relative to the main rotor makes it free of adverse main rotor interaction.

- zone 2, aft sidewind: in ground effect, there is a combination of aircraft height and aft wind which tends to locate the ground vortex on the tail rotor. Due to the direction or rotation of this ground vortex, and exactly as for a conventional tail rotor, the blade bottom aft direction of rotation is unfavourable and the bottom forward direction of rotation has to be selected.

- zone 3, LH sidewind (main rotor turning counter-clockwise): in LH sidewind, the tail rotor flow opposes the wind and can enter the vortex ring state or recirculation mechanism resulting in pedal reversal or in erratic thrust response and large pedal activity. The T/R disc loading of the tail rotor is the critical parameter. Ref.[9] concludes that with a bottom forward direction of rotation the vortex ring state is retarded, and "that

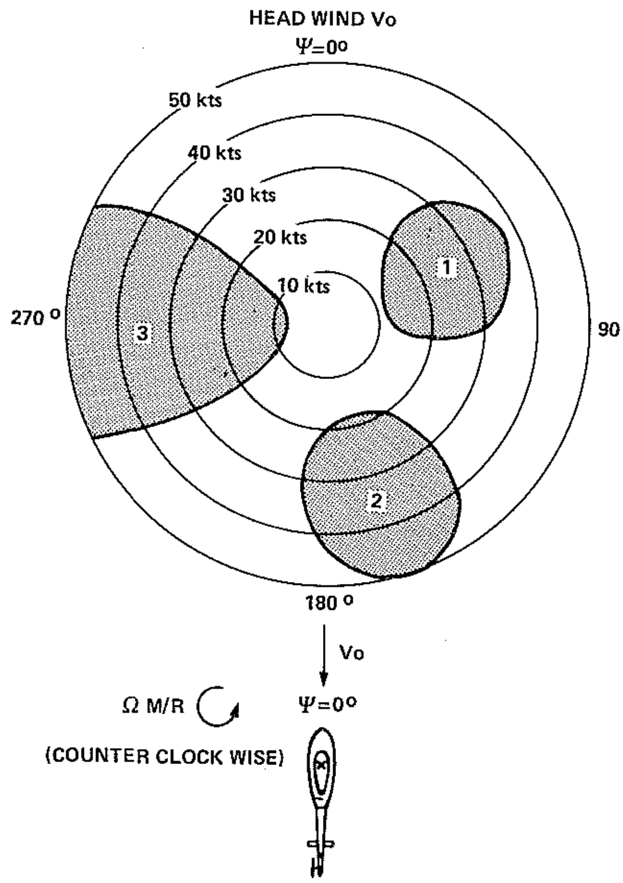

Fig.-3 Hovering critical zones

larger helicopters with higher main rotor disc loading optimize with a tail rotor loading that permits good left sideward flight qualities up to 35 kts. For smaller helicopters, or those where minimum power to the tail rotor was the major consideration, left sideward flight up to 35 kts is not possible without large right pedal excursions". Assuming that the fenestron rotor diameter is half the equivalent tail rotor diameter, the momentum theory indicates that the mean induced velocity will be $2\sqrt{2}$ or 2.8 higher on the fenestron for the same anti-torque thrust. So, especially for light helicopters, the fenestron is very advantageous in left sidewind, opposing the wind direction. The bottom forward direction of rotation is also favourable to delay the flow recirculation phenomenon occurrence, as in the case of zone 2, aft sidewind.

Helicopters equipped with the fenestron have proven smooth handling and excellent yaw manoeuvrability: for example, the Coast Guard version of the Dauphin has demonstrated to be able to reach a 22°/sec yaw rate after 1.5 sec, in 35 kts left sidewind (main rotor turning clockwise) under critical altitude/temperature conditions at maximum gross weight.

- FORWARD FLIGHT

In cruise flight, in order to get the best lift-to-drag ratio of the tail vertical surfaces, it is preferable to fully unload the fenestron. So, all the anti-torque thrust required has to be supplied by the fin which is of relatively large area. It is set at a given angle of attack with respect to the aircraft centerline and has a cambered section. Consequently, the required power by the fenestron is extremely low as it only consists of the profile power which corresponds to one half the conventional tail rotor profile power in proportion with the blade area ratio.

The unloading of the fan in cruise has several other positive consequences as for instance:

- minimizing strains on all the rotating parts of the fenestron,

- or the capability of flying and landing with the tail rotor inoperative in case of failure.

Tests have shown that the directional stability depends almost entirely on the tail vertical surfaces sizing and very little on the fan. In early designs, it has been felt that the yaw control efficiency was poor in cruise within a three degrees sideslip zone, corresponding to a "deadband" appearing for neutral position of the pedal. Wind tunnel tests have provided a comprehensive analysis of this problem which is not relevant to the fan-in-fin concept in itself: the overall directional stability depends on the isolated fenestron stability (without fin) combined with the airframe directional stability. Tests clearly indicate that, as isolated, the fenestron is stable in yaw with no pecularities, FIG.4. The problem is related to airframe stability and to wake effect due to the main rotor head and fuselage, reducing the control efficiency of rear surfaces. So, with the fenestron, it is necessary to improve the fuselage yaw stability if possible by reducing the wake effect, by improving tail surface efficiency and possibly by adding endplates on the horizontal stabilizer which can easily be adjusted during the development process of the aircraft, ref.[10].

3.2 SAFETY AND VULNERABILITY

In addition, the shroud naturally protects the rotor against external agressions and originally, the concept has been developed for the safety purpose. In fact, it remedies almost all drawbacks specific to conventional tail rotors.

It is the reason why for about two million flight hours have already been logged on helicopters fitted with fan-in-fin rotor, there has not been a single serious accident due to the fan-in-fin concept. This has to be compared with the above mentioned rate of helicopters crashed due to failed or impacted conventional tail rotors, which is in the order of 0.15 per 10,000 hours of flight as reported in the accident log book.

