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DESIGN PHILOSOPHY FOR HELICOPTER ROTOR HEADS

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I. SUMMARY

Since the birth of the helicopter, new designs of rotor head have been proposed fairly regularly.

What the constructors are looking for is not novelty for its own sake but, above all, it is simplification from which derives lighter design, reduction in production and operating costs, a higher reliability level with a possibility of improvement in flying qualities.

All the various approaches followed have some points in common :

- Reduction in the number of parts,
- Deletion of fatigue-stressed components, whenever possible,
- "Fail-safe" design of these components,
- Total or partial deletion of lubrication requirements.

The technology retained may be very different according to the basic processes used :

- Plain or thrust bearings made of laminated elastomer or self-lubricating material,
- Glass, carbon or kevlar composite materials associated with various resins or elastomers.

The work carried out by Aerospatiale starting from the "Alouette" fully-articulated rotor head has led to various designs, such as the "NAT" (drag restrained) rotor head, fitted on the production "Gazelle" and single-engined "Dauphin" helicopters, and the "STARFLEX" rotor head mounted on the "Ecureuil" and the twin-engined "Dauphin".

The "STARFLEX" rotor head represents a synthesis of the various basic processes which may be used to simplify the rotor heads. When compared with the "Alouette" or the "Gazelle" "NAT" rotor head, it shows an appreciable weight saving which may reach 45%. Its manufacture is very economical and it requires practically no maintenance. Its effect on the aircraft operating cost is very appreciable, both by its direct cost (purchase and maintenance) and by the resulting payload increase.

However, research works is continuing on a "TRIFLEX" rotor head which could lead, at least for some applications, to a still greater simplification.

WHY NEW DESIGNS FOR HELICOPTER ROTOR HEADS ?

In analysing the operation of existing helicopters, it is noted that main rotor head is a very significant element due to its weight, production and operating costs which are conditioned by the service life of components, time between overhauls and maintenance to be performed by the operator.

On the "Alouette II", for instance, the main rotor head weight corresponds to approximately 6 percent of the aircraft gross weight, its cost amounts to 15 percent of the total cost while its part in T.O.C. (Total Operating Cost) is 5.2 percent, i-e about 25% of total maintenance cost.

Hence, it is of the greatest interest to find solutions leading to significant progress in these three areas. Furthermore, an improvement in reliability and flying qualities of aircraft may be attempted at the same time.

Of course, the rotor head is not the only helicopter component worthy of care and progress should be made for every component, principally the engine, as shown in figure 1. However, to-day, our purpose is to deal with the rotor problem which is even more significant if progress is made in all other areas.

HOW TO FIND NEW SOLUTIONS ?

The search for new solutions starts by a critical analysis of the functions to be performed by the rotor head and then retain those which are strictly required only. After, comes the quest for technological solutions ensuring the performance of these functions while integrating them; i-e while trying to have several functions performed by the same parts, this leading to cost reduction and, often, also, to weight saving. The parts will be made of property selected materials so that fatigue problems can be overcome easily, if possible, have "fail-safe" characteristics and require no maintenance.

This is a conventional "value engineering" process which is not outstanding at all but which entails, to obtain interesting results, a good knowledge of the technical problems raised and proper control of the available technologies, based on extensive basic research work.

For main rotor heads, the questions immediately raised cover the requirement for flapping, drag and feathering hinges, drag dampers and other devices such as droop restrainers, all these being found in conventional articulated rotors.

The solution of the two-bladed "see-saw" main rotor system, with cantilevered blades in drag, is both simple and interesting, particularly in the form developed by the Bell Company for their latest models. However, it was not considered by Aerospatiale in their research programme for new solutions due to the limited control power of this rotor type, resulting in lack of agility and also, the difficulty to maintain the vibration level at an acceptable value, particularly when the helicopter speed and weight increase, as the 2/rev. excitation in a two-bladed aircraft is very high.

As a matter of fact, the first blade flapping mode, located between 2/rev. and 3/rev. is excited both by the "2/rev" harmonic of aerodynamic excitations giving vertical bumping excitations and the "3/rev." harmonic giving an "2/rev." excitation in the rotor plane, along the fixed axes. The filtering system, which is essential, must be particularly efficient, but its weight and cost are far from being negligible.

The multi-bladed solution (more than 2 blades) is preferable from these two points of view. Also, it was traditionally used for all Aerospatiale helicopters and, therefore, was used as the basis for new solutions involving, beside the above specific advantages, a simple and light design offering low purchase price and maintenance costs.

Rotor heads with first drag mode above "1/rev." were also ruled out, although they permit the deletion of drag dampers, due to their associated very high drag stresses and the resulting significant effects on weight.

IV. TECHNOLOGIES AVAILABLE TO DATE

The articulated rotor heads still in production consist of a number of steel components articulated on each other through needle and cylindrical or taper roller bearings while often stacked contact ball bearings are also used for the feathering hinge. The SA 330 Puma rotor head is a good example of one of the most modern articulated rotor designs (figure 2).

Titanium, lighter but more expensive, made its appearance in some rotor heads, in substitution for steel. Furthermore, stacked contact ball bearings were sometimes replaced by torsion tie-bars made of stacked stainless steel strips (Alouette rotor head) or of steel wire wound around two spools (Bendix tie-bar), associated with needle bearings.

Dry self-lubricating bearings were greatly improved in the recent years; their use in highly loaded hinges such as those of a helicopter rotor becomes possible, provided movements have a low amplitude (NAT rotor head).

Bearings made of laminated elastomer offer the advantage of requiring practically no maintenance but their weight and cost are relatively high and there is no other advantage than the deletion of lubrication requirements if they only replace articulated rotor head bearings.

The replacement of bearing type hinges may be differently contemplated as, for instance, metal strips bending around a shoe, having a shape determined to limit the bending stress in the strips to a reasonable value (Hughes 500 rotor head). However, these hinges may be also replaced by the elastic deflection of parts especially designed for the purpose. These parts may be made of metal and then a metal like titanium with a proper "fatigue strength/young modulus" ratio, should be selected (WG 13 rotor head). They may be also made of composite materials, still more favourable from this stand point which, besides a light weight, have the "fail-safe" feature inherent to their fibrous nature.

Finally, the damping required may be obtained, now, through the use of a high hysteresis type of elastomer providing simply, economically and without maintenance, spring and damping effects (frequency adaptor of "NAT" rotor head).

The Aerospatiale policy in the definition of new rotor heads is based on these new technologies and, in particular, on the use of composite materials and laminated or high hysteresis type of elastomers.

ROTOR HEADS EXPERIMENTED by AEROSPATIALE

Various types of rotor head were experimented on a SA 341 "Gazelle" helicopter (figure 3) and compared with the conventional "Alouette II" articulated rotor (figure 3 bis). They are :

- The "NAT" rotor head (figure 4)
not articulated in drag, featuring a flapping hinge on needle bearings a feathering hinge on needle bearings and a frequency adaptor made of visco-elastic elastomer semi-restraining the blade in drag, around its attachment on a self-lubricating bearing.
- The "MIR" rotor head (figure 5)
is fully rigid with only a feathering hinge on needle bearing and Bendix tie-bar. This is a Bolkow type concept where the blade stem flexibility replaces the flap and drag hinges.
- The "BIFLEX" rotor head (figure 6)
flexible in flap and drag, is made of a composite glass/resin material. It is fitted with a feathering hinge at the end of each arm and drag deflections are damped by small hydraulic dampers.
- The "STARFLEX" rotor head (figure 7)
flexible in flap and drag, also made of composite material, with feathering hinge realized through a laminated elastomer stop and self-lubricating spherical bearing.
- The "TRIFLEX" rotor head (figure 8)
having arms, made of glass fibers imbedded in an elastomer and flexible in the flap, drag and feathering planes.

The tests conducted have produced a good crop of results. They have allowed the selection of the solutions retained for production aircraft; in this connection, the logic appearing in the successive application of these solutions is noteworthy. After the aircraft fitted with conventional articulated rotor head such as the "Alouette", "Super-Frelon" and "Puma", we see the advent of the single-engined "Gazelle" and "Dauphin" helicopters fitted with the "NAT" rotor head, where only the conventional drag hinge has disappeared to the benefit of an elasticity localized through a frequency adaptor. This frequency adaptor, made of high hysteresis elastomer, ensures also the drag damping function required. Then, comes the "Ecureuil" and, in the near future, the twin-engined "Dauphin", with "STARFLEX" rotor heads, where the conventional drag and flapping hinges are replaced by a frequency adaptor acting in the drag plane, as in the "NAT" rotor head, and by the vertical flexibility of central star arms in the flapping.

The feathering hinge is obtained through an elastomeric spherical thrust bearing transmitting the blade centrifugal forces to the centre of star, and to a self-lubricating spherical bearing terminating the arm.

The next step may well be the complete deletion of the three hinges and the integration of the corresponding functions in a single part, provided that solutions are found to the many technical and technological problems raised and that, furthermore, the global weight and cost analysis is positive.

As a matter of fact, it is necessary to include in this analysis the main associated components, the definition of which may be affected by the solution retained.

