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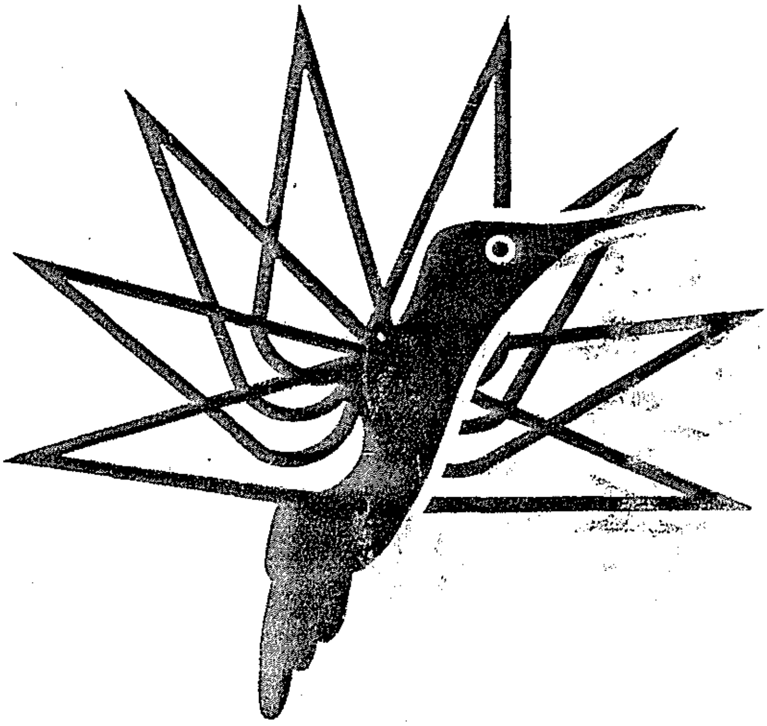

DESIGN, MANUFACTURING, AND OPERATIONAL BEHAVIOUR OF HELICOPTER COMPOSITE BLADES

by

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1 - INTRODUCTION

The factors guiding nowadays the technological choices taken by helicopter manufacturers are the constant improvement in the operational capabilities both of civil and of military helicopters, and the reduction in their production and operating costs.

Rotors are, in this connection, a vital factor governing to a large extent the characteristics and qualities of a helicopter.

Consequently, Aerospatiale has devoted much effort to this area, over a period of more than ten years, and especially to the design of composite blades.

In this lecture, we shall be examining the various stages in the life of a blade, with the respective technical methods and options involved, and the principal results achieved.

2 - DESIGN

2.1 - BLADE SHAPING

This new technology based on composite materials makes for better optimization of the rotor aerodynamic characteristics :

- The use of cambered airfoils.
- Decreasing relative thicknesses spanwise, for better airfoil adaptation in the stall range (high $C_{L\ Max}$) and the transonic range (high critical Mach number).
- Use of high blade twist, sometimes non-linear, to improve rotor performance, especially in hover.
- Root area design aimed at reducing drag to a minimum.
- Optimization of blade tip shaping.

Because of this increasing complexity of blade shaping, C.A.D. (computer-assisted design) is now used for blades (fig. 1). Moreover, thanks to the numerical generation of shapes, much time is saved at the later stages of design :

- The molds are manufactured by means of numerical control machine tools, directly from the C.A.D. numerical generation system.
- Direct chaining of dynamic and strength calculation programs.

2.2 - DYNAMIC DESIGN

With the advent of semi-rigid rotor heads, it is no longer possible to consider the head and the blades separately. It becomes necessary to design a head and blade assembly, adapting the characteristics of each element to those of the other. Also, because of the phenomena of air resonance and ground resonance, the dynamic compatibility of the head/blade assembly with its supporting structure has to be considered.

