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THE SHROUDED TAIL ROTOR "FENESTRON"

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- INTRODUCTION.

I.1 - Necessity of a tail rotor.

The most common helicopter formula consists of a single rotor driven by a mechanical transmission system. This type of rotor drive generates, of course, a reactive torque tending to rotate the aircraft in the reverse direction.

This induced torque is usually counteracted by a tail rotor rotating in the vertical plane. In general, this tail rotor is fitted with flapping hinges and also includes a feathering hinge allowing directional control. However, this tail rotor can be detrimental at all points of view because of the mechanical complexity due to the permanent power transfer essential for its operation, the danger and the fragility of blades rotating at a small distance from the ground and obstacles, and the very disturbed aerodynamic environment.

I.2 - Advantage of a shrouded rotor.

The idea of using a shrouded rotor for this anti-torque function has been first applied successfully by AEROSPATIALE on the SA.341 "GAZELLE" helicopter which flew for the first time with the "Fenestron" in 1968.

The shrouded rotor, integrated in the fin and called "Fenestron" is more attractive than a "free" rotor, having the same diameter, for the following reasons :

- The annular shroud reduces blade tip losses.
- The difference of pressure resulting on each side of the fin contributes to the thrust for more than 30 %.
- The interference problem between the fin and the "free" rotor disappears.
- Finally, the integration of the rotor in the fin gives a more attractive line to the helicopter.

However, to match harmoniously the general structure, the shrouded rotor must have a much smaller diameter than the "free" rotor it replaces. The final compromise retained consists in obtaining a total power efficiency in forward flight equal or slightly better than the solution with the conventional rotor, but some 4 % less in a hover.

- DESCRIPTION.

Two "AEROSPATIALE" helicopters, now in production, are fitted with the "Fenestron :

- AS 341/342 "GAZELLE" (fig.1) - single engine, 1900 kg end 5 seats.
- AS 360 "DAUPHIN" (fig.2) - single engine, 3000 kg and 10/13 seats.

Figure 3 shows the main characteristics of these achievements.

The "Fenestron" shrouded rotor consists of a small diameter multi-blade rotor operating inside a shroud integral with the rear structure (fig.4). This shroud includes a rounded imput lip and a slightly divergent section intended to improve the efficiency of the assembly.

The "Fenestron" is surmounted by a cambered profile fin, judiciously set in incidence and ensuring most of the anti-torque function in forward flight. The lower section of the tail boom supports either an expendable tail bumper, as on "GAZELLE", or a tail wheel in the case of "DAUPHIN".

Figure 5 shows a schematic section of the tail rotor transmission system.

The blades, made of light alloy, and from precision die forging, are hinged in incidence on self-lubricating bearings.

The blade horn consists of a die forged protrusion, in the shape of a crankpin, on the cylindrical blade root.

A torsion tie-bar, made of a stack of stainless metal star-shaped strips, absorbs the centrifugal forces.

The hub casing is directly secured to the tail gearbox output flange.

The helicopter is controlled in yaw through a servo-unit, fitted on the tail gearbox and actuating the pitch change spider axially.

This transmission system is attached to the structure through a tripod shaped fitting.

III - OPERATIONAL POSSIBILITIES.

III.1 - Safety in operation.

III.1.1 - Safety in flight.

a) Vulnerability.

Considering the reduced size of the rotor disc and its solidity ratio, the "Fenestron" has less chances to be damaged by light weapon fire than a conventional rotor.

But the most important point is that damage to one of the blades would have less serious consequences as regard flight continuation.

Recent tests involving tree branch impacts have shown that no damage would occur with wood sticks less than 15 mm in diameter.

Moreover, it is only with 35 mm diameter sticks of wood that the unbalance becomes important without, however, resulting in an explosive failure of the rotor (fig. 6).

b) Failure of tail rotor.

As most of the anti-torque thrust is ensured, in forward flight, by the fin, any failure of the rear transmission system which would affect the operation of the shrouded rotor, does not prevent the helicopter from flying to a more suitable area, or establish good conditions of speed and altitude before landing in autorotation.

c) All-weather flights.

As shown by tests carried out in icing conditions on Gazelle, the relative protection of the tail rotor by the shroud eliminates the need for a rear blade de-icing system which is heavy and expensive. In addition, the risks of impact on the blades caused by the ice blocks separated from the main rotor or air intakes are practically eliminated, especially in forward flight where the air flow through the shroud is nearly nil.

III.1.2 - Safety near the ground.

a) Low level flight.

The risks of the tail rotor blades contacting tree branches, bushes and stones during manoeuvres in glades is particularly reduced, as the "Fenestron" shroud protects the rotor much more efficiently that the tail rotor guard. Then, one can appreciate the advantage offered, by this possibility of hiding under the foliages, to an armed helicopter engaged in an anti-tank mission.

b) Protection on landing.

In this case also, the protection provided to the rotor allows marked "tail down" landings and severe "quick stops".

It is to be noted that the "Fenestron" ensures a much better ground clearance : with a conventional rotor, the same clearance can be obtained at the cost of a very high complexity only : tail boom pylon, intermediate gear box, inclined drive shaft which are heavy and expensive assemblies (fig.7).

III.1.3 - Ground personnel security.

The conventional tail rotor is very often the cause of fatalities among the ground personnel moving around the helicopter during loading operations, or on starting and stopping the rotor.

This danger is entirely eliminated with the "Fenestron", the installation of which is justified on a military aircraft, operating in the intricate situation of a battle field, or in limited visibility conditions, as well as on a civil helicopter, easily accessible to curious people, during casualty evacuation or even on an aero-club field.

III.2 - Handling of the aircraft.

The elimination of the conventional, heavy, hindering and fragile tail rotor blades facilitates aircraft handling in hangars and tail boom folding for ship borne helicopters.

III.3 - Maintenance and Reliability.

III.3.1 - Service lives.

Stresses on mechanical parts and on blades are low due to the low thrust, hence the low power absorbed by the "Fenestron" rotor during forward flight, that is during most of the flying time, and to the protection offered by the shroud against all alternating phenomena acting on the blades (no dissymmetry of speed between the advancing and retreating blades, no random stresses due to main rotor generated vortices). It results that these elements have very high TBO and MTBF or infinite service lives.

III.3.2 - Technological simplifications.

There is a great deal of simplifications with respect to the conventional rotor :

- Elimination of flapping hinges, hence deletion of associated bearings and lubricators.
- Elimination of feathering hinge bearings, which are replaced by self lubrificating bearings.
- Elimination of Intermediate Gear Box.