For instance, a very high control power may require more or less sophisticated high speed stabilization devices as the high speed pitching instability of the rotor increases in direct relation with the rotor rigidity. A design leading to higher control loads may require sturdier controls and doubled or trebled servo-controls.

A rotor head applying to the structure higher vibratory excitations may require a more sophisticated mount and, even, additional anti-vibration systems, non-negligible from the weight and cost aspects.

Therefore, the designer should be very cautious and make comparisons as exhaustive as possible for every application because the best solution is not necessarily the same for all aircraft sizes and uses.

VI. THE "STARFLEX" ROTOR HEAD

The "STARFLEX" rotor head, which is being launched in production, seems to be globally the most interesting solution for the AS 350 - "Ecureuil" three-bladed rotor and twin-engines "Dauphin" four-bladed rotor.

Its construction and operation may be easily understood from a schematic diagram (figure 9). This diagram shows how the centrifugal forces generated by the blades are transmitted to the star central section through two wound glass roving plates and a laminated elastomer spherical thrust bearing. The small thickness of the star arms submitted to flapping deflections is noteworthy. There are also two layers of a high hysteresis elastomer inserted at the arm end between the star and the sleeve, and allowing stiffness adjustment and drag damping. Finally, there is the arm end self-lubricating spherical bearing connecting the star and the sleeve and allowing incidence angle variations in conjunction with the spherical thrust bearing.

Thus, the different functions are ensured :

- Flapping, by the vertical deflection of star arms and rotation of the blade-sleeve assembly around the spherical stop centre,
- Drag, by shear loading of both layers of high hysteresis elastomer, which provide also some damping, and rotation of the blade-sleeve assembly around the spherical thrust bearing centre,

- Incidence angle variation, by torsional deflection of elastomer spherical thrust bearing and rotation around an axis passing through the spherical stop centre and self-lubricating spherical bearing,
- The blade holding at rest is ensured by the rigidity of the star arms, sufficient to avoid excessive droop at blade tips.

Several functions are performed simultaneously by the same parts, which explains the very limited number of components, as shown in figure 10 illustrating the comparison between "Alouette", "NAT" and "STARFLEX" rotor heads and the "STARFLEX" version with yoke type blades root where the sleeves, integrated to the blades, are deleted :

- 377 parts for the "Alouette" rotor head,
- 202 parts for the "NAT" rotor head on "Gazelle",
- 64 parts for the "STARFLEX" rotor head on the "Ecureuil",
- 30 parts for the "STARFLEX" rotor head with yoke type blades root (figure 11)

Furthermore, the "STARFLEX" rotor head components are easy to manufacture and, therefore, their cost is low. The star is made of punched out pre-impregnated fabrics laid-up in a metal mould, pressed and cured in oven. The sleeves are made of wound and superimposed roving hanks. The other components, of lesser significance, have a moderate price. The spherical thrust bearing has been the subject of an extensive production research which has allowed the halving of its cost.

No wonder, therefore, that the total production cost of the "STARFLEX" rotor head reflects a significant reduction relative to that of "Alouette" and "NAT" rotor heads. According to the latest estimates, taking the most recent changes of definition into account, the "STARFLEX" rotor head cost would be 3.8 times lower at the same production level.

The weight is also highly reduced :

- . 100 kg for "Alouette" rotor head;
- . 95 kg for "Gazelle" NAT rotor head,
- . 57 kg for "Ecureuil" STARFLEX rotor head,
(i-e 3 percent of helicopter gross weight).

Maintenance is practically not required, except for the replacement of spherical thrust bearing (which is possible in the field) after, at least, 2.000 hours of operation; their condition can be checked, at a glance, before every flight.

The glass-resin composite components are very reliable and they have "fail(safe)" characteristics allowing "on condition" maintenance, without any T. B. O limit.

Dynamic analysis

From the dynamic analysis standpoint, the "STARFLEX" rotor head may be assimilated to an articulated rotor with elastic return in flapping and drag planes, as shown on figure 12.

The flap and drag hinge offset corresponds to the position of the spherical thrust bearing centre (it is equal to 3.84 percent of R for the "Ecureuil" STARFLEX rotor head against 2.1 percent for the NAT and 1.67 percent for the "Alouette" rotor head).

As the end of the pitch change lever is located opposite the thrust bearing centre, there is no Δ_3 effect and no "flapping-pitch" or "drag-pitch" geometrical coupling.

The first blade frequencies associated to the rotor head are located at :

- . 1.04 /rev. for flap,
- . 0.6 /rev. for drag.

There is practically no out of phase in the pitch control comparatively to an articulated rotor. The damping provided by the frequency adaptor amounts to 15-20%₀₀ approximatively. However, due to the amount of flapping hinge offset and the elastic return provided by star arms, control power is significantly greater than that of "Alouette" and "NAT" rotor heads, three times that of "Alouette" and twice that of the "NAT". The elastic return of star arms accounts for approximatively 25 percent of this control power.

In-flight behaviour

The "Gazelle" and "Ecureuil" aircraft, with the "STARFLEX" rotor head, have a very sound behaviour corresponding to that of an aircraft fitted with an articulated rotor head having a large flapping hinge offset or a rigid rotor head having a moderate stiffness.

Furthermore, as there is no possibility of geometrical coupling, the "STARFLEX" rotor is protected against any attitude variation phenomenon of the "pitch-up" type.

The pitching stability may be ensured at high speed by a fixed stabilizer of reasonable size and without any artificial stabilizing system. The "stick longitudinal displacement VS. load factor" curves clearly show the pitching stability, in maneuvers, of the "STARFLEX" rotor (figure 13).

The control loads remain sufficiently low in the three-bladed version of the "Ecureuil" aircraft and a single servo-control per channel is sufficient.

All these results explain the selection of the "STARFLEX" rotor head for the "Ecureuil" and twin-engined "Dauphin" helicopters.

The advantages may be summarized as follows for the AS 350-"Ecureuil" (figure 13 bis) :

- Significant weight reduction
(43 kg less than the "NAT" rotor head)
- Appreciable price reduction
(3.8 times less expensive than the "NAT" rotor head)
- Practically no maintenance required,
- Reduction of rotorhead D. O. C. by 67 percent, i-e 8 percent reduction of total aircraft T. O. C.
- Aircraft cost effectiveness improved by 16 percent (for 2 flying hours) taking into account :
 - . the 8 percent increase in payload,
 - . the 8 percent reduction in aircraft T O. C.

In this connection, the chart of figure 14 illustrates the T. O. C. improvement obtained on the "Ecureuil" in comparison with the "Alouette". It shows a reduction of 54 percent for the airframe and 27 percent for the engine, i-e a total reduction of 37%. The crew cost item remaining as it is.

The improvement in cost effectiveness is still more significant, as the increase in payload, achieved on the "Ecureuil", should be taken into account. Estimates are showing a T.O.C. reduction of 63% per kilogram transported in the "Ecureuil" relative to the "Alouette", i-e about 3 times less expensive.

I. RESEARCH WORK IN PROGRESS : THE "TRIFLEX" ROTOR HEAD

In line with the above outlined logic of the main rotor head improvement, the three basic functions : flapping, drag and pitch change, should be, in the future, fully integrated in the same part and the research work is directed along this line.

The process is already completed for tail rotors. On american UTTAS aircraft, tail rotors include a composite material strip providing drag restraint, flapping flexibility and incidence angle variation through torsion.

Aerospatiale is currently developing such a tail rotor for a SA 330 - "Puma" helicopter for the purpose of comparing it with the shrouded rotor "Fenestron" solution which is already flying.

The "Ecureuil" is also fitted with a two-bladed tail rotor featuring a single composite glass/resin strip providing, through torsion, the incidence angle variation required.

However, problems met in developing a main rotor of this type, are much more intricate. As a matter of fact, it is very difficult, on the one hand, due to the scale, to set the first drag mode above 1/rev. and, then, drag moments are very high. On the other hand, by setting this mode below 1/rev., a damping action is soon required to avoid ground and air resonance instabilities. Finally, the flexibility of the torsion strip leads to relatively large blade droop at rest. Nevertheless, research work is in progress in this field and, very probably, solutions will be found.

Another line of approach was followed with the "TRIFLEX" rotor head (figure 15).

It is a rotor head with arms made of epoxy glass fiber strands imbedded in a flexible elastomer; these arms have some torsional flexibility while the flapping and drag rigidity remains relatively high.

The elastomer deflection under shear loads providing the torsional flexibility is also at the origin of a "S" shape deflection in the flapping and drag planes (figure 16), resulting in coupling, principally a "flap-pitch" coupling which may be property used to restrict slightly the control power and introduce an aerodynamic damping.

The flight test results of the three-bladed "TRIFLEX" rotor head, fitted on "Gazelle", have been encouraging. The flight envelope explored is quite wide :

Speed : 250 km/hr in level flight - 300 km/hr in dive
Load factor : 2 g at 180 km/hr - 1.4 g at 235 km/hr
Altitude : 4.000 m.
Full autorotations at an all-up weight of 1600 and 1800 kg.

Good handling qualities and longitudinal stability over the whole flight envelope explored.

However, some features are still to be reviewed before proposing an application for this type of rotor head.