The dynamic design will thus pass through the following stages :

- The preliminary design will include the calculation of the rotor's natural modes whether coupled or not and whether in vacuum or in air. Then the head/blade assembly characteristics must be adjusted so as to avoid any coupling of the natural modes among themselves or with rotor speed harmonics - fig. 2 -.

- Analysis of the natural modes coupled with the structure, to avoid any resonance with it.

- Calculation of rotor loads :

  This is done throughout the flight envelope, by analogy with an articulated rotor.

  In the case of forward flight, it is possible to calculate blade response with precision (modal method or direct integration of the differential equations), and thus optimize stress levels for this flight configuration.

- Calculation, using the rotor loadings, of the forces transmitted to the structure and of the vibration level in the cabin. For this stage of the calculations, it is necessary to know the structure's load transfer functions, which may either be established by calculation or measured by means of a ground vibration test.

- Analyses of the instability phenomena, arising from particular coupling with the structure or linked to aerodynamic phenomena occurring at high speeds (stall, compressibility). These partial analyses are generally carried out during in-flight rotor development.

2.4 - STRESS ANALYSIS

— *Initial sizing :*

The stresses in the various materials and for each cross-section are automatically calculated by computer, based on the shapes generated by C.A.D., the technological option considered and the theoretical loads.

These stresses are then compared with the average fatigue limits of the materials, established by experiments on specific test samples corresponding to the blade design.

The fatigue diagrams are prepared for various levels of static stresses (Goodman diagrams) - figure 3 -.

— *Determination of blade service life*

A blade service life will be definitely known only at the end of the design process. At that point the definite safe fatigue limit, for a given risk, will have been established by fatigue testing on full-scale blade sections (see § 6) and by in-flight measurement of actual stresses and elongations.

2.5 - MATERIAL PROPERTIES

The use of composite materials has led to a better optimization of the blade mechanical and dynamic characteristics. Compared to metals, composites have better "specific" mechanical characteristics, that is in relation to their density : specific moduli, static and fatigue strength (figures 4 and 5).

Moreover, because of their anisotropic properties, the qualities of these materials can be optimized in the desired direction by appropriate orientation of the fibers (fig. 5).

However, these materials have the inherent disadvantage that their final properties, especially in fatigue, are affected by a large number of parameters :

- the type of fibre, resin and interface,
- the proportions of the constituent elements,
- the direction of stress (anisotropy),
- the manufacturing process of the material (especially the parameters of pressure, time and temperature),
- the influence of the environment during and following manufacture (temperature, relative humidity, ultra-violet radiation, etc ...).

Because of these different influences, optimization is complex and for the material to qualify, a large number of sample tests are required, especially in fatigue. Nowadays, once the material has been chosen and its physical and chemical make-up has been clearly defined, static and fatigue tests are carried out on specimens at ambient temperature and at the extreme temperatures of the flight envelope, both before and after an accelerated ageing process.

3 - TECHNOLOGY

3.1 - MAIN ROTOR BLADES (figures 6 and 7)

— The spar is the part which receives the heaviest stress loadings (centrifugal and bending). It is also the element which makes the blade fail-safe. For these reasons, it is always made of R-glass rovings, specially developed for aeronautical applications : this material is far superior in performance to E-glass, which is in common use, and its manufacture is strictly monitored.

— The skin must often ensure the greater part of the blade's stiffness to torsion. Depending on the degree of stiffness, weight and cost requirements, the skin may be made of glass cloth (SA 341 and 350), tapes of unidirectionnal of high modulus carbon laid at ± 45° to the centreline of the blade (SA 360, 365 C and 330) or a combination of high modulus and high strength carbon (SA 365 N).

In some cases, the front part of the blade consists of a torsion box in filament wound R-glass (for the 350 blade) or layered carbon (for the 365 N blade).

— NOMEX honeycomb was used as the filler for the SA 341, 330, 360 and 365 C blades. But this material has a very high cost price, and so when light, temperature-stable foams appeared on the market,they were selected for filling the SA 350 and SA 365 N blades, such a choice being also dictated by the new technology. Meanwhile, a cheap paper-based honeycomb is being developed and should soon be ready for use in our blades.