As illustrated on FIG.5, enclosed and sheltered in the duct, the fan cannot hit ground obstacles whatever the helicopter evolutions are. In flight, it is difficult, if not impossible, to have the fan hit by elements detached from the helicopter structure or from main rotor blades such as snow packs, ice accretions,..., or to catch cargo slings or hoist cables. Furthermore, when the aircraft is grounded, and the tail rotor operating, people can see the shroud and are not able to be injured by the shroud.

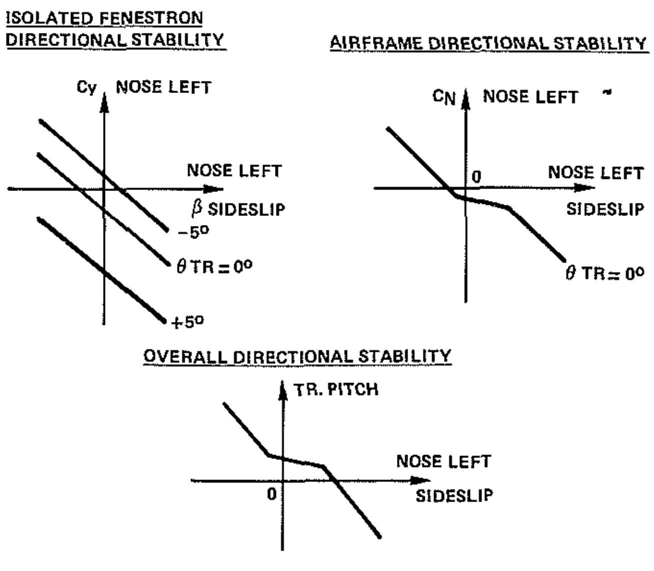

Fig.-4- Yaw stability in forward flight

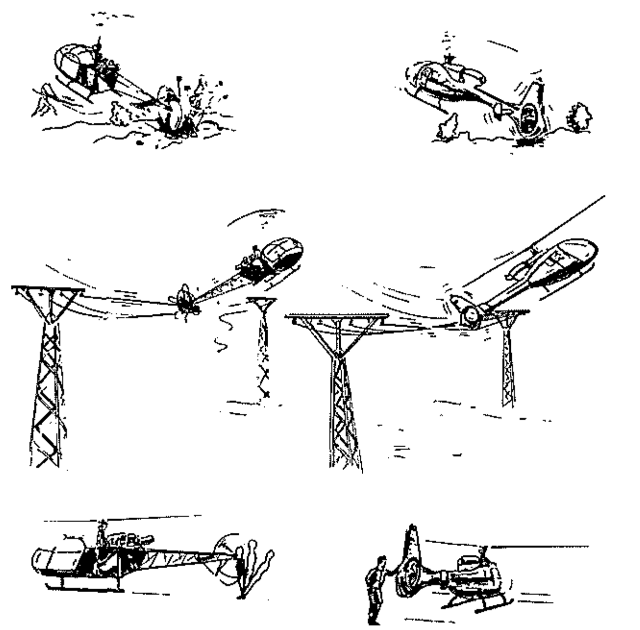

Fig.-5- Operational safety improvement by fenestron

The tail rotor is almost kept away from almost all possible external agressions.

As reported in ref.[1] and as demonstrated by numerous tests, this gives several advantages over the conventional tail rotor as far as sand or rain erosion is concerned in forward flight. Under snow or icing conditions, tests have also shown a better behaviour. In hover, and at low forward speeds, provisions must also be made, as for a conventional tail rotor for sand or dust protection, but due to higher centrifugal forces, ice accretion does not show up on the blades.

The experience shows that mean time between removal on tail rotor blades on the whole fleet of Aerospatiale Helicopters is about three times higher for fan-in-fin concept than for conventional tail rotor. It seems to need no special equipment for icing conditions as it has been experienced during numerous flight hours performed in these conditions.

Vulnerability tests have been undertaken which show that no serious damage occurs when 7.5 mm cartridge casings are thrown into the fan, and pellet impact of 7.5 mm caliber on a blade has practically no effect on the fan operation. It has been further shown that due to the large number of blades, the loss of one blade does not result in an immediate loss of the rotor, as it is generally the case for conventional tail rotors.

3.3 NOISE AND DETECTABILITY

It has been demonstrated, ref.[1], that the fenestron radiates less noise than the conventional tail rotor. Furthermore, the noise attenuation with distance is normally stronger than for conventional tail rotor, as the noise fundamental frequencies are higher by an order of magnitude approximately. Visual detectability when the helicopter is on watch, hiding behind tree lines is reduced in most cases (the conventional tail rotor will emerge from tree tops line but not the fenestron). Finally, reduced radar detectability can be obtained by the use of appropriate composite materials for the structure and for the short dimension blades which could use organic materials for anti-erosion protection devices.

4.0 AERODYNAMICS OF THE FENESTRON IN HOVER

Fan-in fin design criteria are set to provide for a given diameter, maximum thrust capability in hover with a high figure of merit.

From a pure performance point of view, the shrouded rotor is very attractive as, from momentum theory, (see momentum theory in ANNEX, as applied to the shrouded rotor), it offers for the same rotor disc diameter a power saving of about 30%, while developing the same thrust. The total figure of merit of the shrouded rotor can be expressed as follows:

$$Fm = \frac{T^{3/2}}{\sqrt{2\sigma}\,.\sqrt{2\rho S}\,.W}$$

σ being the ratio of the wake to rotor disk area, and S the area of the rotor disk.

How can the shroud improve the rotor efficiency?

The shroud improves the rotor efficiency because it can support the entering flow dynamic pressure, which gives it a thrust component as great as the rotor thrust.

This unloads the rotor which has less head pressure to generate for a given total thrust, and increases the mean depressure above the rotor disc. The wash immediately downstream of the rotor is no more overpressured, as it would be on a free rotor and consequently does not contract.

In these conditions, the wake expansion is estimated as 1 D (D being the rotor diameter) as compared to 0.7 D, from Froude theory, for the conventional tail rotor. So, the thrust is shared as one half for the shroud and one half for the fan.

Furthermore, the diffuser even permits a slight depressure to be settled immediately downstream of the rotor and a slight expansion of the wake.