A simple mean of increasing drag damping, which is now insufficient and responsible for the appearance of air resonance in some forward flight conditions, should be found.

Also, the knowledge of the effect of several rotor heads and blade characteristics should be improved as the optimum adaptation seems quite hard to achieve principally due to the effect, on the "flapping-pitch" coupling of centrifugal forces and relative "flap-drag" rigidities of rotor head and at blade root end.

A very good rotor head-blades-structure-suspension adaptation is also required both from the rotor stability and vibration aspects.

Finally, control loads are high due to the torsional stiffness of arms and rotor blade deflections. For aircraft of "Gazelle" on "Ecureuil" size, the servo-control installation has to be doubled.

Solutions to the various problems noted seem however possible. Then, a weight and price analysis will have to be made and compared with that of other solutions; this may lead to different conclusions according to the helicopter size.

VIII. CONCLUSION

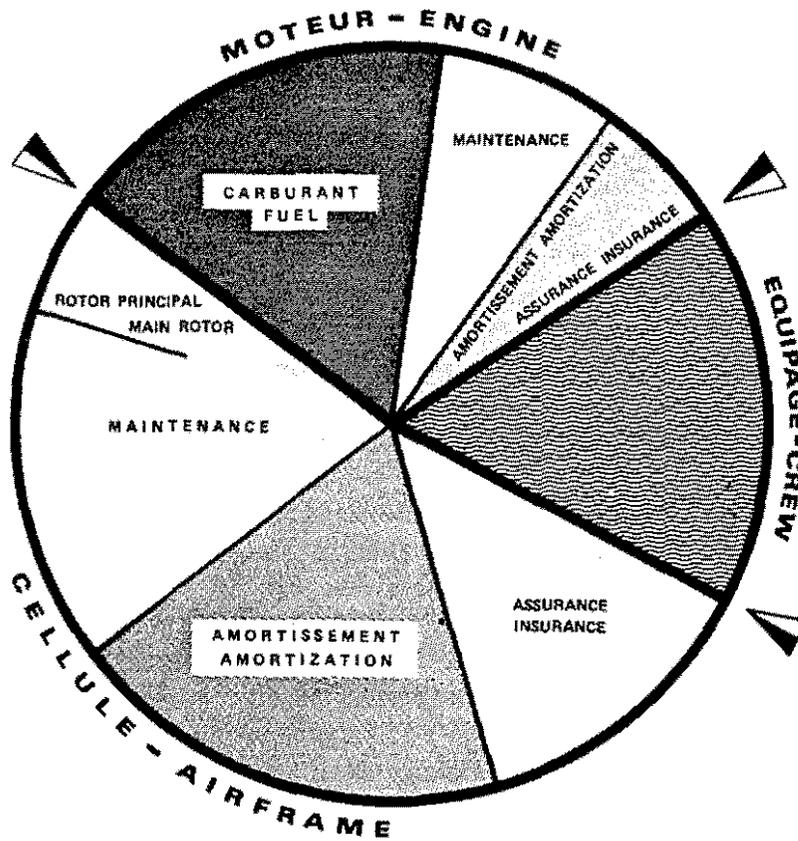
The search for new main rotor head solutions is important for improving the helicopter cost effectiveness as it is possible to increase very significantly the payload and strongly reduce the purchase price and direct operating costs.

Among the various solutions tested by Aerospatiale, the "STARFLEX" rotor head is the most interesting, to-date, for application to the AS 350 "Ecureuil" and twin-engined "Dauphin" helicopters.

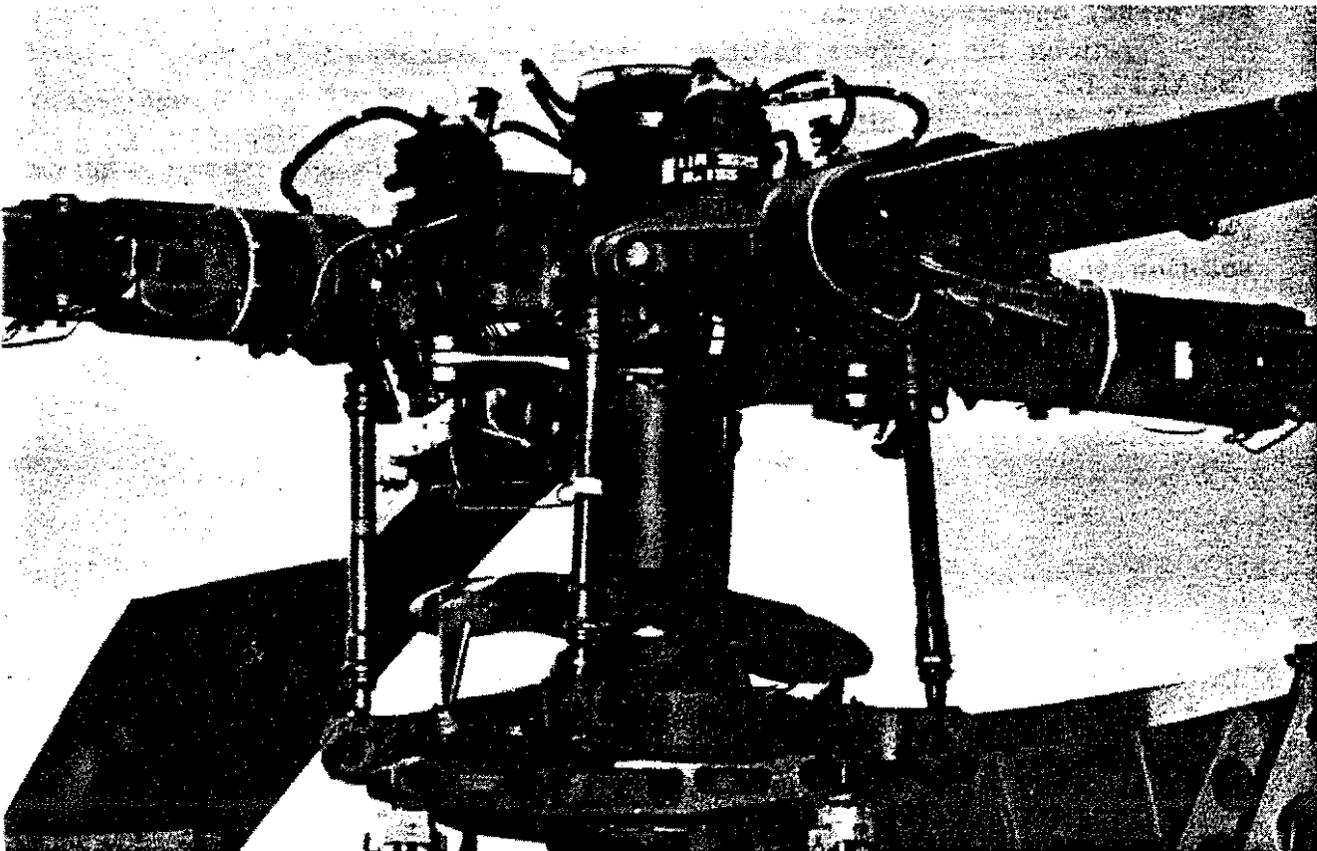
Research work is continuing to find other solutions which may be even more promising, at least for some applications. However, consideration should be given, in every specific case, to the full effects of the solution selected on the complete aircraft definition.