- Reduction in the number of parts making-up the rotor head assembly.

III.3.3 - Reliability and Maintenance.

The good reliability of the "Fenestron" and the resulting reduced maintenance costs are due to the simplified design and the particularly favourable operating conditions.

Moreover, its low vulnerability reduces the number of unscheduled removals. The very easy replacement of all components, especially the fitting of blades without any adjustment, entails little work only, hence a gain of time.

In addition, the "Fenestron" assembly which is very accessible, facilitates periodic inspections and therefore the application of the "on condition" maintenance concept, thus avoiding any premature removal.

IV - NOISE AND COMFORT.

IV.1 - Noise.

IV.1.1 - Frequency spectrum.

Due to the high rotational speed and the large number of blades, the noise produced by the "Fenestron" is characterized only by two high frequency lines, corresponding to the rotational noise first and second harmonics (1300 cps and 2600 cps for the SA.341).

This spectrum is sensibly different from the that generated by a "free" rotor ; because of its low rotational speed, the latter produces a low frequency rotational noise (about 70 cps), a spectrum very rich in harmonics (7 lines very visible), as well as a wide band noise.

IV.1.2 - Attenuation with the distance.

Comparative values recorded on "Dauphin" and "Alouette III" helicopters are shown on figure 8. Although the noise level heard at a short distance is slightly higher with the "Fenestron", but noise attenuation increases as distance grows ; at 100 metres, for instance, the "Fenestron" nuisance in less than with a conventional rotor.

IV.1.3 - Forward flight.

Although no accurate measure could be made, the "Fenestron" rotor, relieved from its anti-torque function and protected, by its shroud, from the effects of speed dissymmetry and compressibility phenomena, contributes very little to the aircraft general noise.

IV.1.4 - Further investigations on noise.

The analysis of the "Fenestron" noise directivity has evidenced the effect of the tripod arms supporting the tail gear box (fig.9).

This aerodynamic interaction can be reduced by optimizing the arm geometry, their setting and their distance from the disc plane.

To reduce the noise level, studies should be directed, for future designs, towards a decrease of blade tip speed to the cost of increasing the blade chord to keep an equal efficiency. The use of composite materials for the blades will allow the increase in chord without affecting the centrifugal forces.

It is to be noted how important it is, from the noise aspect, to obtain a "sound" flow in the rotor plane ; this is possible by eliminating all sources of disturbance at the shroud inlet and carefully fairing-in the shroud to tail boom connection.

There is no doubt that the "Fenestron", in a near future, will be only a source of secondary noise compared to that of main rotor or power plant.

IV.2 - Vibrations.

As already mentioned, the "Fenestron" is never the source of a high vibration level of the aircraft, since it works in aerodynamic conditions much better than a conventional tail rotor.

Due to the number of blades and to the rotational speed, we have high frequency and low amplitude excitations, practically imperceptible, more especially in forward flight, where the rotor thrust is nil.

IV.3 - Control loads.

The helicopter directional control is facilitated by a hydraulic single body servo-unit. Should the hydraulic system fails, loads remain low in forward flight due to the blade geometry and weight. The control loads are higher in hover only, immediately before landing.

- "FENESTRON" AERODYNAMICS - PERFORMANCE AND FLYING QUALITIES.

V.1 - Hover.

V.1.1 - Performance.

As already mentioned, the small diameter of the shrouded rotor, allowing a harmonious integration in the rear structure, causes a slight increase of the power absorbed by the helicopter in hover (about 4 %) with respect to conventional anti-torque system.

This penalty depends on the size of the "Fenestron" and of the conventional rotor to which it is compared. The trend to-day is to reduce the diameters of the conventional tail rotors ; the "Fenestron" penalty is then reduced.

V.1.2 - Manoeuvrability.

Figure 10 compares the change in total thrust with respect to pitch, for two types of "Fenestron" and a conventional rotor.

The thrust increases much more regularly in the case of the "Fenestron", and does not show any reduction of efficiency before the stall area.

The margins at the rudder pedals, remain sufficient in all cases of flight as shown in figures 11 and 12, for various reduced weights or directions of a 30 knot wind.

For a 10 % increment of pedal displacement the helicopter response is pure, perfectly symmetrical in hover ; the turning rate achieved is 40°/sec. on "Gazelle" and 60°/sec. on "Dauphin".

V.2 - Forward flight.

V.2.1 - Performance.

The fin ensures most of the anti-torque function in forward flight ; the tail rotor is then nearly completely unloaded (fig.13). The power so recovered is not integrally included in the total energy analysis, since the additional fin induced drag must be counteracted. There is a slight residual gain of 2 % which can be directly recovered range-wise.

V.2.2 - Manoeuvrability and flying qualities.

The study of rudder pedal displacement curves with respect to the speed and side slipping in forward flight (fig.14) shows that the usual margins are respected.

The static stability is practically obtained only by the fin.

The response to an increment of rudder pedal displacement becomes dissymmetrical in forward flight without affecting handling, as the solution offers good stability.

The maximum thrusts allowed by the "Fenestron" sensibly exceed the possibilities of a conventional rotor developing the same thrust in a hover. So the manoeuvering possibilities, with a "Fenestron", are much less limited in speed and side slipping.

V.3 - Studies on the "Fenestron" aerodynamic behaviour.

Studies are actively going on to improve the "Fenestron" aerodynamic behaviour, especially to reduce the power loss in a hover, delay blade stall, study the influence of ground effect and main rotor interaction, reduce drag in forward flight, etc...

Wind tunnel tests are carried out, first on the "Fenestron" alone, or on a powered helicopter model (fig.15) then on a full scale test bench (fig.16). Finally configurations showing some promises are checked in flight.

V.3.1 - Optimization of blades.

Further to tests, some modifications have shown interesting results. These modifications concern blade profile, twist and "blade to inner tunnel" link shape.

These modifications, which have been embodies on the "AS.342", up-rated version of "Gazelle", then on "Dauphin", have brought a 35 % gain in maximum thrust, an improvement of the negative thrust and a better thrust gradient at approximately zero pitch (fig.10).

V.3.2 - Selection of an appropriate rotation direction.

On the "Dauphin" a slight transient discontinuity in the yaw control has been noted in ground effect and a 15 knot tail wind blowing from the L.H. sector. This phenomenon has been visualized on the aircraft and then on the wind tunnel model, and the conclusion was that this discontinuity was due to the suction, by the fenestron, of the tip vortices shed by the main rotor (fig.17). By reversing the direction of rotation this discontinuity has been eliminated and the rotor efficiency improved.