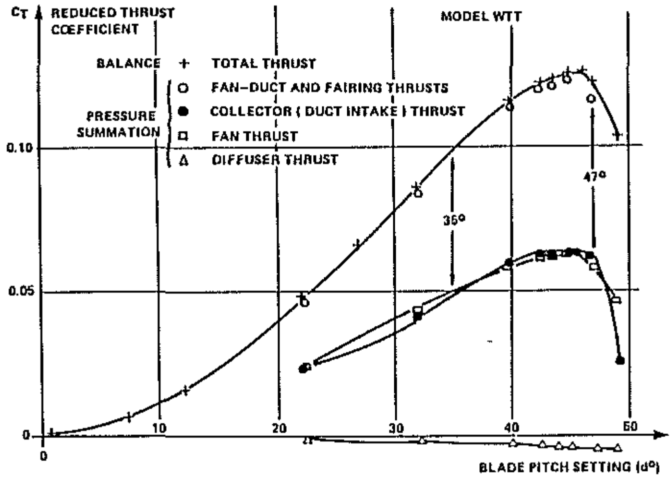

Fig.-6- Thrust sharing between fan and duct fairing

The measurements are well in agreement with this general theory.

FIG.6 shows the thrust versus pitch setting of a fenestron with a typical twist of -7°, as measured on a half-scaled model of the Gazelle fenestron. The fan thrust is derived from total pressure integration downstream of the rotor blades. The collector and diffuser thrust are derived from static pressure integration on the shroud, which is presented on FIG.7 for two values of the 0.7R pitch setting: 35°, which is characteristic of the current regime and 47° which is just beyond stall which occurs at 45° on this model fenestron. As previously explained, let us note that the flow is always depressed within the shroud. On the collector lips, high depressure levels are reached corresponding to maximal local flow velocities. The pressure profile depends on the curvature of the lips which determine the streamline curvature and the local depressure level. Immediately after the depressure peak, the flow has to face an adverse gradient which can result in a separated zone in the front of the rotor tip if the lip is not well rounded or if the collector length is too short.

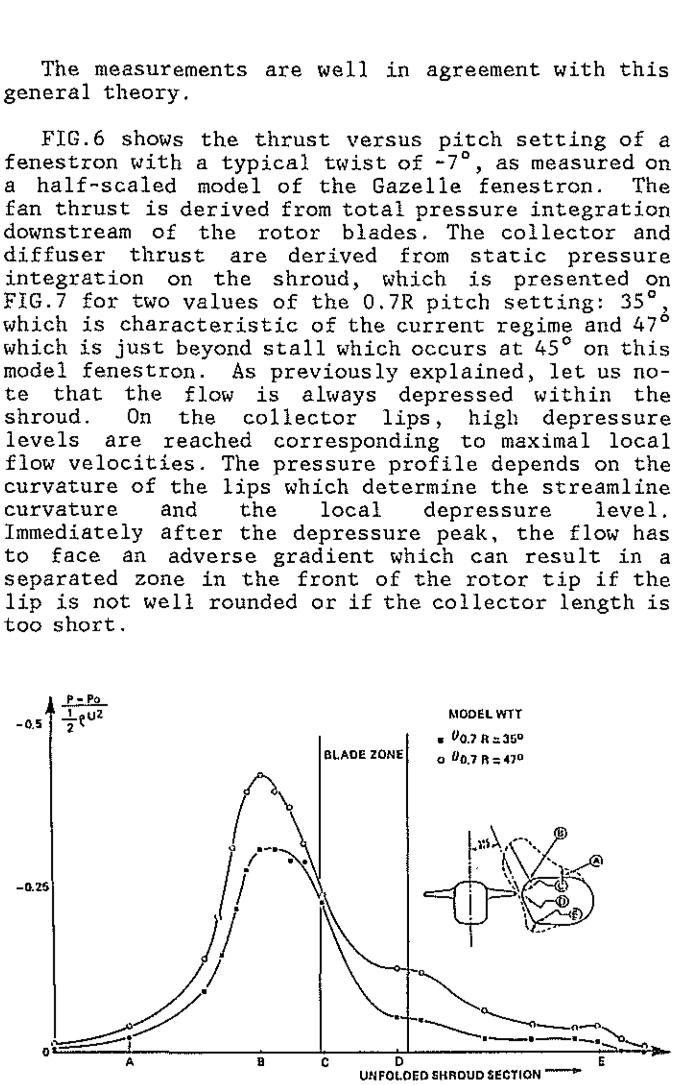

Fig.-7- Hover static pressure survey along the shroud

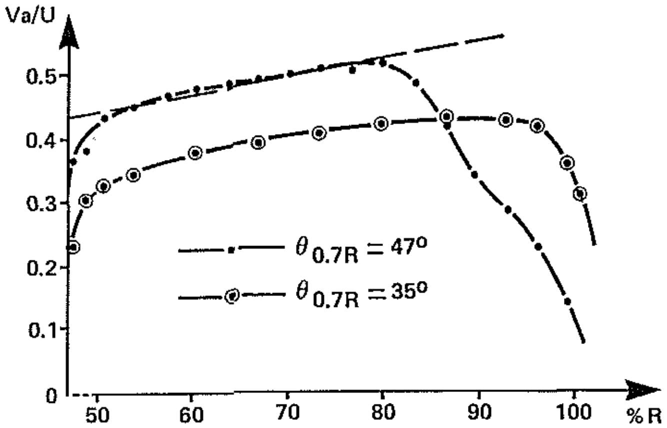

Fig.-8- Axial velocity distribution downstream the rotor blades

Velocity profile measurements have been achieved immediately downstream of the disc with a five-hole pressure probe which can give - after adequate calibration - total pressure, static pressure and airstream velocity components.

On FIG.8 and again for the same two characteristic values of pitch setting, the velocity profiles have been plotted. They illustrate the stalling mechanism of the fenestron: when the airfoils at the tip reach their Clmax, they cannot supply head pressure any longer to activate the flow in this area. The velocity profile is thus altered near the shroud and can no longer depress the inlet lip which limits the collector thrust.