ALOUETTE II - SA. 318

1. Répartition des coûts en utilisation Operating cost distribution



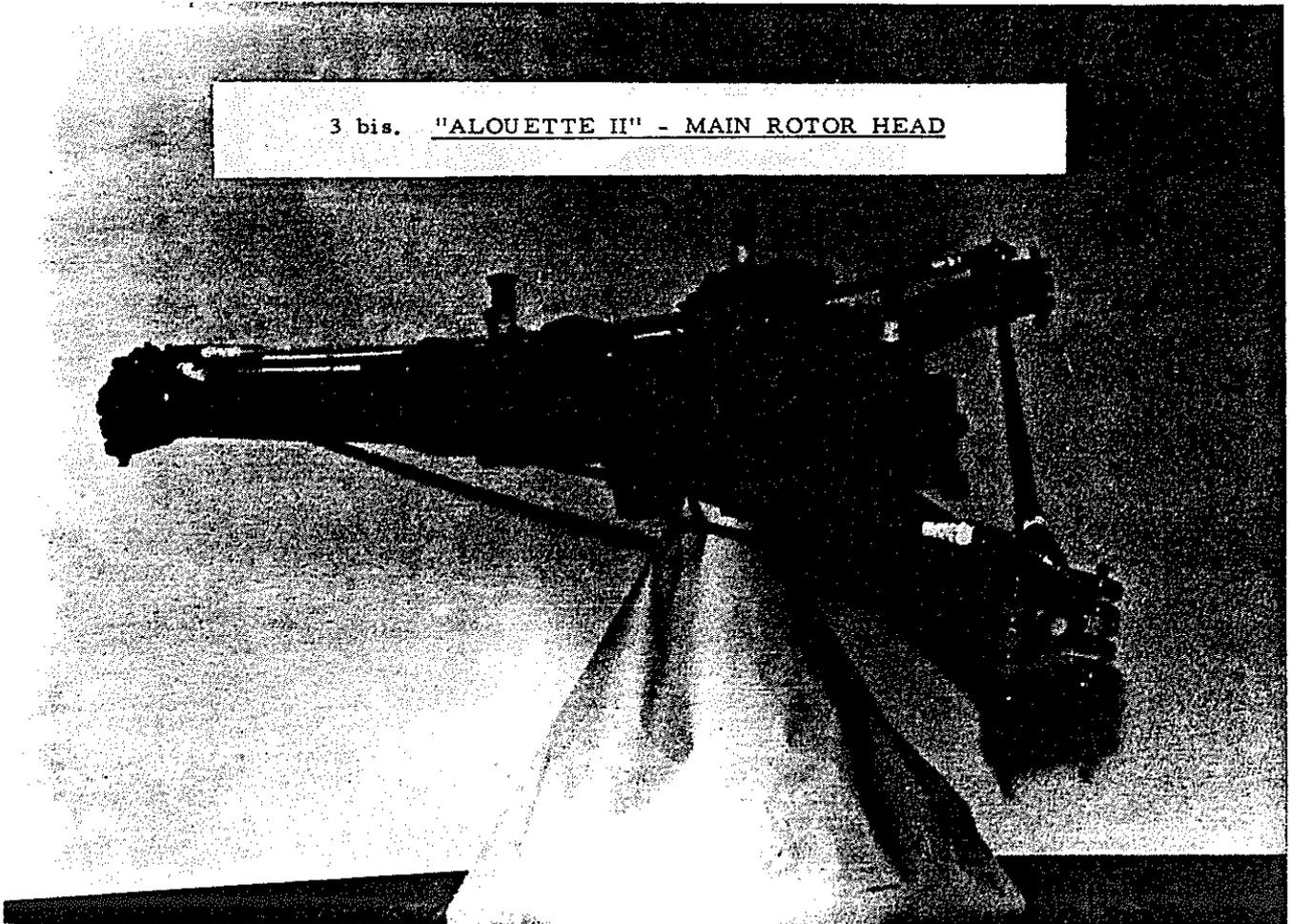
2. SA 330 "PUMA" - MAIN ROTOR HEAD



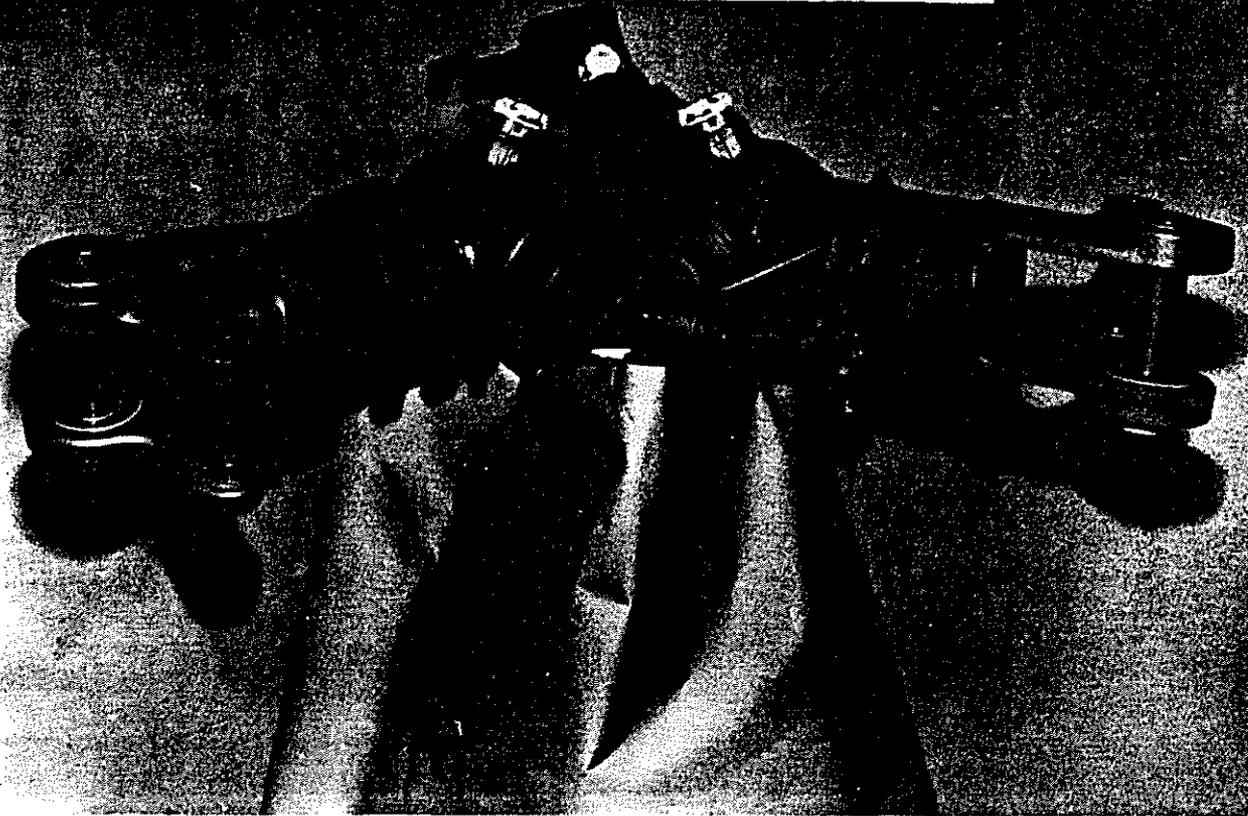
3. SA 341 "GAZELLE"