— The trailing edge strip is made of glass or carbon fiber depending on the drag stiffness and the balance required.

— Blade root doublers are made of glass or carbon composites, either cured then bonded or moulded in situ.

— Blades are attached to the rotor head by a 2-pin system, with the spar rovings wound round the bushes and compound wedges.

Another possible method, still in the design stage, would in some cases make it possible to have fewer parts ; this consists of a blade ending in a fork attaching directly to the rotor head.

— The protection of helicopter rotor blades against erosion by sand and rain remains an unsolved problem, for no method of protection seems to be effective against both types of erosion. Currently, the protection used is either polyurethane-type thermoplastic or a metal cover made of stainless steel, titanium or nickel.

Qualification testing of these materials is carried out on a rotor enclosed in a tower, 4.5 metres in diameter and subjected to extreme rain and sand conditions (figure 9).

De-icing is possible on composite blades by integrating a rubber/heating resistor system within the leading edge under the metal protection strip.

3.2 - TAIL ROTORS

Some tail rotors (e.g. the AS 350) are somewhat different in structure, the blade and the rotor head being designed as a whole.

The blade spar rovings are continued into the central area as a flexible beam, to form the rotor head.

Pitch actuation is provided by a faired blade cuff, integral with the blade but clear of the central beam (see fig. 8).

4 - MANUFACTURE

The technique retained by Aerospatiale is that of "co-curing", i.e. the polymerization of the entire blade assembly in a single operation. The various elements constituting the blade are placed into two pre-heated metal half-molds (40 to 50° C). The molding takes a full day at the end of which the polimerization is done (figure 10).

The text of the lecture by Mr Epstein at the 32^{nd} AHS convention in May 1976 (ref. 2) accurately describes the entirely manual manufacturing process of Gazelle blades :

- Preparation of metal detail parts.

- Preparation of composite material detail parts : pre-cured doublers, carbon trailing edge strip, machined honeycomb filler, compound wedges.

- Cutting out, layering, and manual impregnation of the skin glass cloth in the two half molds.

- On-the-spot automatic impregnation and manual layering of spar glass-rovings (figure 11).

- Setting of honeycomb filler and installation of detail parts.

- Closing of mold and curing at 120°.

This method which is also applied for the blades of the Puma and Dauphin entails manufacturing times very similar to those for metal blades.

A substantial effort to simplify and mechanize operations was made in 1974 for the manufacturing of the AS 350 Ecureuil blade, while retaining the co-curing principle :

- Reduced number of parts.

- Manufacturing of the spar and of the wound attachment using the "hank technique" under which spars are laid automatically on a large size rotating support then cut into two half-hanks (figure 12).

- Torsion box winding at an angle of ± 45^{o} around the spar and the foam filler (figure 13).

This improvement of the manufacturing process made it possible to divide manufacturing time by 3 as compared with the conventional manual method.

5 - QUALITY CONTROL

Inspection operations are carried out upon acceptance of materials, during the various manufacturing phases and at the end of the cycle, on the molded blade.

5.1 - MATERIAL INSPECTION

Materials used must meet very specific requirements. Therefore various acceptance inspection operations are carried out either at the supplier's plant or at Aerospatiale : infra-red spectrographic inspection, measurement of epoxy contents, flow, volatile products contents, impregnation ratio, weight per unit of area, fiber orientation on prepreg material, mechanical characteristics of dry fibers and of final composite material (figure 14).

5.2 - MANUFACTURING OPERATION INSPECTION

A certain number of precautions are taken in order to limit the influence of various factors that may affect the final properties of a blade e.g. a proper regulation of the hygrometric level and of temperature in the shop, the use of gloves in order to avoid polluting materials, verification of the weight of the constituent elements.