On FIG.9, the flow rotational angle are also plotted for 35° and 47° pitch setting angles. So, the flow rotational angle β gradient generally varies as the axial velocity profile. At $\theta = 35°$, the mean value of the rotational angle is about 10° whereas at $\theta = 47°$, it is increased up to 18° in the potential flow zone. Close to the shroud, a large variation in the β angle up to 50° is noted. This corresponds to a viscous separated flow zone where the axial velocity vanishes due to blade section losses at stall. The flow rotation is due to the cascade deviation angle of the blades which increases as rotor solidity and blade camber. If it is not straightened, it corresponds to an energy loss. Considering these measurements, the idea came out to implement stator blades in order to convert the flow rotational energy into a pressure creating the additional axial thrust.

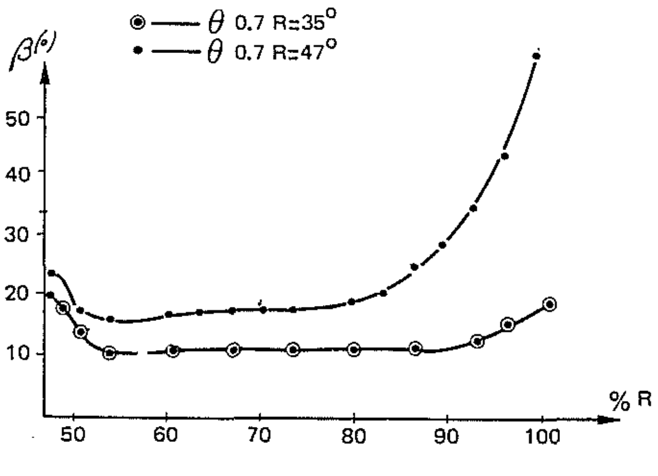

Fig.-9- Flow rotational angle downstream the rotor blades

5.0 FENESTRON CALCULATION METHODS

Two calculation methods are generally used by Aerospatiale.

The first one is directly derived from the local momentum and blade element theory, where the rotor disc is modelled with elementary independent rings. The airfoil characteristics and the local pitch angle are tabulated. It computes the axial and tangential velocities from axial thrust momentum equation and torque momentum equation. The shroud is globally considered in setting a given flow contraction σD from the rotor disc to infinity. This σD is derived from tests and is close to 1, in agreement with general momentum theory presented in Annex. This method is generally in use for performance estimation and sizing purpose.

A more advanced theory has been developed by METRAFLU (ref.[11]) on the basis of a compressor calculation code. This method accounts for the shroud shape interaction on the rotor. It is a quasi-tridimensional method in so far as the actual 3D flow is replaced by two bidirectional superimposed flows (FIG. 10):

- In the circumferencial plane (cascade airfoil calculation); this calculation is made with reference to tables, the NACA correlations issued from a great number of experimental tests on cascades.
- In the meridian plane; in this case, the calculation method uses a matrix resolution method, with an equation discreteness through finite differences. The flow is assumed not to be viscous, to be rotational, compressible and axisymmetric. The basic equations are the classical fluid mechanics equations (momentum, continuity, energy and perfect gas state equations).

  Modifying these equations with additional relation results in:

$$\frac{\partial^2\Psi}{\partial x^2} + \frac{\partial^2\Psi}{\partial y^2} = Q(x,y)$$

Solving the above equation for every axial station allows calculating the flow within a meridian plane and requires data issued from circumferential plane calculation for a given radius. The tridimensional flow is restored by combining both bidimensional calculations in an iterative way.

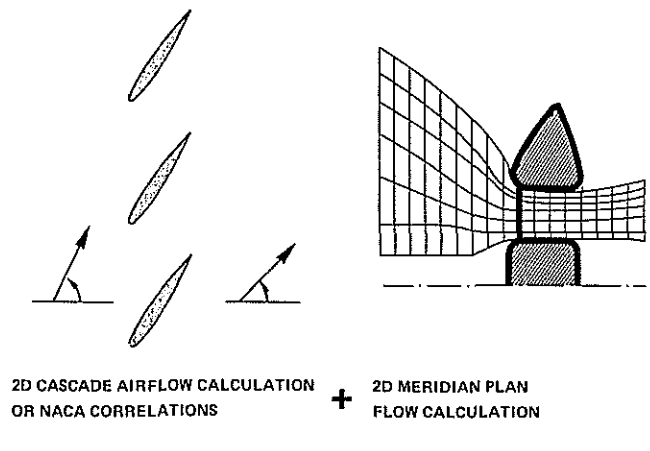

Fig.-10- Fenestron calculation method (METRAFLU)

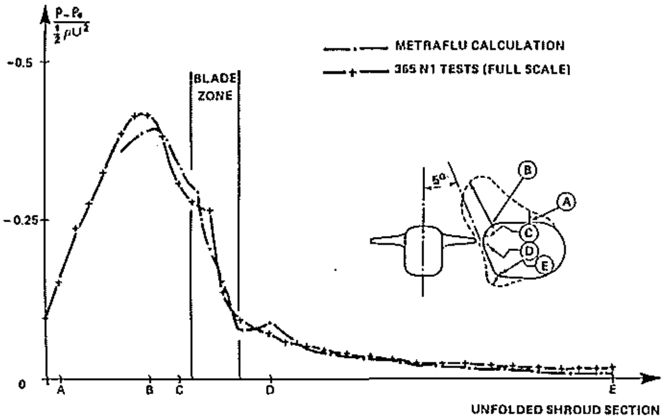

Fig.-11- Static pressure computation on the shroud

These theories have been correlated with test results which have been obtained at the bench at scale 1.

FIG.11 shows correlation obtained with the METRAFLU method on static pressure measurements on the shroud in a meridian plane, at moderate pitch angle setting. Upstream of the depressure peak, the flow modelling is not exactly in accordance with the shroud shape, due to the calculation method assumptions and, the computed results have not been reported. This does not influence the downstream results where the prediction is quite correct, even in the diffuser. In particular, the maximum depressure peak and the pressure recovery gradient are correctly predicted. Some local discrepancies are noted at the blade zone. They are due to blade tip vortices which are not taken into account in the potential calculation.