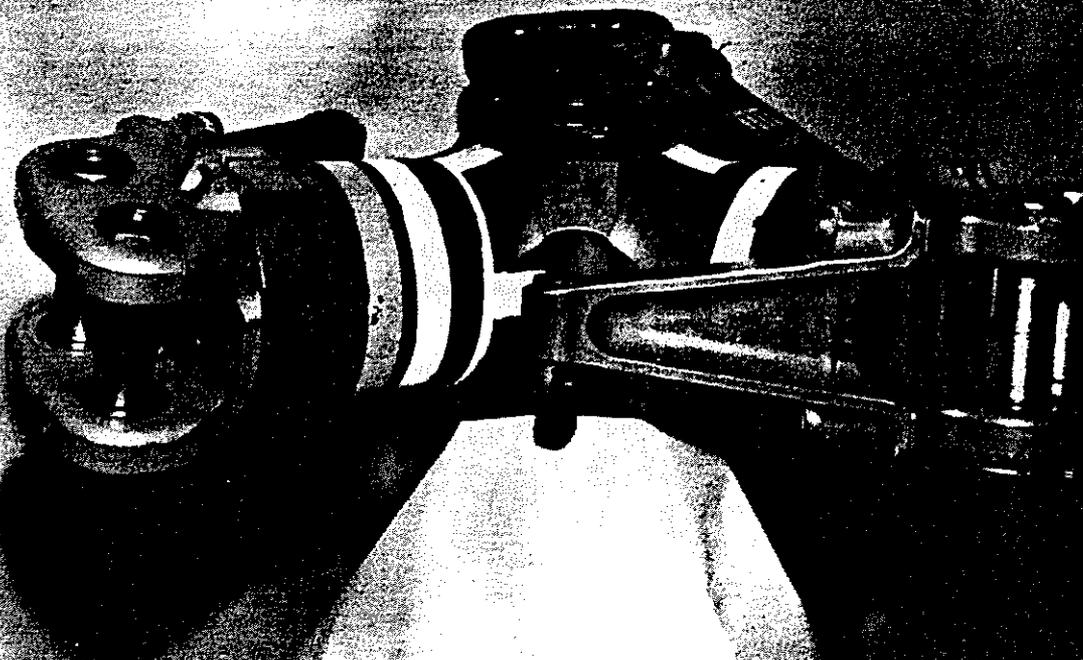
3 bis. "ALOUETTE II" - MAIN ROTOR HEAD



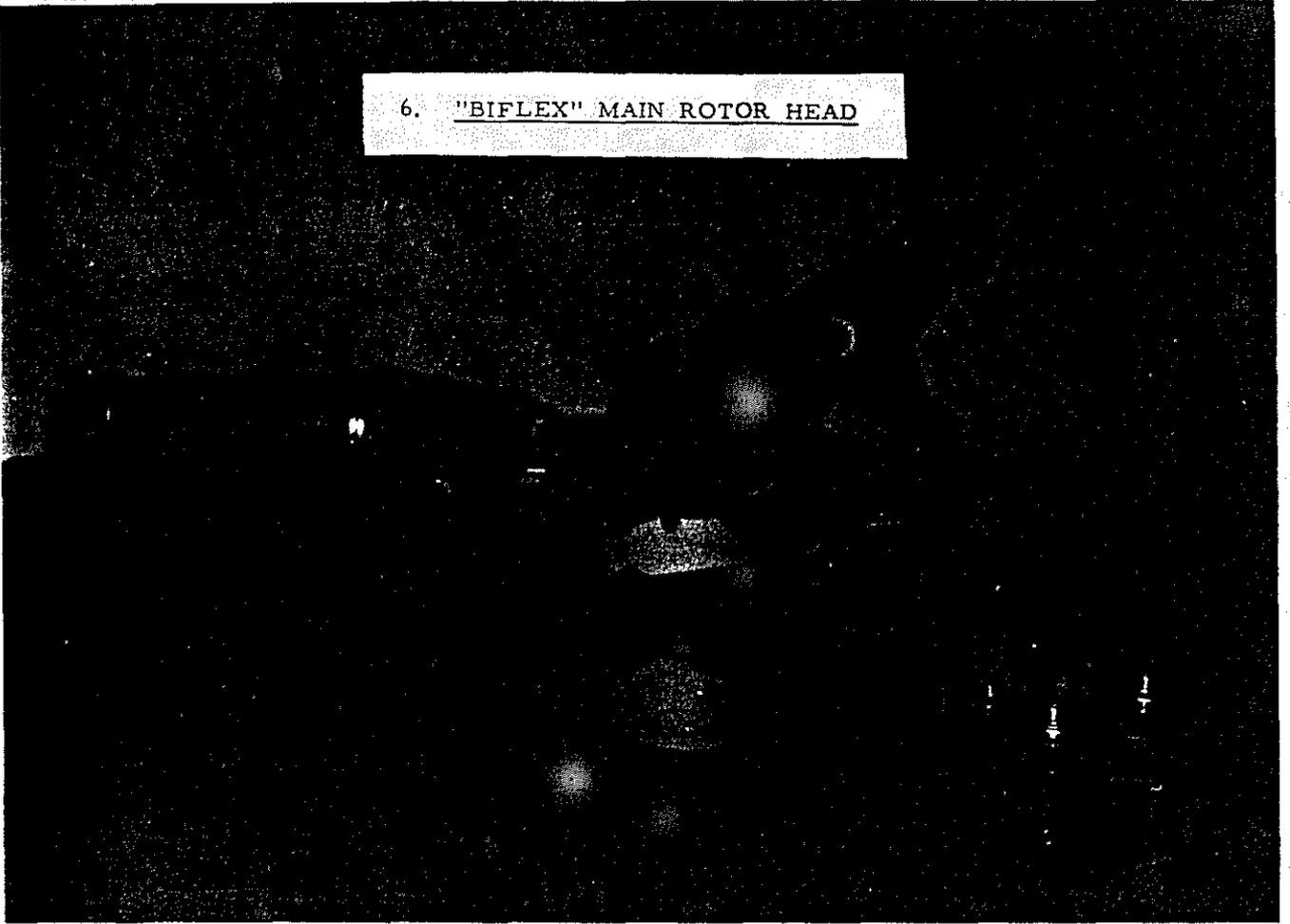
4. "GAZELLE" - "NAT" MAIN ROTOR HEAD



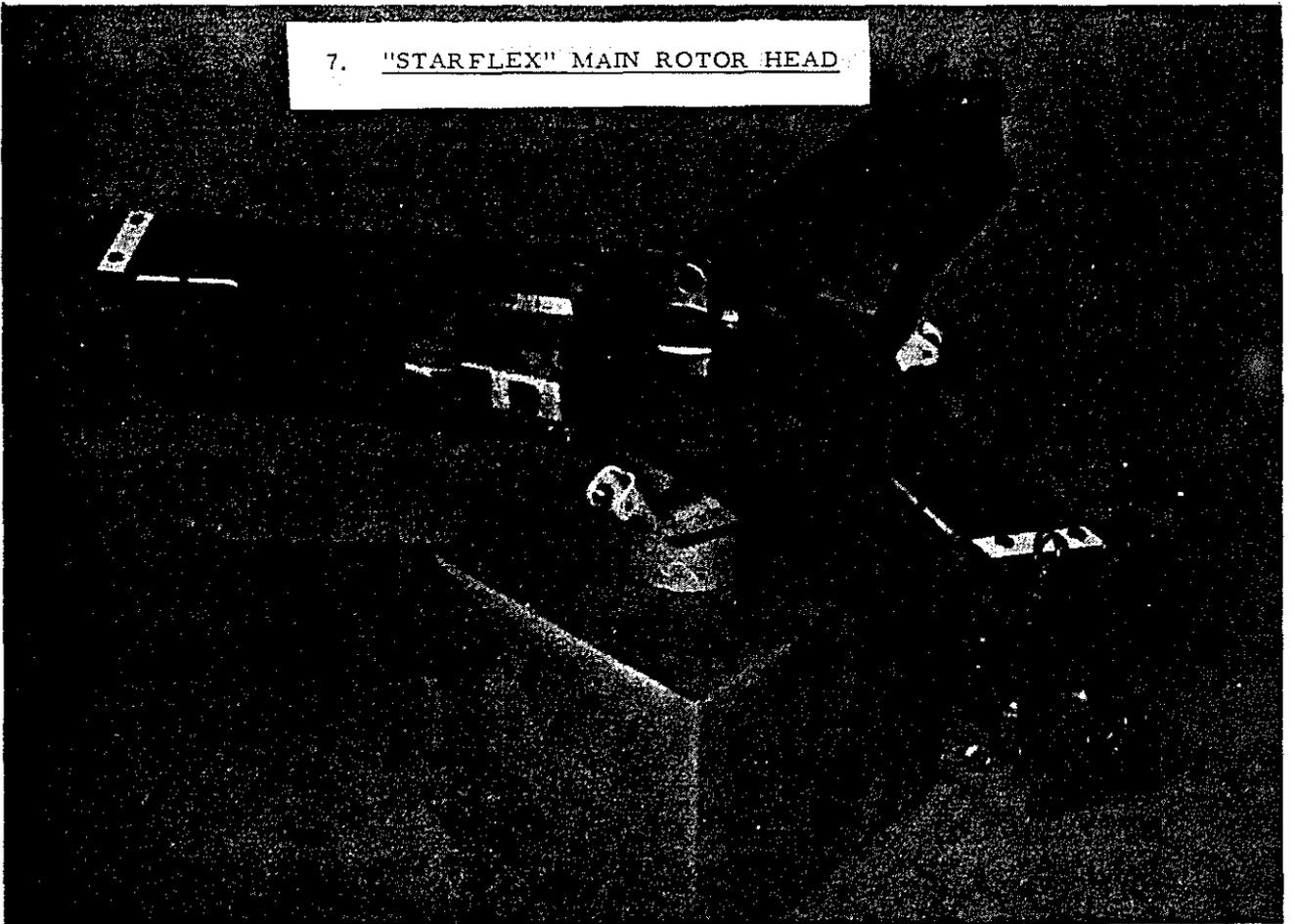
5. INTEGRAL RIGID ROTOR HEAD "MIR"