However the operation sheet for certain operations is frozen and can only be altered with the agreement of the Design Office and of the Authorities. Such is the case for the following operations on the blade of the AS 350 : winding, mold-closing and curing.

The overall inspection of the manufacturing cycle is carried out on follow-up specimens and through periodic tests on blade sections.

5.3 - INSPECTION OF ALREADY MOLDED BLADES

Finished blades undergo 5 types of checks :

- Non-destructive check of the quality of the product : visual check, coin test (figure 15), skin-filler adherence check using suction cups and in the near future laser holographic inspection (figure 16).
- Dimensional checks : straightness of leading edge, twist to length ratio.
- Measurement of mechanical characteristics : torsional stiffness, bending in the drag plane, bending in the flapping plane.
- Measurement of weight characteristics : checking of blade weight and static moment by static balancing.
- Inspection of dynamic and aerodynamic characteristics on rotating blades by setting the pitch angle, the trailing edge tab incidence, and the chordwise distribution of blade tip balance weights (figure 17).

6 - CERTIFICATION TESTS

Composite blades are approved through fatigue tests on full-size sections of blades (figure 18). There are different types of tests :

6.1 - BASIC BLADE APPROVAL

The definition of the blade life is based on these tests. To limit their duration one uses loads that are far heavier than those measured in flight. Generally two areas are tested : the main section (at least 6 test specimens) and the attachment including the transition area between the attachment and the main section (6 test specimens at least).

As far as new generation tail rotors fitted with an integral hub are concerned, further tests must be carried out on the center beam and the control system.

For reasons of continuity in production, there must be a minimum of two supply sources for any stressed material used ; the materials from these two sources are usually approved during the certification tests of the basic blade.

6.2 - MODIFICATION APPROVAL

During development or production of a blade, a blade manufacturer may, for economic or technical reasons, have to midify the blade design, the choice of a basic material, or a manufacturing process.

Such modifications must necessarily be approved and special fatigue tests are carried out on specimens and sections.

6.3 - SUBSTANTIATION FOR REPAIR

Any scheduled standard repair on a blade must be substantiated by at least two fatigue tests on blade sections.

6.4 - SPECIAL TESTS

On this category are tests designed to study the behaviour of the blades after accidental damage : impact with trees, stones, military projectiles or lightning.

All these certification tests involve a large number of test sections : 20 sections on the SA 341 Gazelle and 35 on the SA 330 Puma.

7 - OPERATIONAL BEHAVIOUR

7.1 - RESISTANCE TO THE ENVIRONMENT

In order to study their behaviour in extreme atmospheric conditions, blades were exposed to equatorial atmospheric conditions for 5 years, and then fatigue-tested.

Moreover numerous accelerated ageing tests are carried out on test specimens : exposure to U.V. radiation, combined effects of high hygrometric and temperature conditions.

The results show that composite blade life is little affected by the environment. Their operating range goes from — 55 to + 80° C whatever the hygrometric conditions.

Two measures must be taken to guarantee this good behaviour : protection against U.V. radiation thanks to a polyurethane paint and minimization of water absorption thanks to good sealing.

Composite materials used for blades have a poor resistance to erosion from sand or rain ; it is therefore essential to install a leading edge metal strip for providing protection against rain or polyurethane against sand.

Lightning resistance tests are carried out on every new blade (figure 19) : voltage tests to locate impact zones then electric current tests to evaluate damage and lastly fatigue tests after lightning has struck to evaluate the consequences of damage.

These tests have shown that, provided a certain care is taken during the definition phase , composite material blades have a satisfactory resistance to lightning.

The anti-icing protection which was tested in flight during specific tests allowed the SA 330 Puma to be the first helicopter certified for flight in icing conditions.

7.2 - IMPACT RESISTANCE

The low vulnerability of composite blades to notching effects combined with their outstanding "fail safe" property account for their good resistance to impacts.