FIG.12 show the predicted and measured axial and tangential velocities with the two methods. The viscous effects due to blade tip vortices result in a boundary layer development close to the hub and the shroud which are not computed. It results in a flow blockage which increases the axial velocity in the non-viscous zone. This explains why the axial velocities computed values are underestimated. In the case of the local momentum blade element theory, the axial velocities are a little more underestimated. This is partly due to the fact that computed 2D airfoil characteristics have been used instead of tests values which were not available at the moment. The tangential velocity correlation is generally good for both methods.

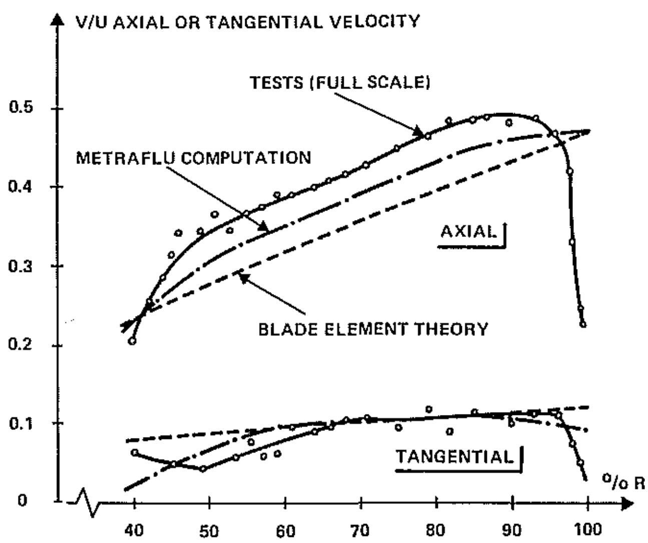

Fig.-12- Flow computation downstream the rotor blades

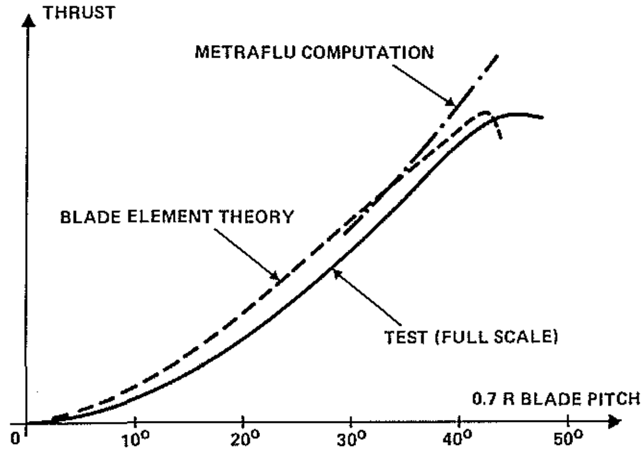

Fig.-13- Predicted and measured fenestron thrust versus pitch characteristic

The predicted and measured thrust versus pitch angle characteristics are compared on FIG.13. Note that the local momentum blade element theory seems to correctly predict the thrust stalling level, although 2D airfoil characteristics are computed values with estimated stall. The METRAFLU method is a potential method and cannot give accurate information after stalling. The stalling can be estimated from the calculated spanwise load factors on the blade.

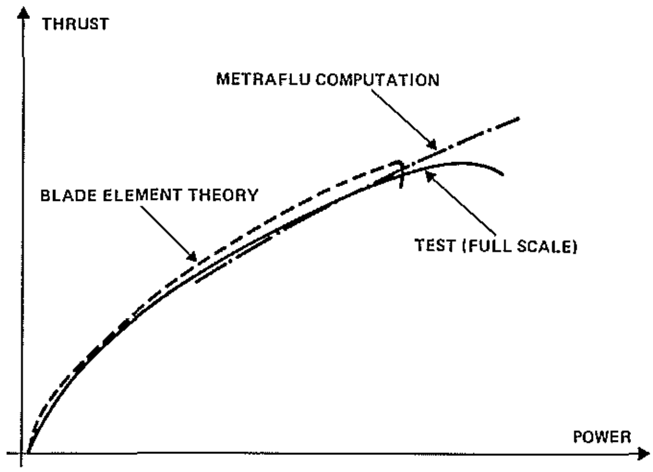

Fig.-14- Predicted and measured fenestron power versus thrust characteristic

The predicted and measured thrust versus power characteristics are compared on FIG.14. The METRAFLU computation gives quite good results before stall. The local momentum theory gives acceptable results, considering the use of 2D airfoil computed characteristics.

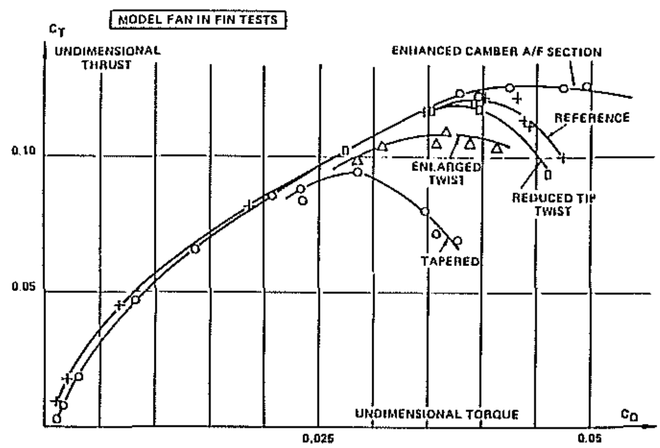

Fig.-15- Thrust / torque relationship for different blade fan geometries

6.0 PERFORMANCE

To improve hover performance, the following parameters have been studied:

- Blade planform, twist, and airfoil sections camber as shown in FIG.15 from earlier tests on wind tunnel model.

- Effect of new airfoil sections, specifically developed in co-operation with ONERA and Aerospatiale, so as to increase maximum lift capability at different blade spanwise sections as represented in FIG.16. This new fenestron airfoil family with spanwise variable relative thickness has essentially been designed with a wiew to increasing the load at the blade tip, so as to get the maximum depressure level on the shroud and delay on as far as possible the blade tip stall.
  camber blade sections has been tested which gave even more thrust at stall. But as the required power at zero thrust, which is important in forward flight, was much higher, due to higher section drag at zero lift, the test results have not been reported.