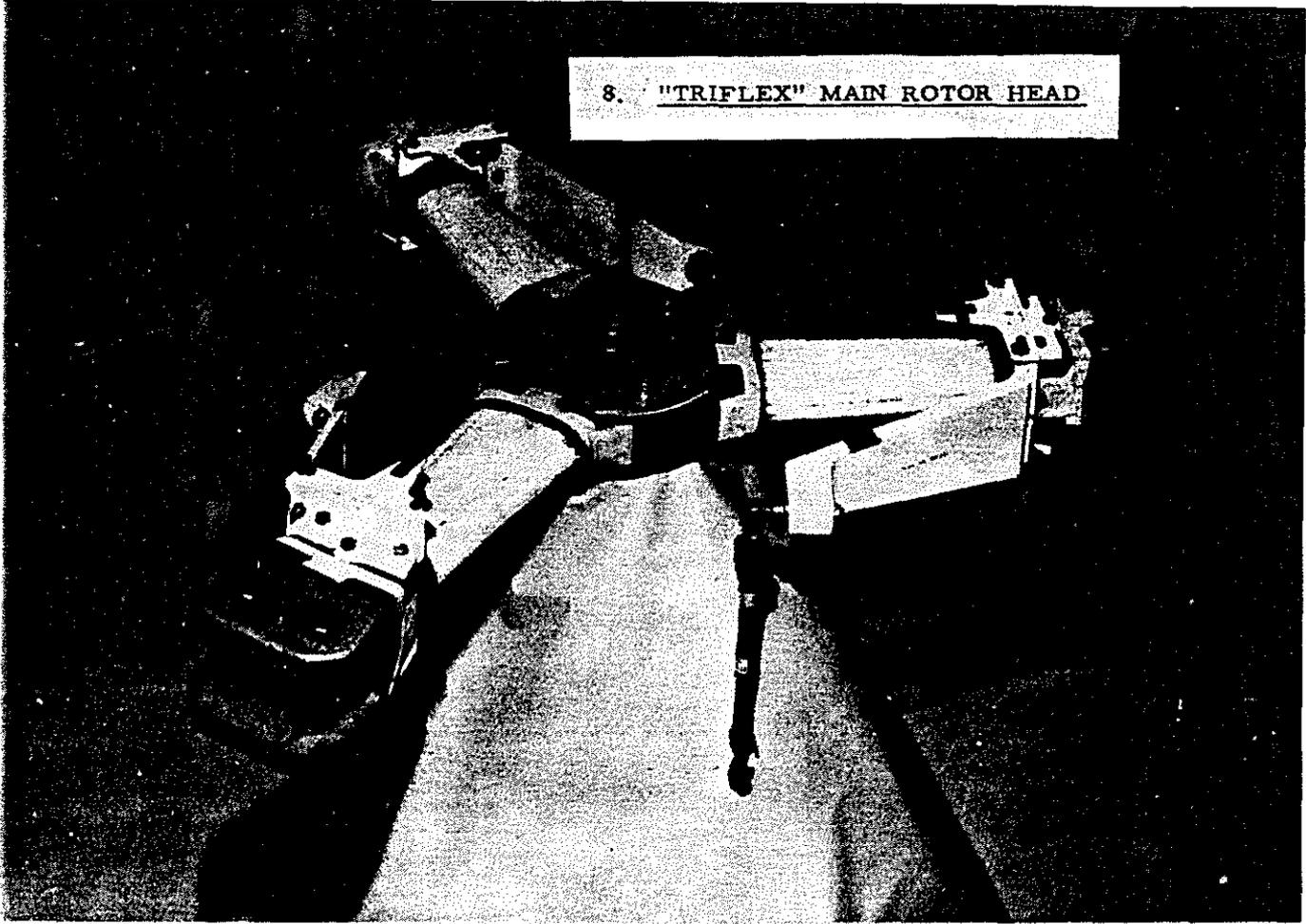
6. "BIFLEX" MAIN ROTOR HEAD



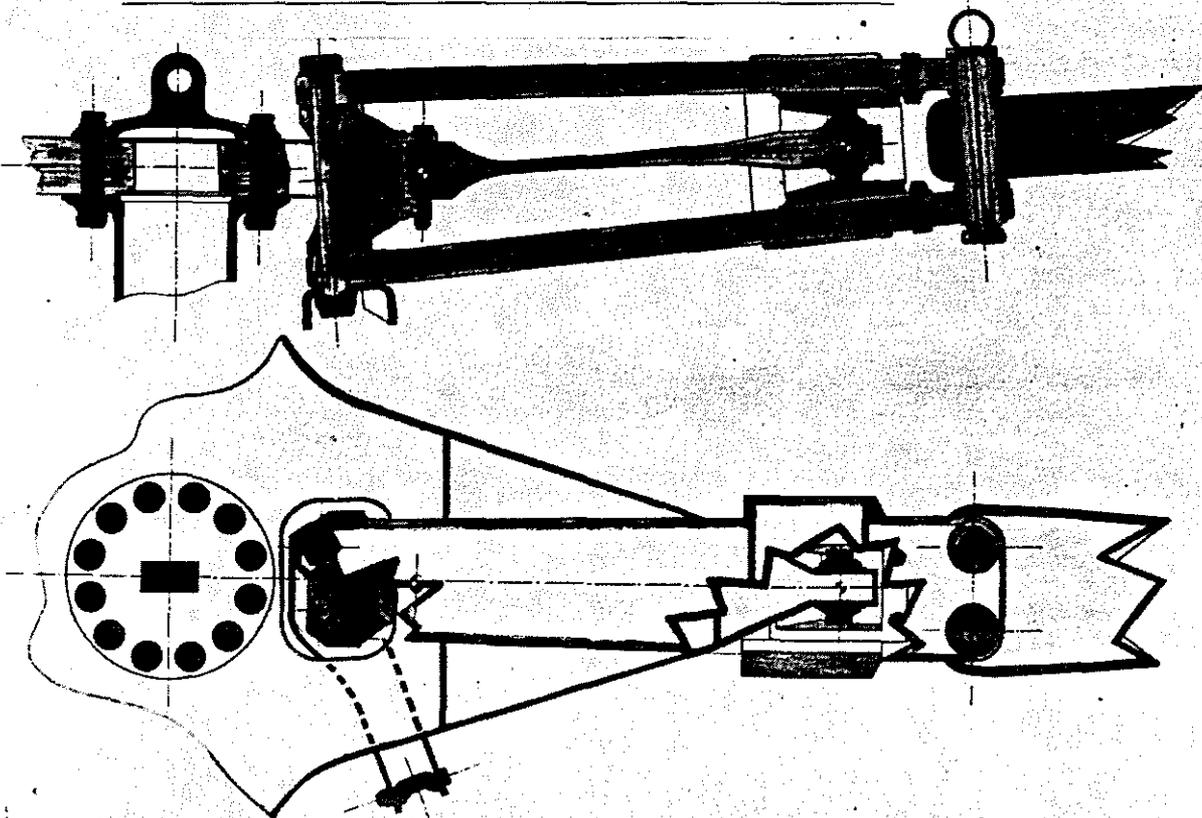
7. "STARFLEX" MAIN ROTOR HEAD



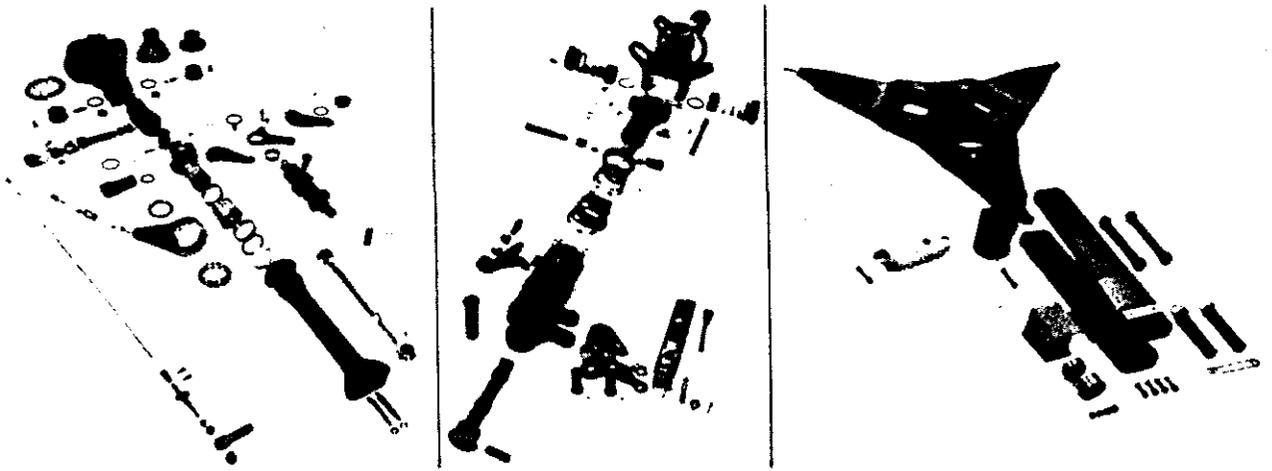
8. "TRIFLEX" MAIN ROTOR HEAD



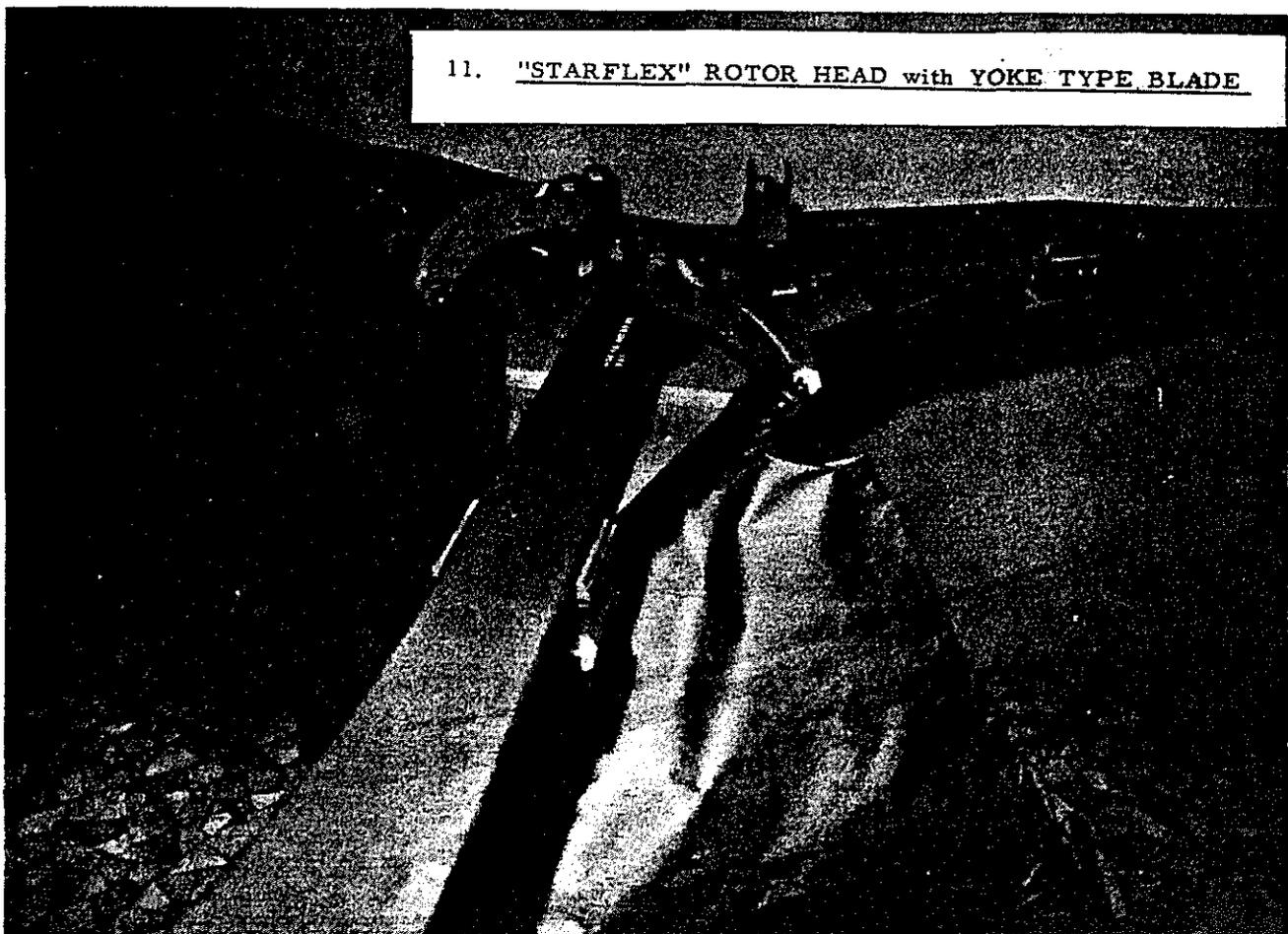
9. "STARFLEX" MAIN ROTOR HEAD - SCHEMATIC VIEW