This defect did not appear on "Gazelle" probably because, in a hover I.G.E, the "Fenestron" is relatively farther from the ground that on "Dauphin".

V.3.3 - Optimization of shroud and rear structure geometry.

Following wind tunnel and bench testing, it has been possible to optimize the shroud inlet radius and diffuser angle. They have shown the interest of a shroud outlet radius to improve reverse thrust.

Finally, it is necessary to take care of the structure design around the rotor to ensure a good stability and minimum drag through a better flow.

All these study results are applied to the new "Fenestron" designs, particularly on the "Fenestron" which is being tested on a "SA.330 PUMA", in view of a possible application on the SA.331 "SUPER PUMA".

I - WEIGHT AND COST ESTIMATES FOR THE "FENESTRON" SOLUTION.

VI.1 - Weight estimate.

Comparisons have been made for light helicopters like the SA.341 "GAZELLE" or AS.350 "ECUREUIL" as well as for heavier helicopters like the SA.330 "PUMA". In all cases the "Fenestron" represents a gain in weight even when compared with the most modern tail rotor solutions, such as the hingeless composite two bladed tail rotor of the "ECUREUIL", or a "cross beam" type, for the "PUMA".

The weight breakdown is of course different ; there is more structure but less mechanical components and rotor in the "Fenestron" solution.

The weight difference is about 5 to 10 kg for a light aircraft like "Gazelle" or "Ecureuil", and from 10 to 20 kg for a heavier helicopter of the "Puma" type.

VI.2 - Production cost.

VI.2.1 - For a medium or heavy weight aircraft, which would require, in the conventional solution :

- a tail rotor with at least four blades
- a sophisticated tail blade de-icing system
- a tail boom pylon with an intermediate gear box and inclined drive shaft to comply with the ground clearance requirements, a "Fenestron" would have a sensibly lower production and operating costs.

VI.2.2 - For a light helicopter, economy being the main objective, the problem was different : a hingeless composite two bladed tail rotor, more simple than the "Fenestron" of "Gazelle" type, was adopted at the begining of the AS.350 "Ecureuil" development programme because of its low production cost.

However, taking into account the advantages of the "Fenestron", a thorough study has been made on a possible development of an economical "Fenestron", using :

- "Value engineering" methods
- new materials and very economical manufacturing techniques for some of the repetitive components (blades for example).

The first results show that, at the same cost, it is possible to design and manufacture a "Fenestron" which will be lighter than the very simplified two bladed tail rotor, at present fitted on the AS.350 "Ecureuil" helicopter.

VII - CONCLUSION.

The "Fenestron", a shrouded tail rotor, incorporated in the fin, presents an important improvement in the field of ground and in-flight safety, and from the maintenance aspect. It increases the helicopter operational possibilities, while reducing the noise level.

At the cost of a slightly higher consumption in hover, the "Fenestron" allows a slight reduction of absorbed power in forward flight.

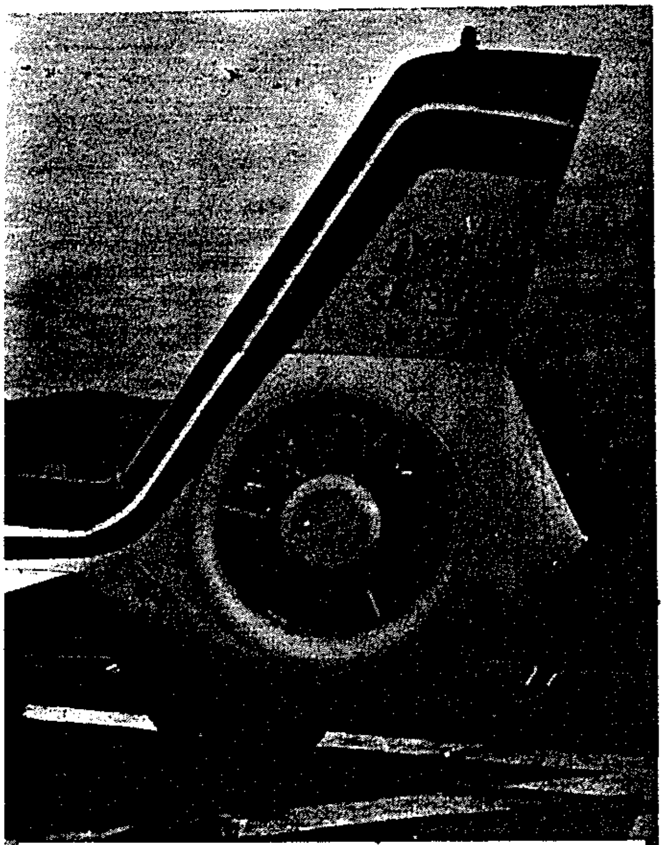
Thanks to its surrounding, the "Fenestron" is protected from high stresses and instability risks, and thus it is very suitable for high speed helicopters.

Finally, it seems that the "Fenestron" is in a favourable position from the weight and cost aspects, even when compared with the most modern and most simplified solutions of conventional tail rotors.