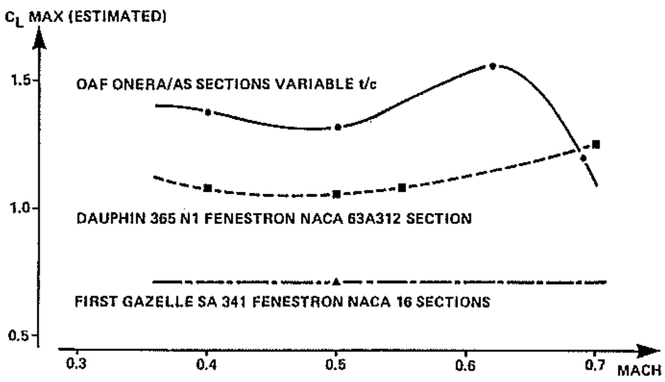

Fig.-16- Fenestron airfoil clmax improvement

- Effect of diffuser angle and static vanes, set downstream of the fan, to improve the flow expansion (higher σD) and to straighten the airflow in order to recover the flow rotational energy as presented in FIG.17. The diffuser angle α is actually limited to a practical angle value of about 10°, as with higher diffusion angles, flow instabilities may occur as interacted with the main rotor. This effect had been evidenced on early versions with the bottom aft fenestron direction of rotation which had been forsaken because of poor performance in rear wind in ground effect.

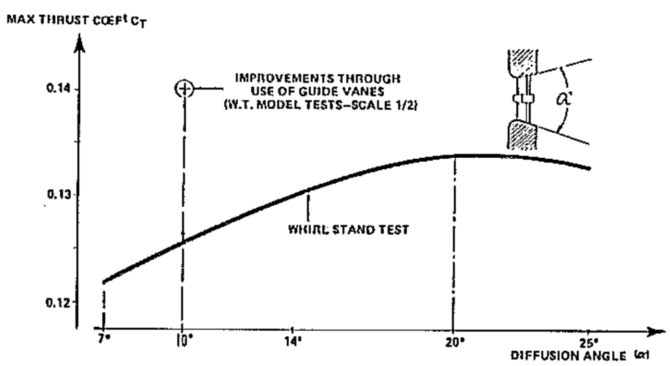

Fig.-17- Influence of diffuser angle and stator blades on fenestron performance

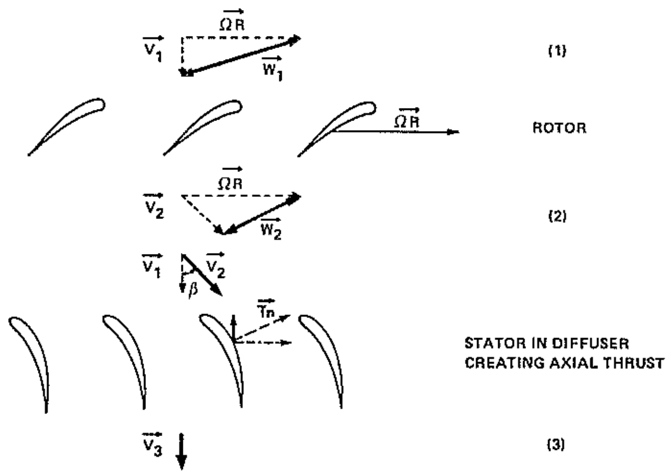

Fig.-18- Influence of stator blades on axial thrust

- The effect of stator blades is illustrated in FIG.18. In the rotating plane, the flow is deviated by the rotor blade. The deviation angle increases with blade solidity and camber. It results, just downstream of the rotor blades, in an absolute velocity V_2 angle β relative to the axial direction. The stator blades deviate the flow from V_2 to V_3, directly creating an axial thrust and some pressure recovery as the velocity slightly decreases.
  FIG. 19 shows (full scale measurements) that the flow has been almost completely straightened with these stator blades.

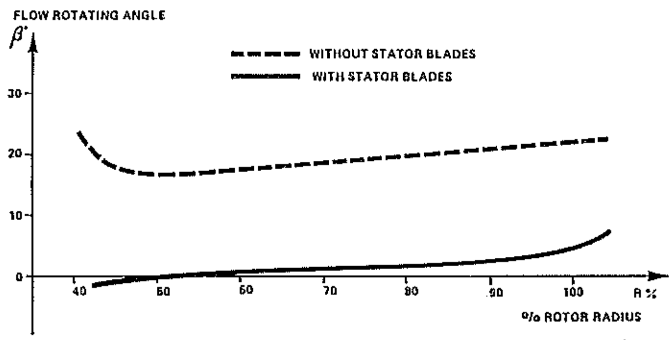

Fig.-19- Influence of stator blades on flow rotating angle at the diffuser exit

The improvements obtained on separate modifications briefly reviewed above, have been integrated on a scale one fenestron research test bench presented in FIG.20, for the Dauphin N1 helicopter. This test

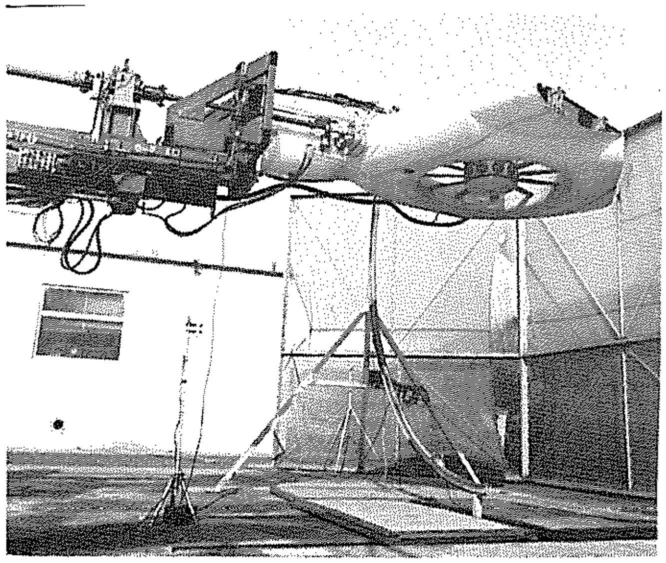

Fig.-20- Tail rotor research whirl test stand facility allows for accurate measurements of tail rotor performance, as well as pressure survey and noise radiation measurements. Several types of blades, duct geometries, and guide vane setting angles have been recently evaluated.