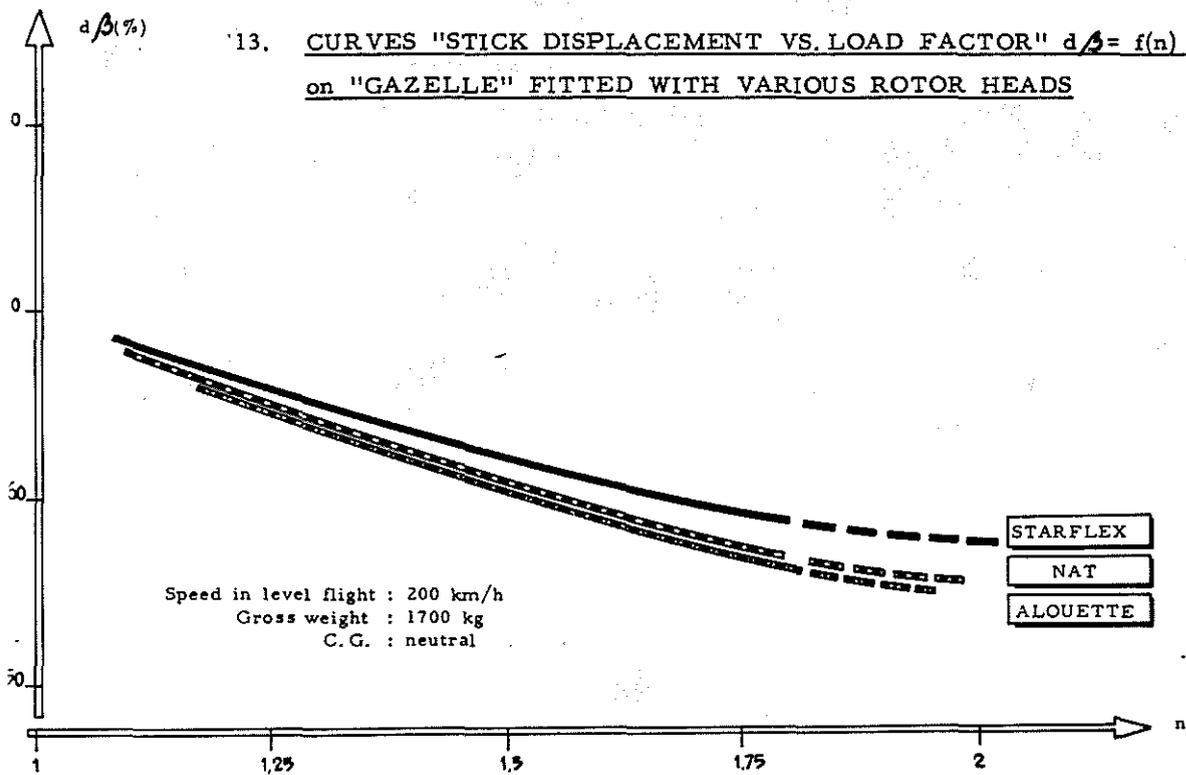
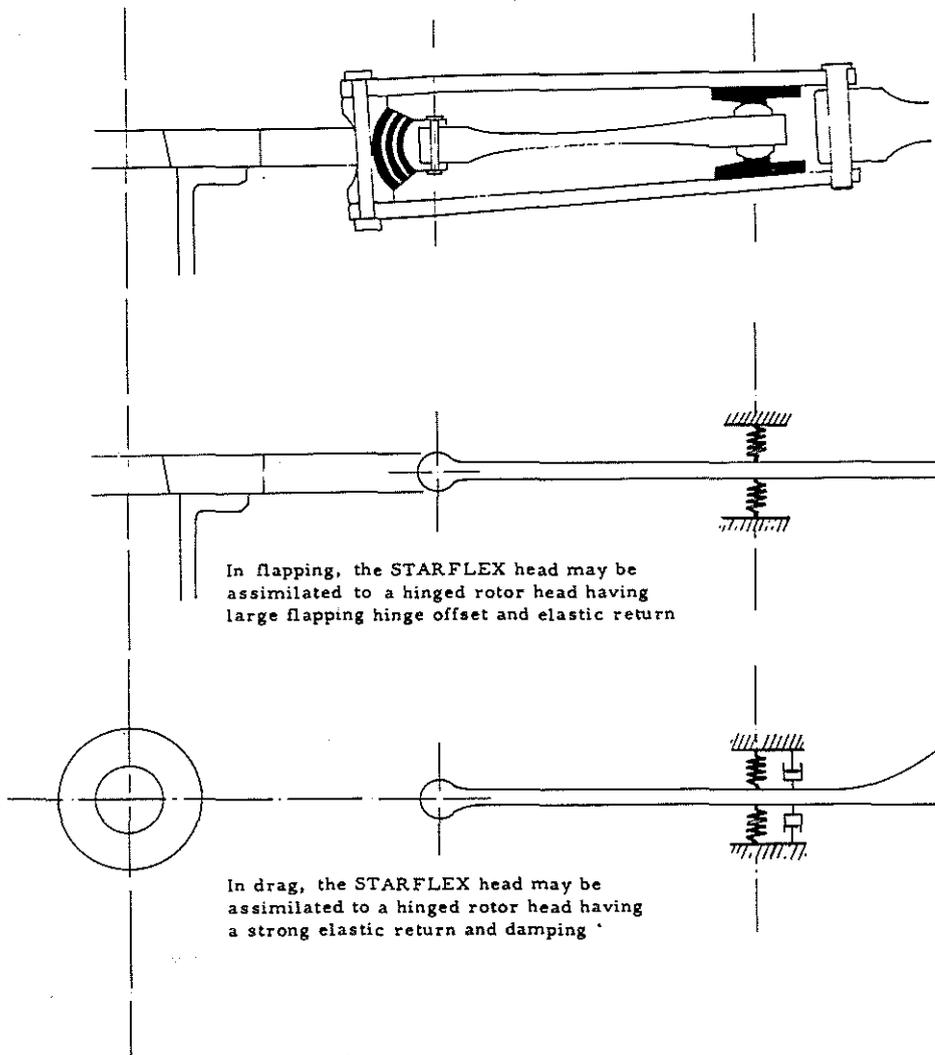
10. COMPARISON BETWEEN "ALOUETTE", "NAT" and "STARFLEX"
MAIN ROTOR HEADS