In civil operations, the good resistance can be illustrated by the following examples :

- Specific tests have shown that Gazelle blades were capable of cutting 200 x 200 mm wooden beams without any serious damage.

- A private operator hit the top of a fir-tree during an unloading operation in a high mountain area. Not having felt his composite main blades hit the tree, the pilot continued his flight and only 15' later, while refuelling, did he notice substantial damage : 400 mm upper to lower surface perforation of the blade.

- In very unfortunate circumstances on November 6th 1975 a Gazelle hit a Bonanza airplane in flight and for the very first time after an airplane/helicopter collision the helicopter was able to land safely with its two passengers safe and sound (figure 21)

In the military field, specific shooting tests followed by fatigue tests have been carried out.

- With a 7.62 mm armor-piercing caliber projectile and a 20 mm shell on the SA 341 blades (figure 21).

- With a 12.7 mm caliber projectile on the SA 330 blades : the projectiles were shot through the spar and chordwise thus ruining most of the blade skin.

These tests have shown that in most cases it is possible to return to the base after impact.

7.3 - MAINTENANCE

Composite blade maintenance is very limited. It mainly consists in verifying periodically the external aspect of the blade and in renewing leading edge protective material when operating conditions are very severe.

Since composite blades have an unlimited life, periodical mounting and removal operations necessary in case of a limited life thus become superfluous.

Moreover the use of such new materials makes repairs possible in most cases.

In some cases the customer himself can carry out the repair, for example :

- Replacement of blade tip trailing edge.

- Repair of trailing edge or of skin in case of limited impact or perforation.

Other repairs must be done by authorized repair-shops. They must be followed by static or dynamic balancing. Here are a few examples of such repairs :

- substantial skin repairs (separation of layers, perforation),
- replacement of attachment bushing,
- repair of spar.

7.4 - DIRECT OPERATING COST

In the preceding paragraphs we have highlighted the great reliability of composite blades and the substantial reduction of maintenance operations. On that basis it has been possible to divide by 3 the DOC of the SA 330 blades.

However the cost-effectiveness balance must be supplemented by increased performance directly derived from the optimization of rotors made possible by the use of composite materials (see para 2).

The maximum take-off weight of the SA 330 Puma for example has been increased by 5.7 % (400 kg) and its cruise fuel consumption has been reduced by 6 %.

Such improved performance results in a 13 % reduction of the kg/km cost.

8 - CONCLUSION

In the course of this lecture we have presented the various aspects of composite blade design and manufacturing and the main results achieved thanks to this new technology.

To date, nearly 4000 composite blades have been produced for 5 different types of aircraft. They have a total of 2,000,000 flying hours in a wide variety of environmental conditions in 49 customer countries.

Thanks to the experience generated by 14 years of activity in this field, it has been possible for technology to progress especially towards a good optimization of dynamic and weight characteristics, towards reduced manufacturing costs, and a better knowledge of blade behaviour in flight.

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FIG. 1 : COMPUTER ASSISTED DESIGN