FIG.21 presents figure of merit data as a function of the mean blade loading coefficient Czm, obtained by direct on line data processing at the test bench site which allows to obtain precise data in the complete thrust domain of the fan-in-fin. Each characteristic is presented with list square curve fitting on about 150 test values.

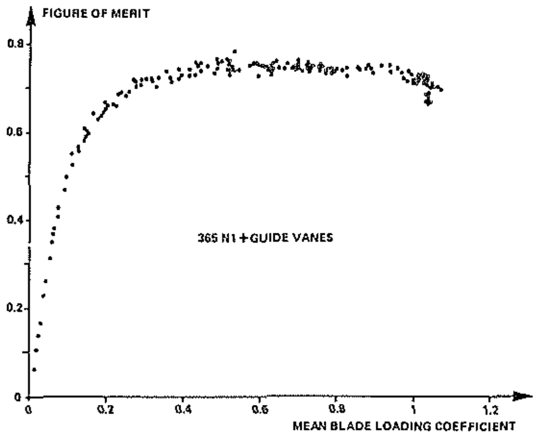

Fig.-21- On line data processing of whirl test stand data

As presented in FIG.22, maximum figure of merit can be increased by 7% and maximum thrust by 37% as compared to the present production 365 N1 Dauphin fan-in-fin due to guide vanes (or stator blades) and new airfoil section shapes for the fan blade. Furthermore, the figure of merit stays quite constant for large mean lift coefficient (or thrust) of the fan-in-fin. Substantial efficiency improvements are shown in FIG.23 compared to current conventional tail rotor with two- or four-bladed design using new airfoil sections technology.

	CONFIGURATION	$(FM)_{max}$	$(C_{Zm})_{max}$
①	365 N1 (REFERENCE)	0.71	0.825
②	WITH GUIDE VANES	+4.2%	+26%
③	WITH OAF AIRFOIL SECTIONS + G. VANES	+7.0%	+37%

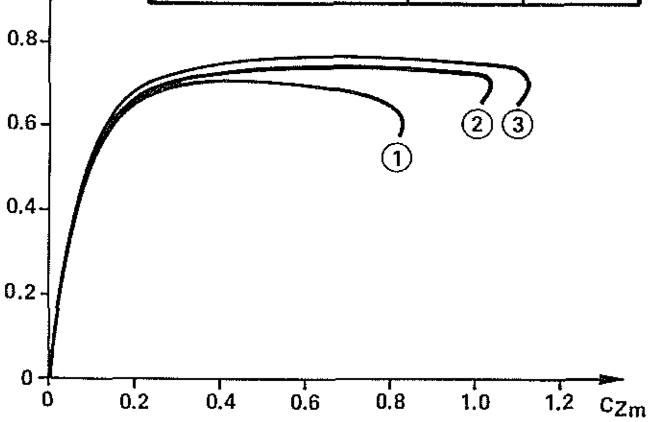

Fig.-22- Fenestron performance improvements (full scale ground tests)

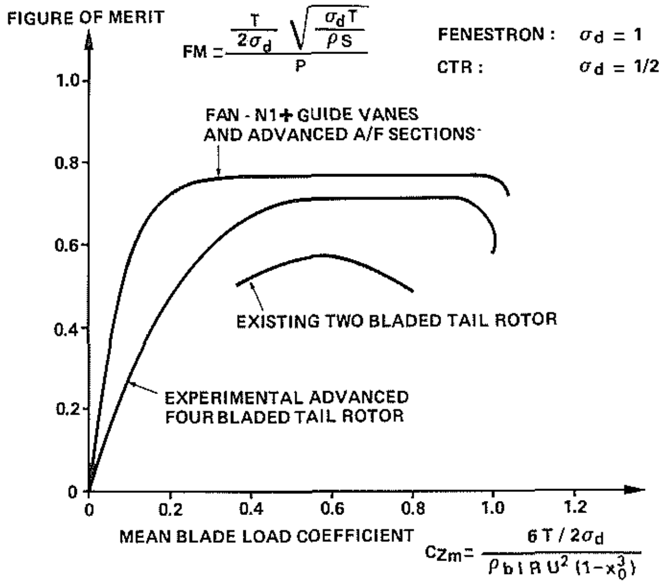

Fig.-23- Isolated tail rotor efficiency

It is to be noted that comparisons between conventional and fan-in-fin tail rotor performance should take into account not only the isolated tail rotor efficiencies - as shown in FIG.23 - but also the fin blockage effect normally present on conventional tail rotor. This effect is illustrated in FIG.24, which presents for a given tail rotor power the equivalent fenestron/classical rotor diameter ratio as a function of figure of merit ratio and fin blockage in percent of thrust. In particular, for an improved figure of merit of 30% (FM ratio of 130%) and 5% fin blockage effect, an equivalent fan-in-fin would have half the diameter of a conventional tail rotor

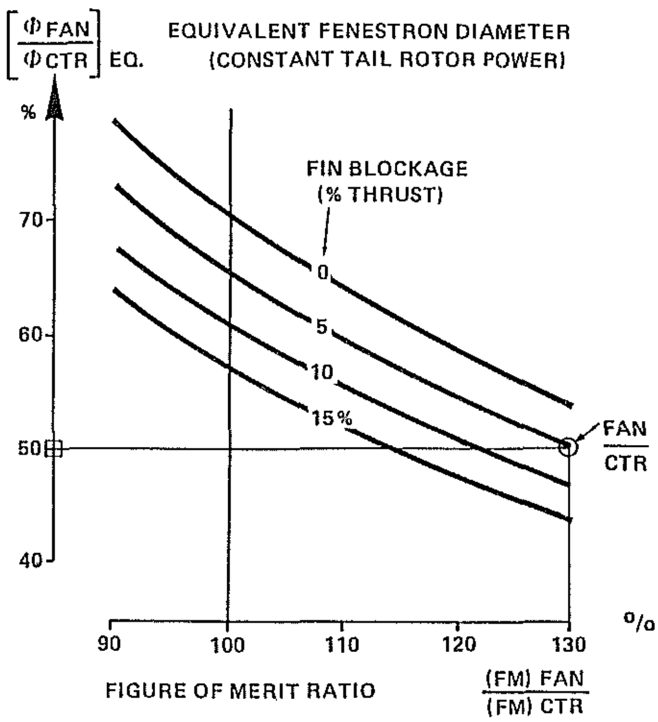

Fig.-24- Determination of fenestron / conventional tail rotor equivalent diameter at constant power