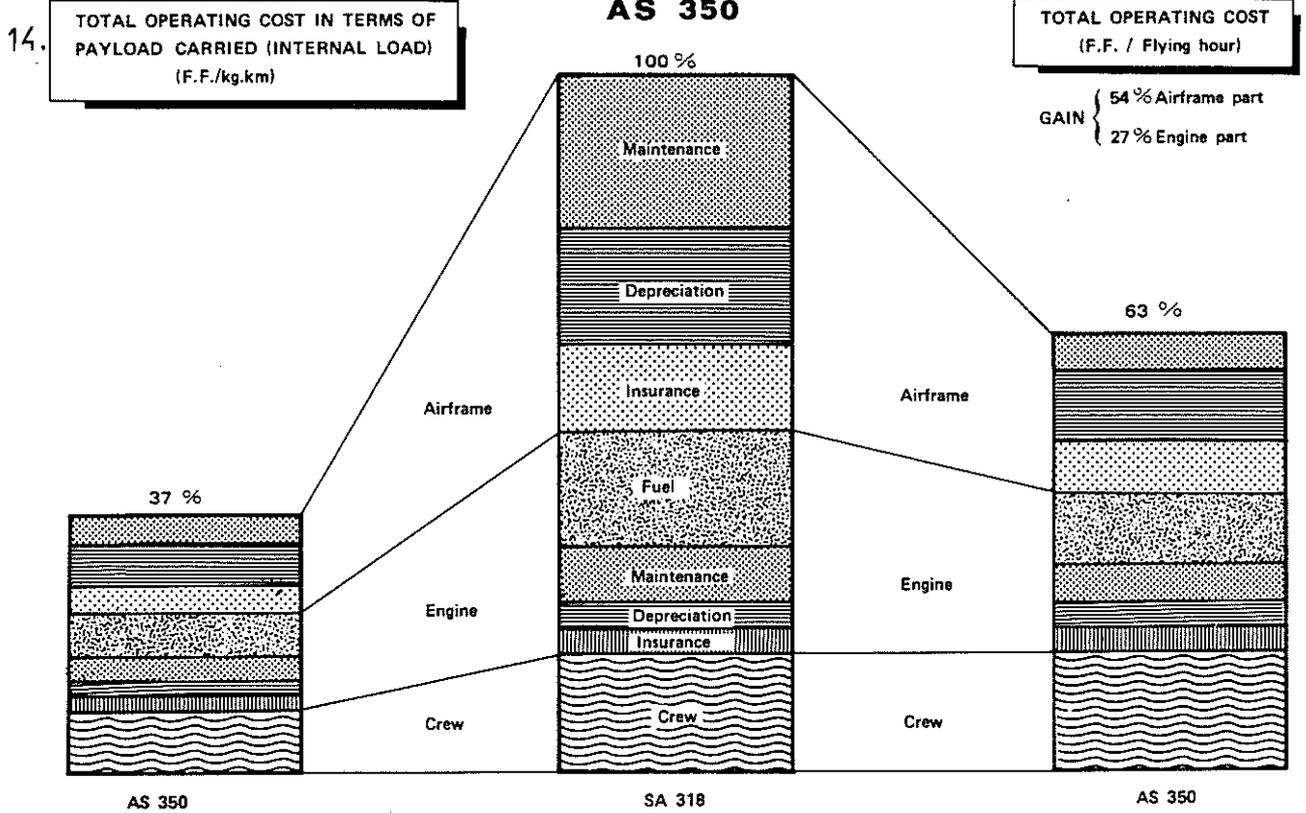
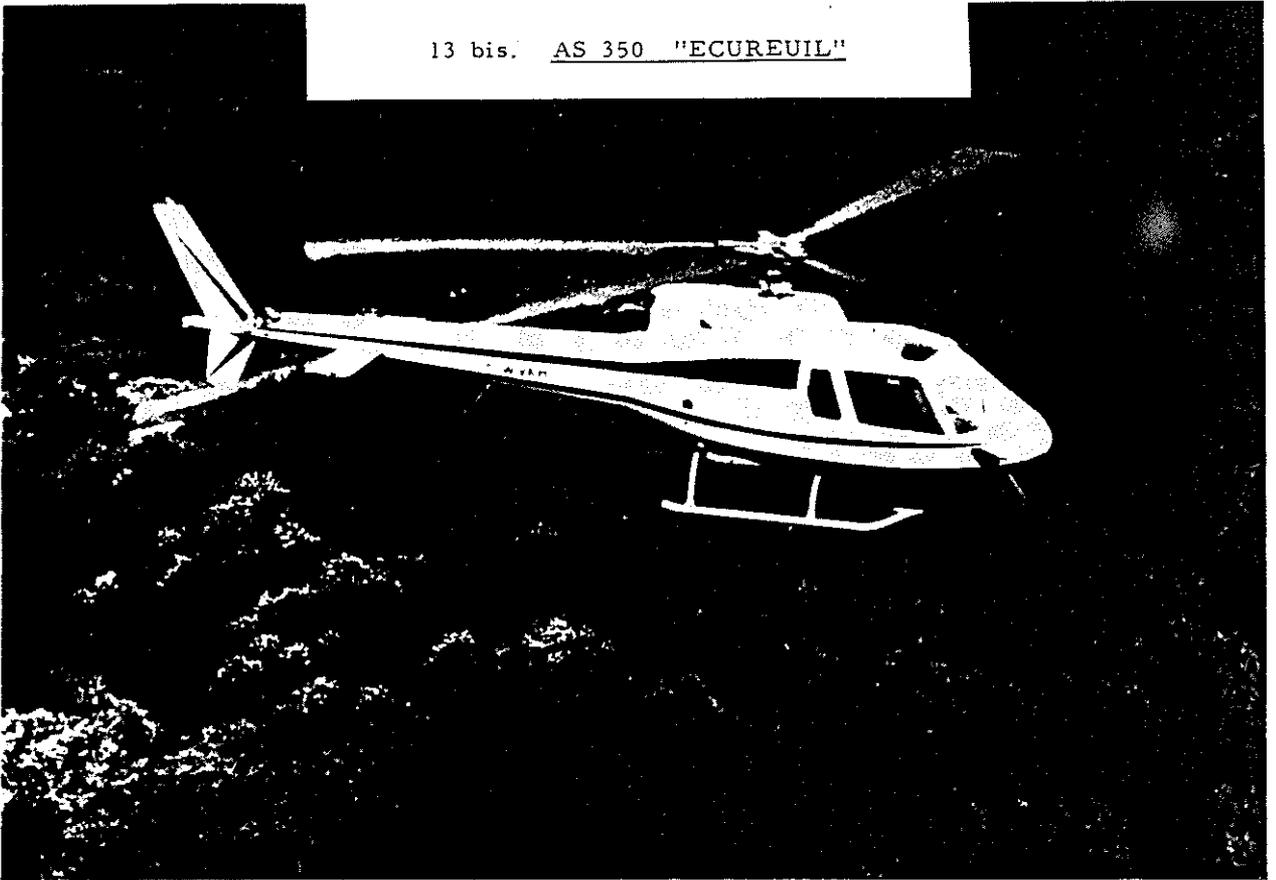


Number of parts		ALOUETTE	NAT	STARFLEX	STARFLEX Yoke type blade
TOTAL		377	202	64	30
among which	Bearings	30	21	0	0
	Seals	45	27	0	0
	Lubricators	22	3	0	0
	Self-lubricating bearings	0	0	3	3
	Laminated bearings	0	0	3	3
	Dry bearings	0	0	0	0

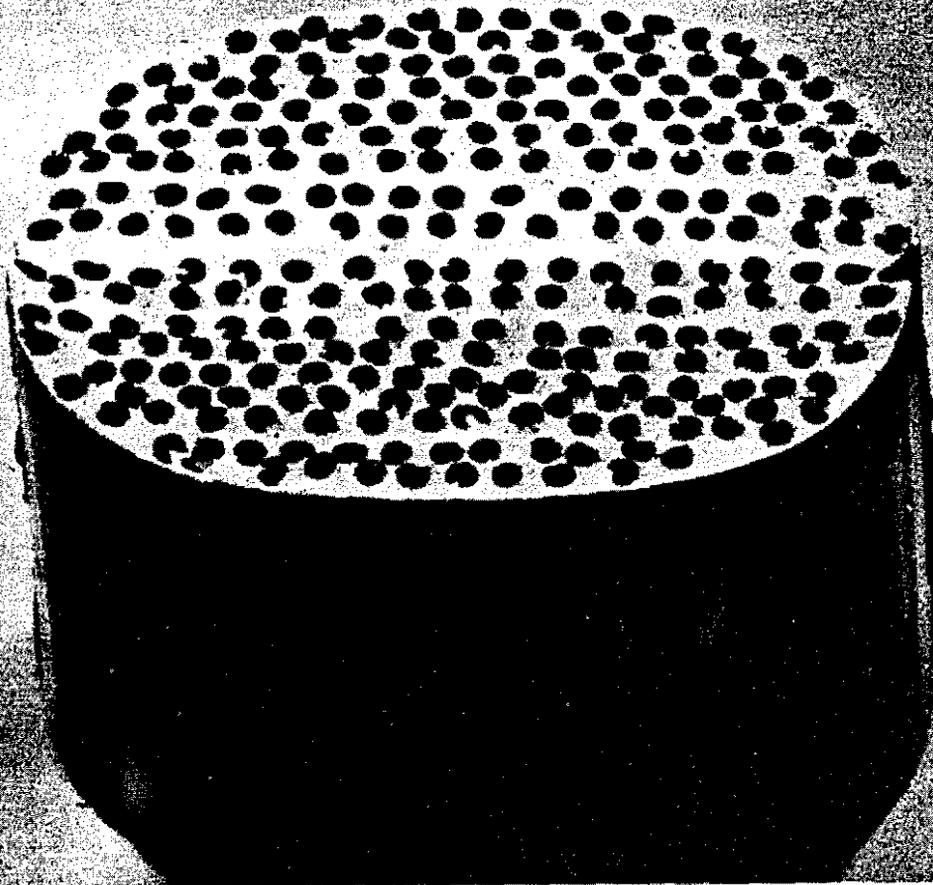


12. "STARFLEX" ROTOR HEAD - FUNCTIONAL DIAGRAM





15. "TRIFLEX" ROTOR HEAD - CROSS SECTION OF ARM



16. "S" SHAPE BENDING DEFLECTION OF A "TRIFLEX"
ROTOR HEAD ARM