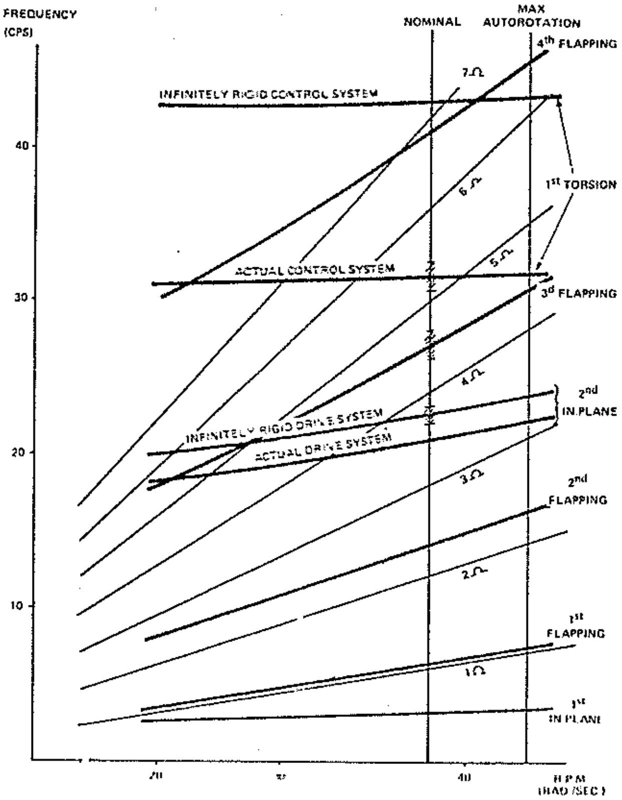

FIG. 2 : NATURAL FREQUENCIES OF SA 365 TYPE MAIN ROTOR BLADE

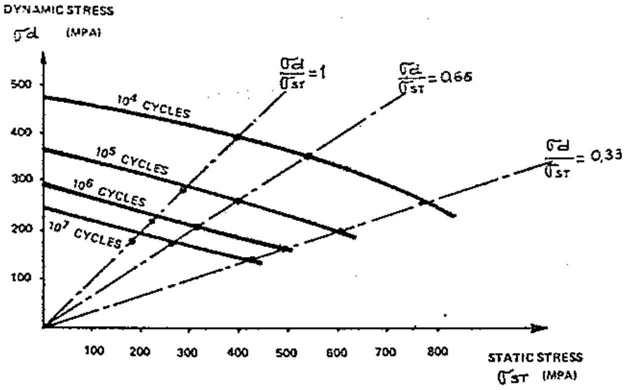

FIG. 3 : FATIGUE CHARACTERISTICS OF UNIDIRECTIONAL GLASS

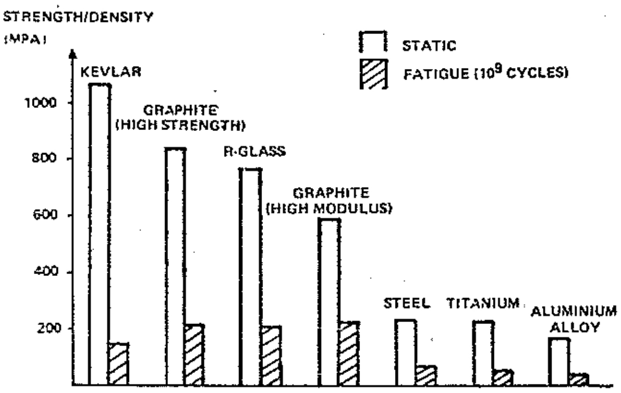

FIG. 4 : "STRENGTH/DENSITY" RATIO FOR VARIOUS MATERIALS