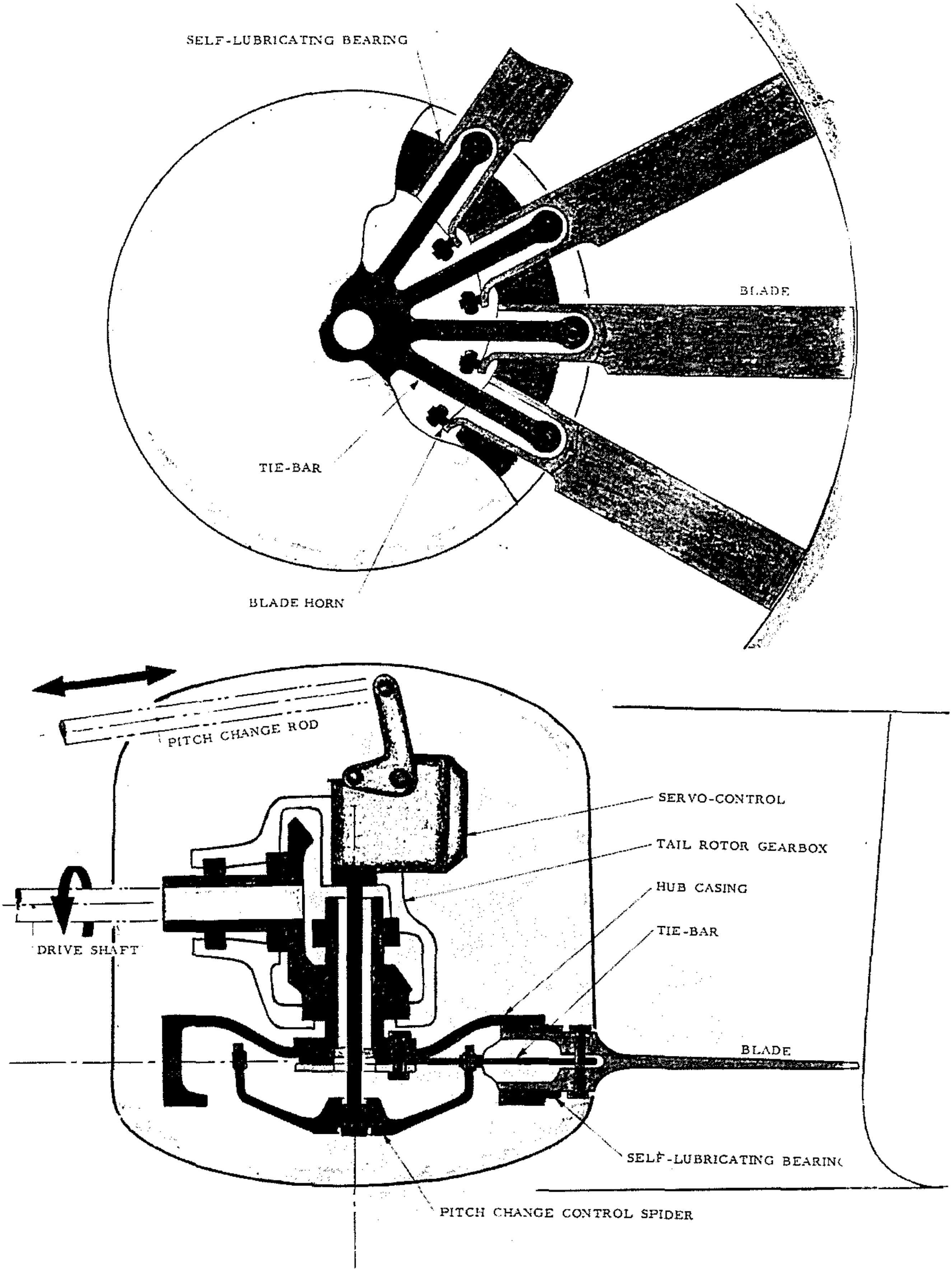
1. SA 341 "GAZELLE"


2. SA 360 "DAUPHIN"

3. LEADING PARTICULARS		
AIRCRAFT	AS 342 "GAZELLE"	SA 360 "DAUPHIN"
ROTOR DIAMETER	700 mm	900 mm
NUMBER OF BLADES	13	13
BLADE PROFILE	NACA SERIES 63 A	NACA SERIES 63 A
CHORD	39 mm	43,5 mm
ROTATIONAL SPEED	5 880 R.P.M.	4 693 R.P.M.
FIN PROFILE	NACA 4412	NACA 4415
FIN SETTING	2°	1,5°