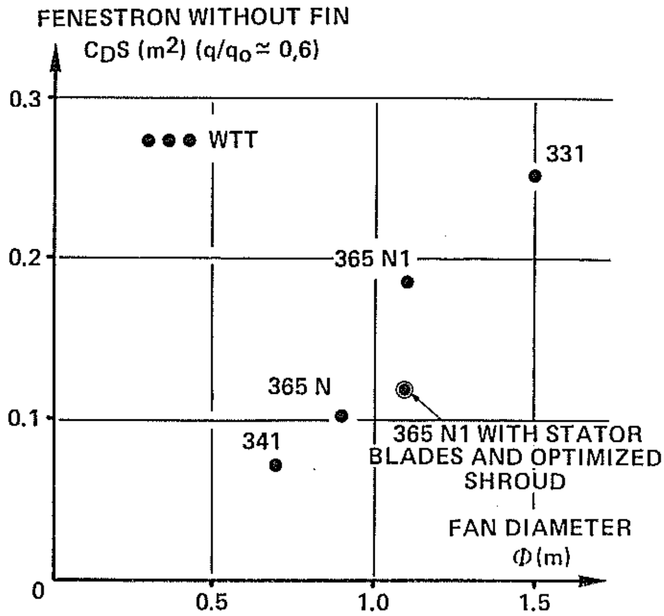

Fig.-25- Fenestron drag

The implementation of the stator blades in the diffuser has also improved the pressure recovery and tests have been completed with a reduced diffuser length, resulting in a narrower shroud. The tests have demonstrated that up to a certain limit, it does not affect the performance. This finally results in lower drag of the fenestron. The drag saving is estimated to be as high as 40% on the Dauphin 365N1 fenestron. FIG.25 compares these drag values with the drag of various Aerospatiale helicopter fenestrons, without fin, and assuming that the dynamic pressure is reduced to 60% of the freestream dynamic pressure due to fuselage and main rotor hub wake.

7.0 CONCLUSION

The fan-in-fin or fenestron concept has been originally developed for the only sake of improved safety and at an accepted penalty of weight, required hover power and cost.

The operational experience shows that the improved safety was indeed demonstrated, as no major accident occurred due to fenestron problems on nearly thirteen hundred fenestron-equipped helicopters, which have been flown for more than two million hours.

In addition to the research and development work conducted for eighteen years, recent research work at scale-one bench in hover have enabled new performance gains with optimized airfoils and stator blades in the diffuser, as well as the possibility of reducing the shroud width, without hover performance penalty, which results in drag saving in forward flight. Two calculation methods have been correlated on this tests giving quite good performance and flow predictions in hover.

This has brought the fan-in-fin concept to a level which makes it attractive, as compared to the classical tail rotor, on nearly all points of comparison for light- and medium-weight helicopters:

As regards performance: fan-in-fin with equivalent effectiveness can be designed with a diameter almost half the classical tail rotor diameter, due to aerodynamic improvements on airfoil shapes, duct geometries and stator blades.

As regards handling qualities: appropriate choice of fin geometry and size, and duct geometry provides better handling qualities.

As regards overall weight and cost: the fan-in-fin concept developed with advanced composite technology is equivalent to the latest conventional tail rotor for light helicopters and shows substantial reduction in weight and cost when compared to tail rotor mounted on top of a tail pylon.

Considering the complementary advantages of improved safety and reliability, reduced detectability and vulnerability, the "fenestron" fan-in-fin concept can presently be considered as the best anti-torque system for the single main rotor light and medium size helicopters.

8.0 REFERENCES

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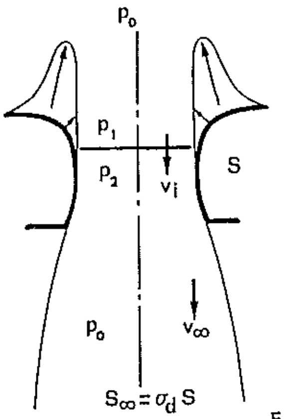
ANNEX 1

MOMENTUM THEORY



BERNOULLI EQ :
$$\begin{cases} p_1 + \frac{1}{2}\rho v_i^2 = p_o \\ p_2 + \frac{1}{2}\rho v_i^2 = p_o + \frac{1}{2}\rho v_\infty^2 \end{cases} \qquad (1)$$

MASS CONSERVATION :
$$\rho S v_i = \rho(\sigma S) v_\infty \qquad (2)$$

MOMENTUM EQ :
$$T = T_{ROTOR} + T_{SHROUD} = (\rho S v_i) v_\infty \qquad (3)$$

ENERGY EQ :
$$P_i = (\rho S v_i) \frac{1}{2} v_\infty^2 \qquad (4)$$

FROM :

(1)
$$T_{ROTOR} = (p_2 - p_1) S = \frac{1}{2}\rho v_\infty^2 S \qquad (5)$$

(3,5)
$$\frac{T_{ROTOR}}{T} = \frac{v_\infty}{2 v_i} = \frac{1}{2\sigma} \qquad (6)$$

(2,3)
$$v_i = \sqrt{\frac{\sigma T}{\rho S}} \qquad (7)$$

(4,5,6)
$$P_i = T_{ROTOR} v_i = \frac{T}{2\sigma}\sqrt{\frac{\sigma T}{\rho S}} = T\sqrt{\frac{T}{4\sigma\rho S}} \qquad (8)$$