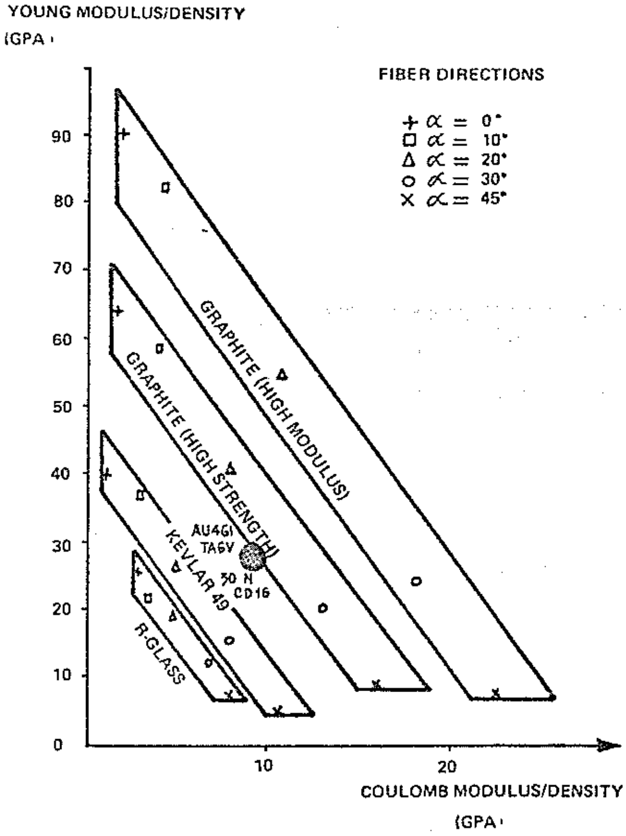

FIG. 5 : ANISOTROPY OF COMPOSITE MATERIAL

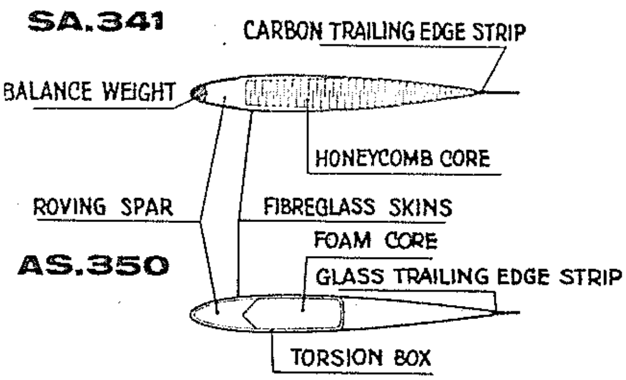

FIG. 6 : SA 341 & AS 350 BLADE SECTIONS

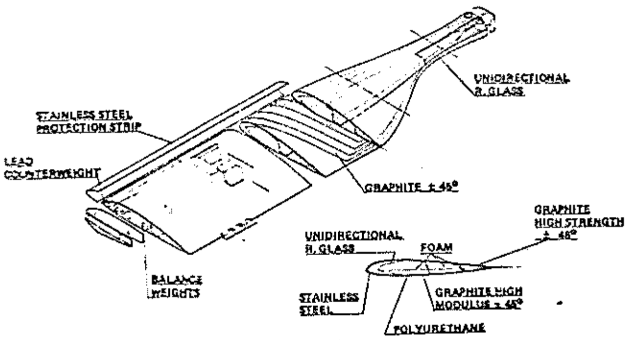

FIG. 7 : SA 365N COMPOSITE MAIN ROTOR BLADE

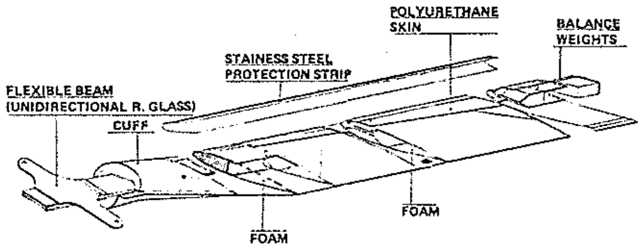

FIG. 8 : AS 350 ECUREUIL COMPOSITE TAIL ROTOR