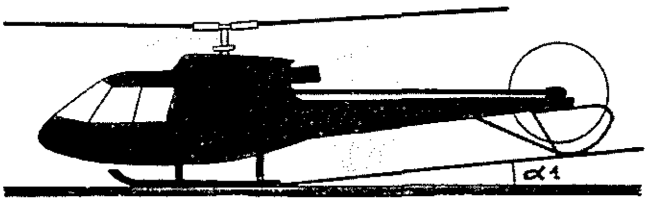


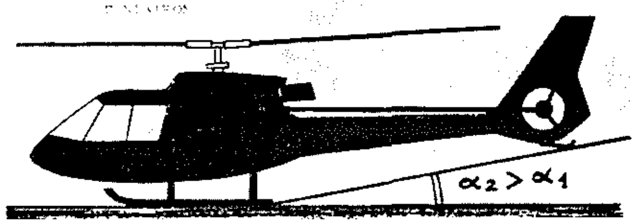
4. "FENESTRON" ON "DAUPHIN" HELICOPTER



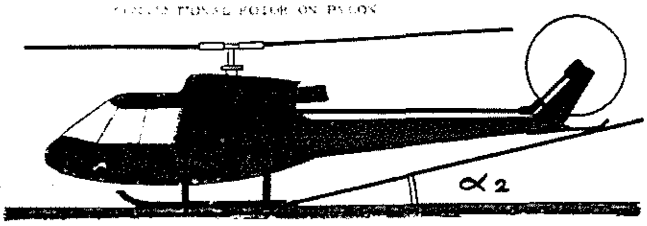
5. SCHEMATIC CROSS-SECTION - REAR TRANSMISSION ASSEMBLY

6. TREE-BRANCH IMPACT TESTS

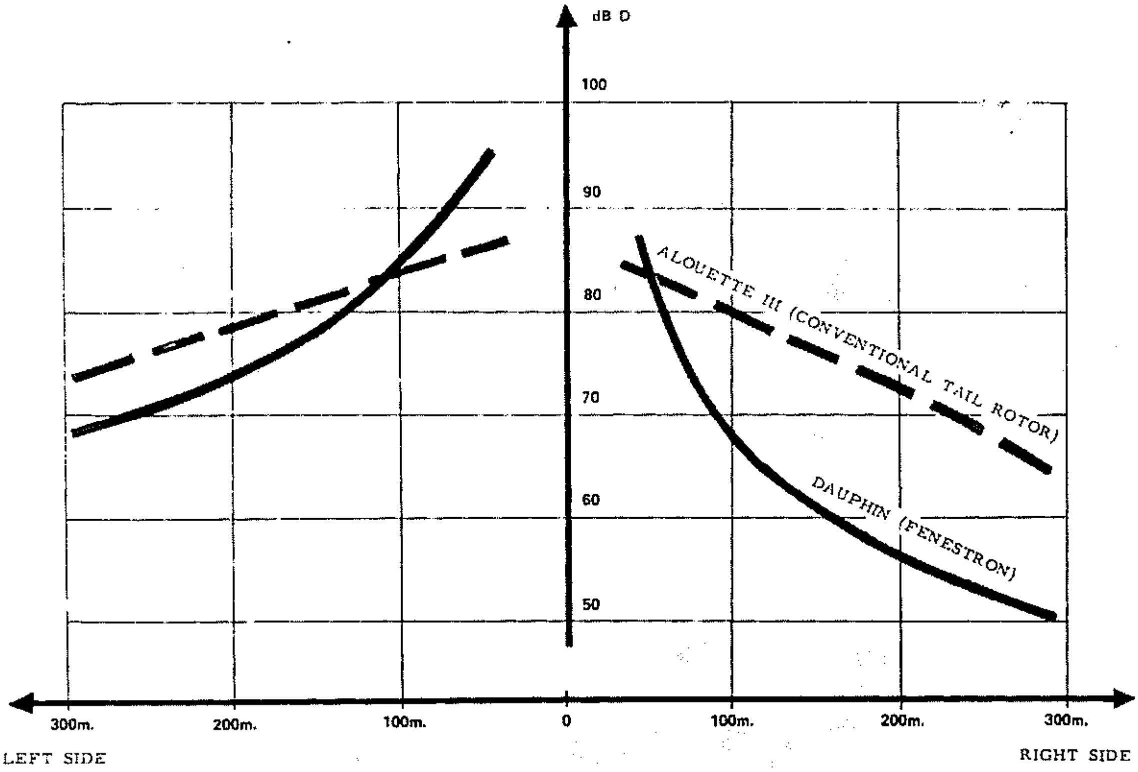




ROTOR ON PYLON

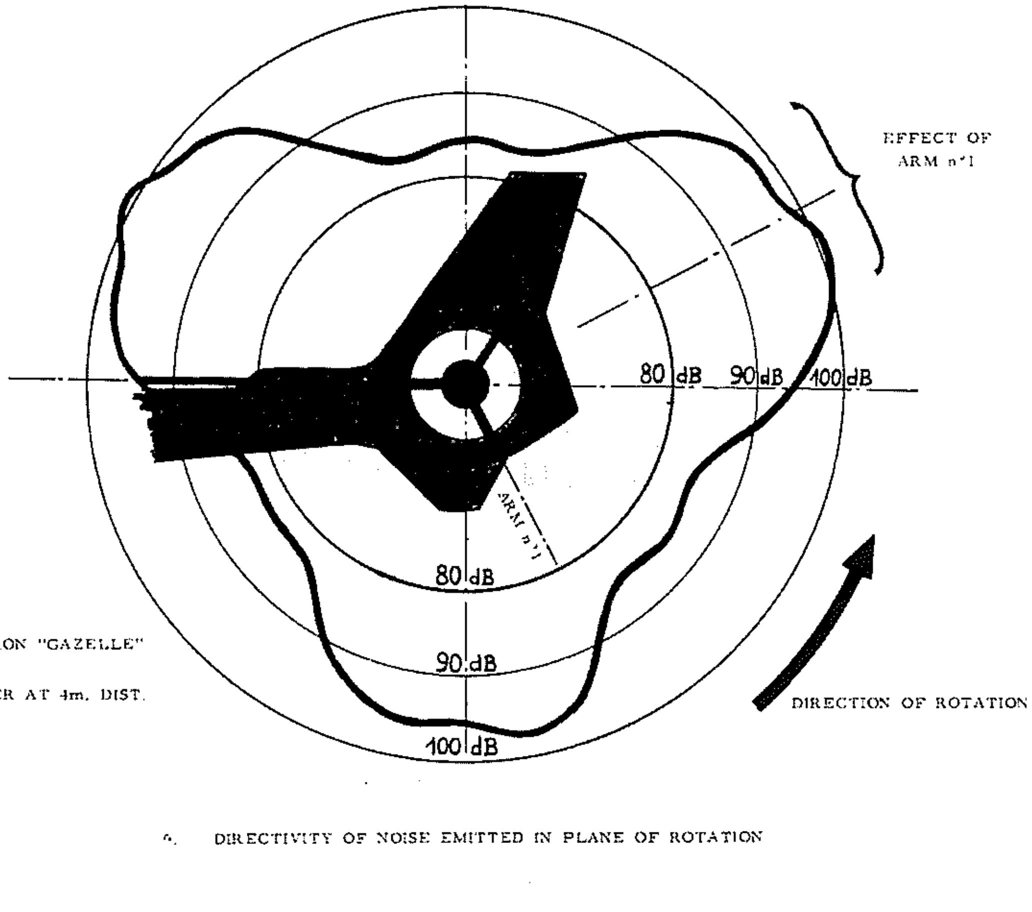


7. GROUND CLEARANCE

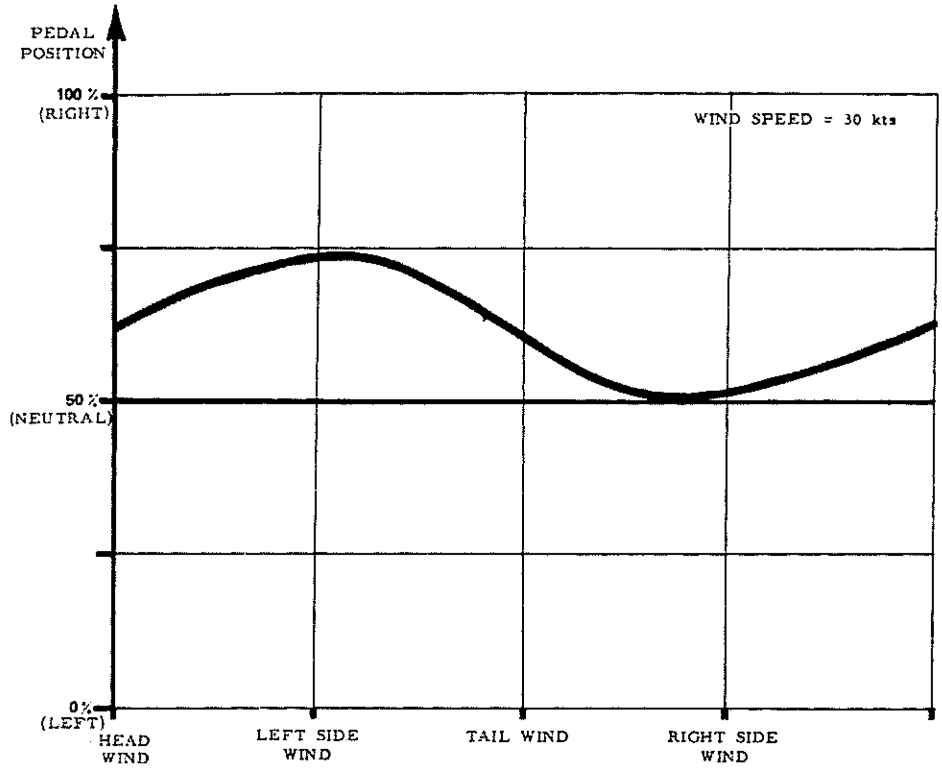


8. LATERAL DISTANCE FROM OBSERVER TO AIRCRAFT CENTRE LINE

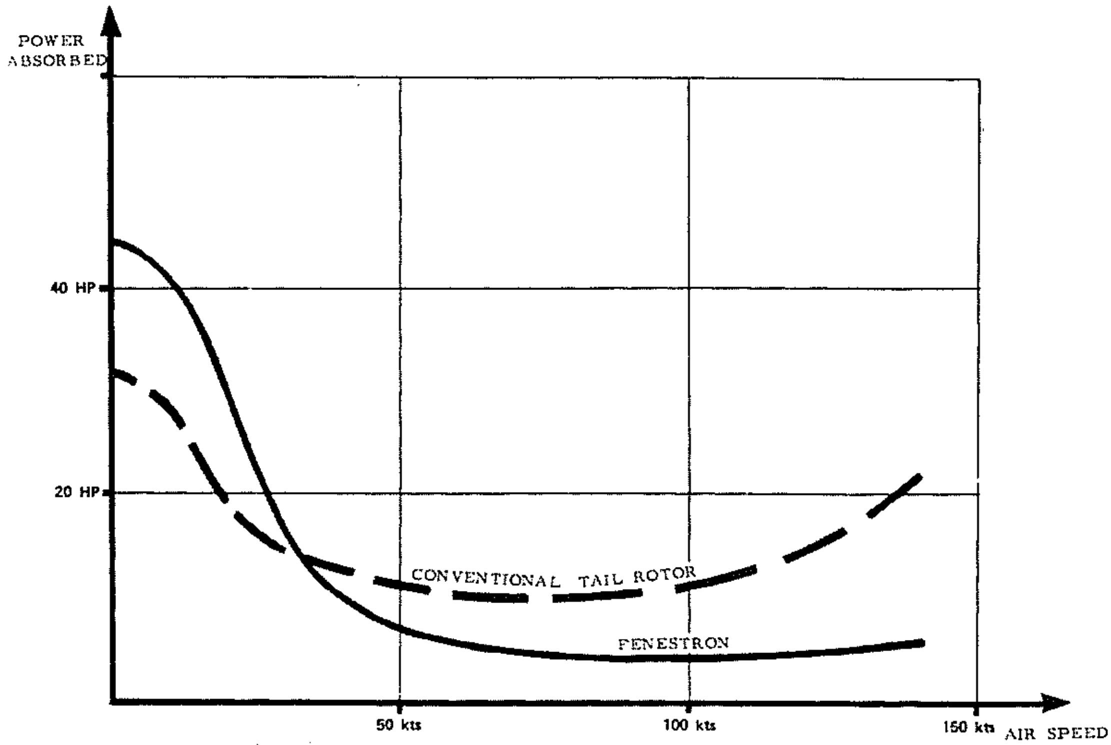
NOISE ATTENUATION VS. DISTANCE



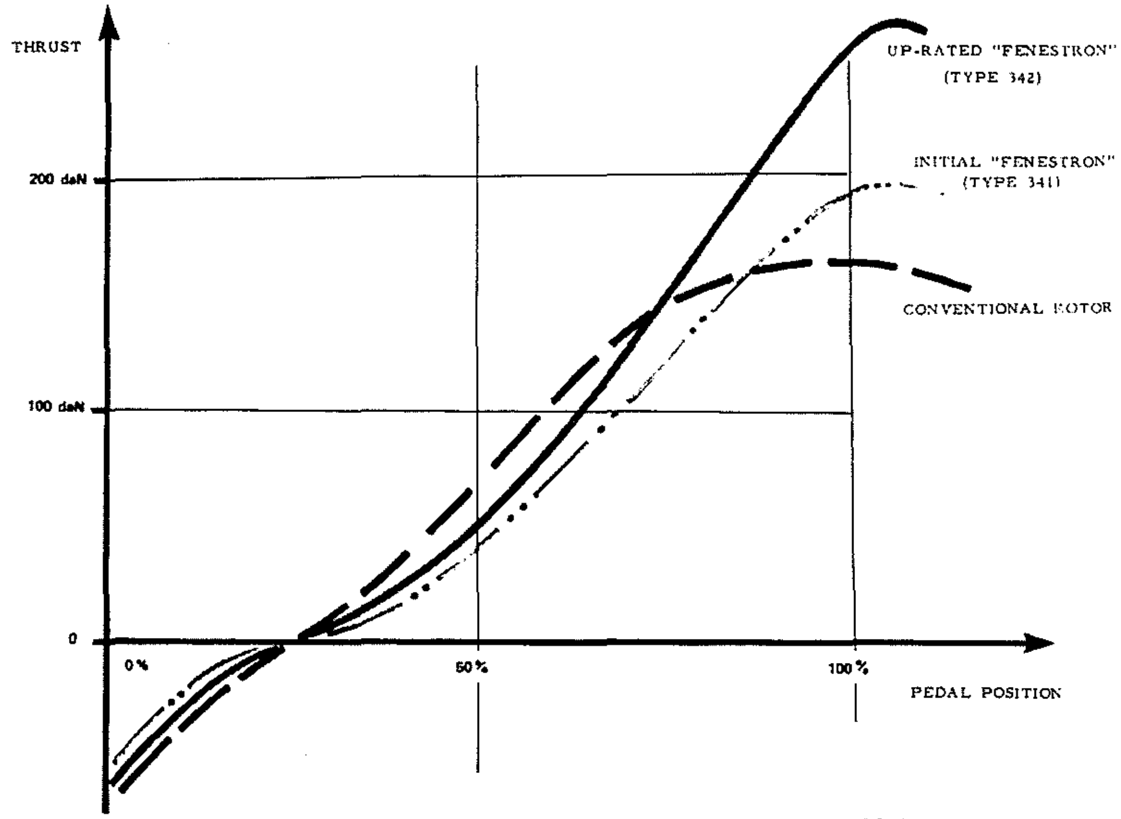
9. DIRECTIVITY OF NOISE EMITTED IN PLANE OF ROTATION



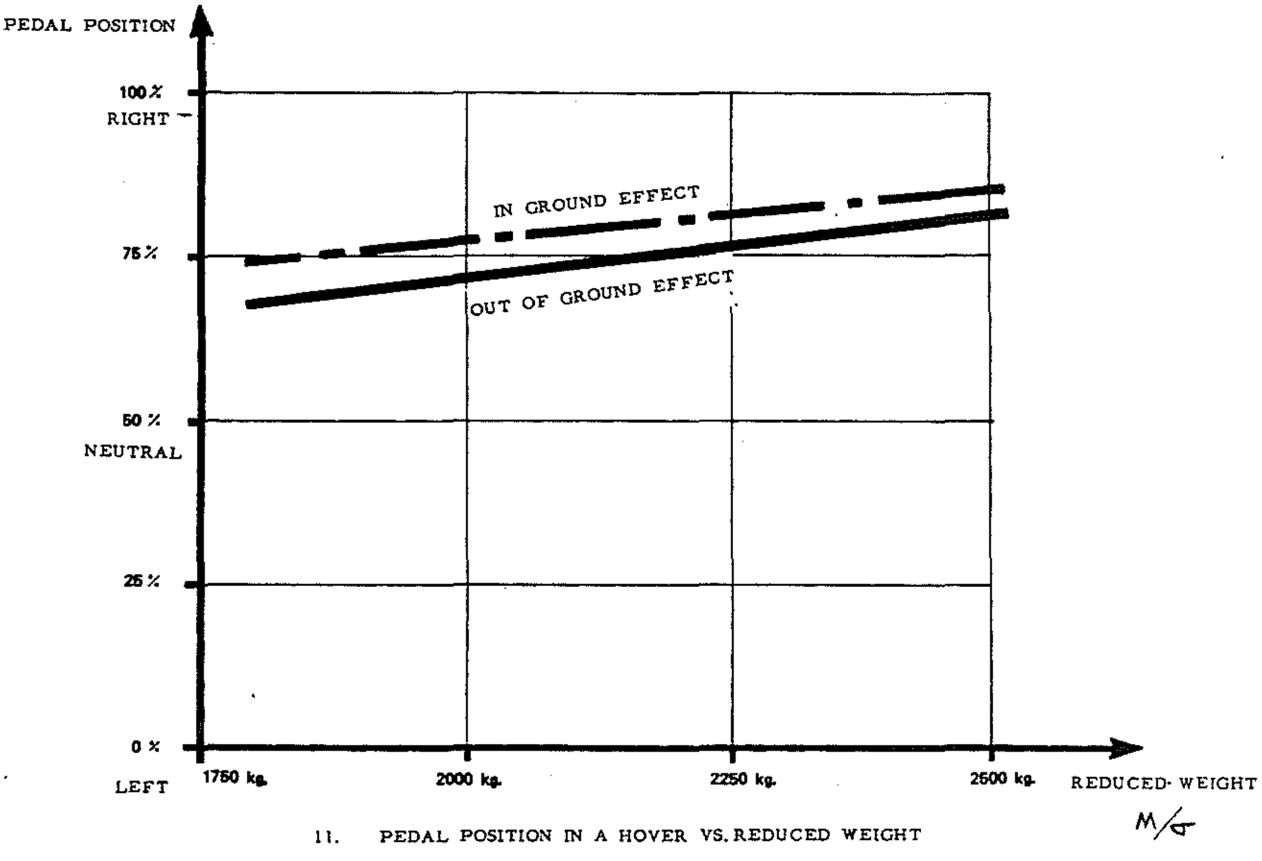
12. HOLDING OF HOVER IN VARIOUS WIND DIRECTIONS



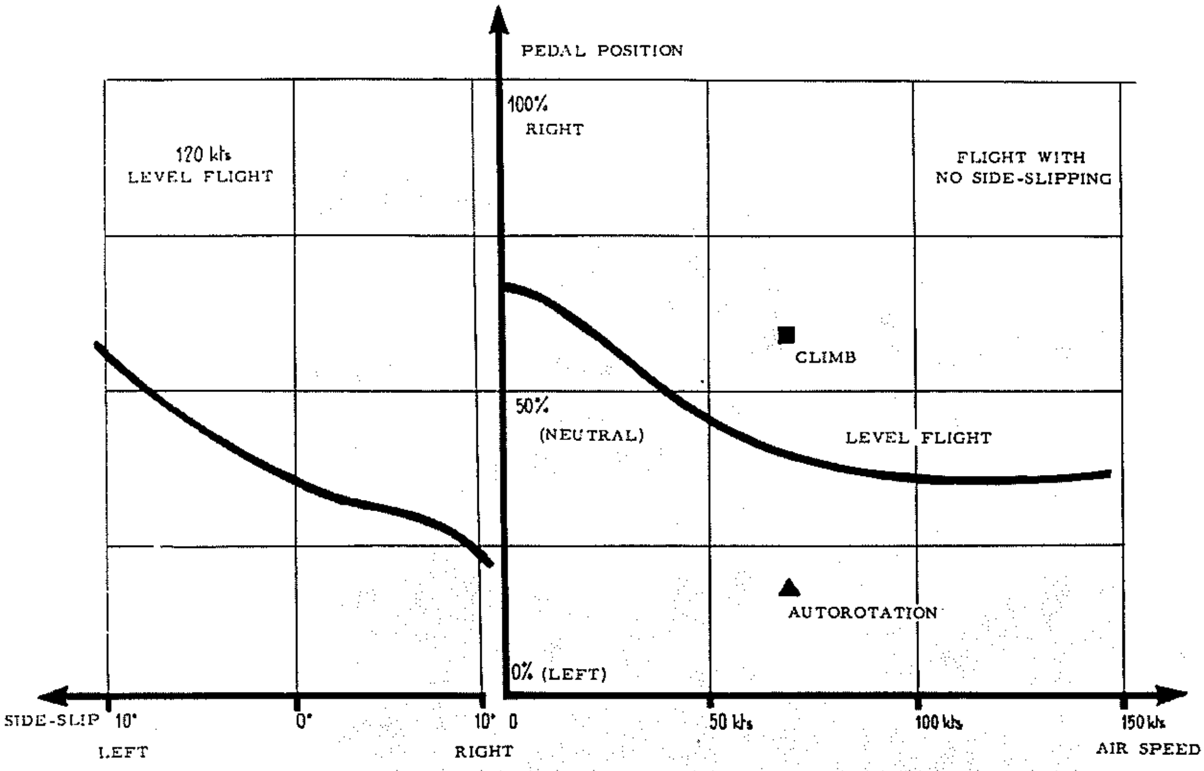
13. COMPARISON OF POWER ABSORBED IN LEVEL FLIGHT



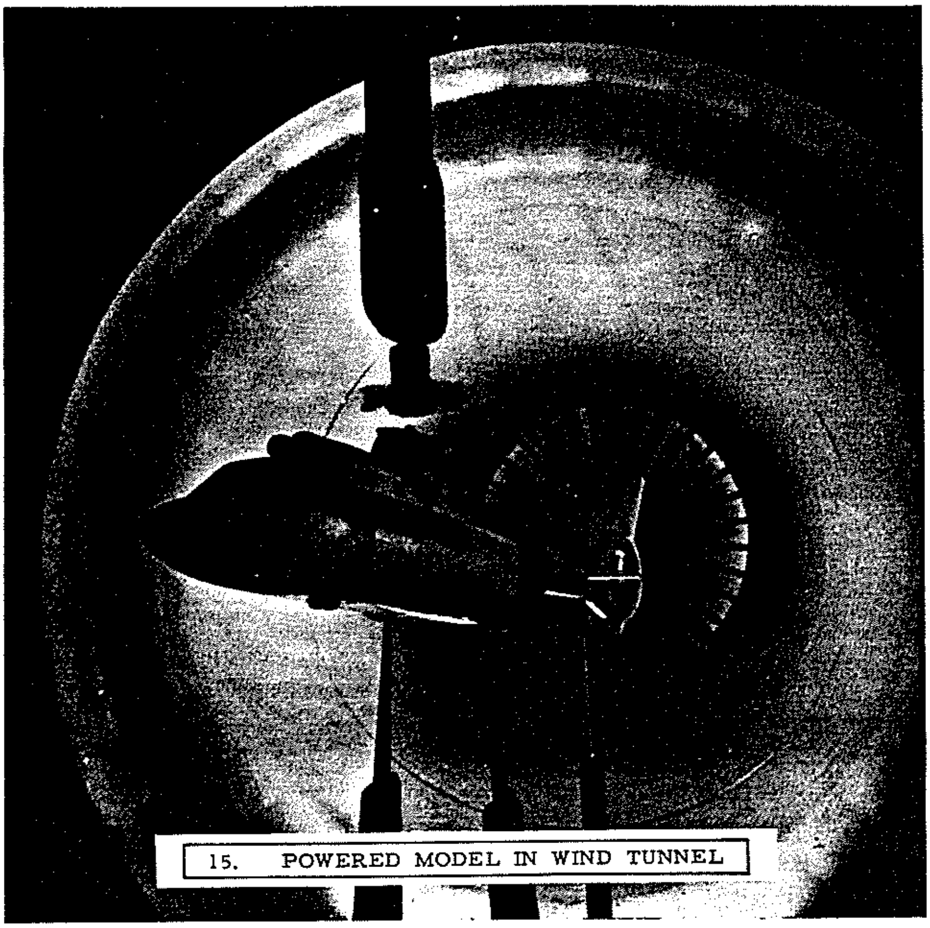
10. COMPARISON OF THRUST PROVIDED BY VARIOUS TYPES OF TAIL ROTOR



11. PEDAL POSITION IN A HOVER VS. REDUCED WEIGHT

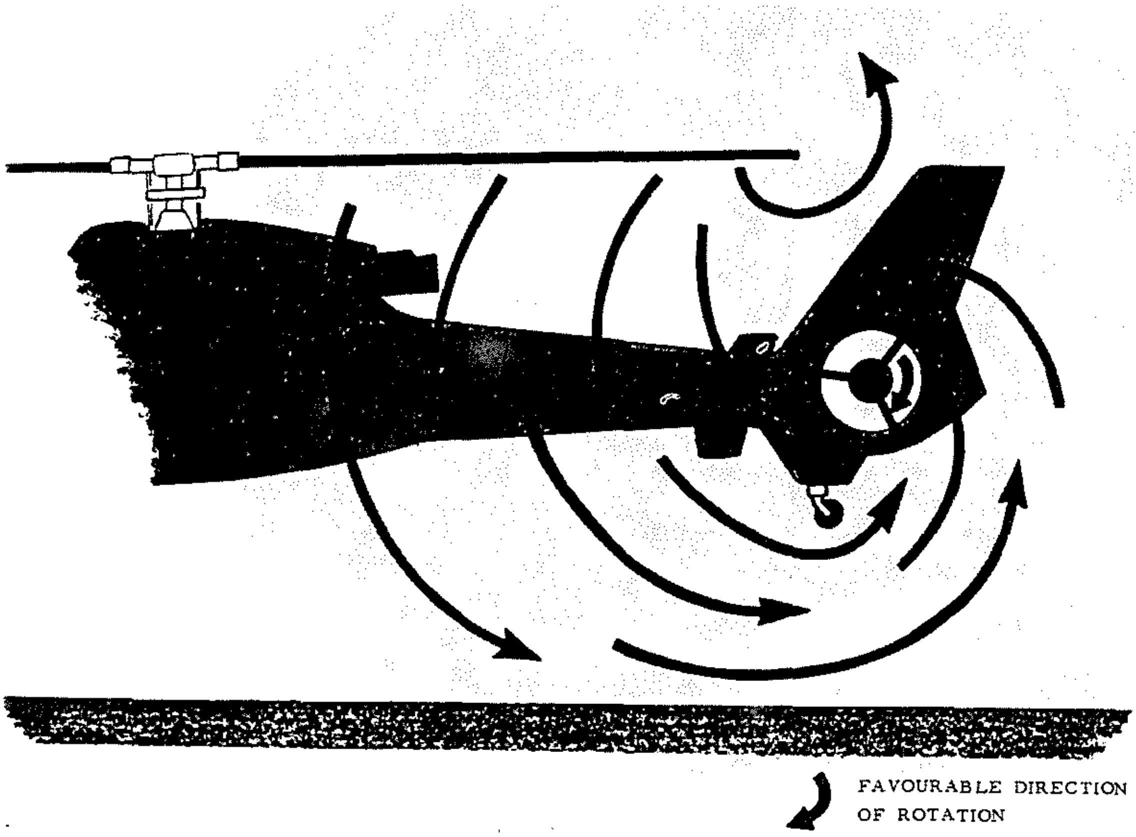


14. PEDAL POSITION IN FORWARD FLIGHT



15. POWERED MODEL IN WIND TUNNEL

16. BENCH TESTING OF FULL SCALE "FENESTRON"



17. SUCTION OF TIP VORTICES BY THE "FENESTRON"