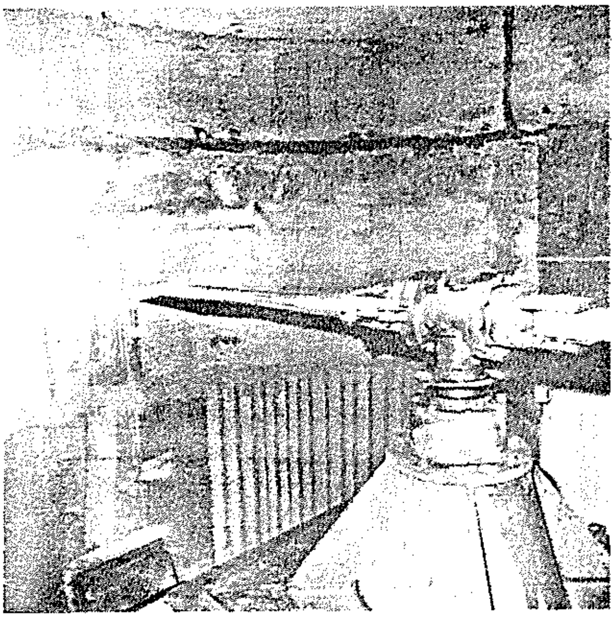

FIG. 9 : EROSION TEST RIG

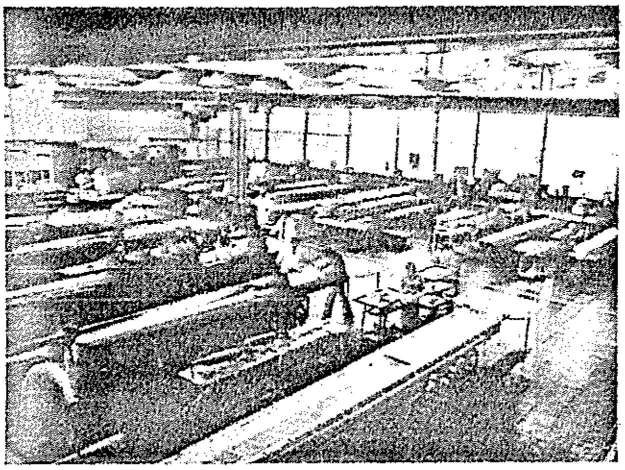

FIG. 10 : COMPOSITE BLADE PRODUCTION WORKSHOP

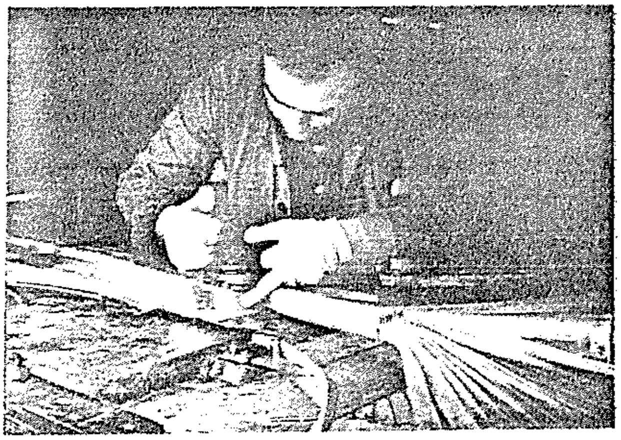

FIG. 11 : HAND SMOOTHING OF ROVING SPARS

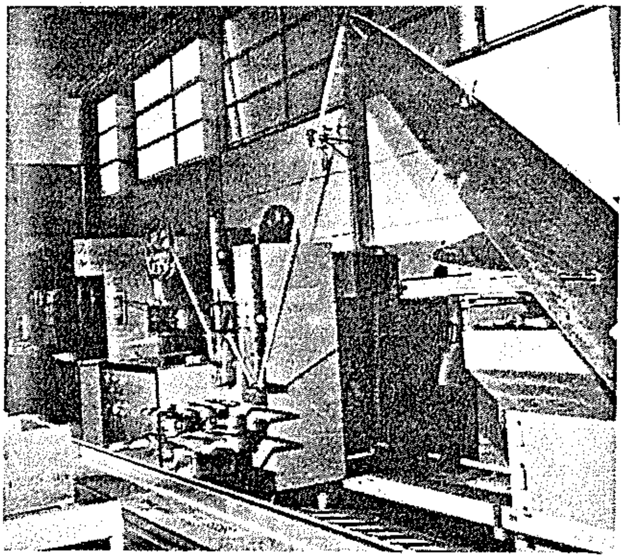

FIG. 12 : AUTOMATED MANUFACTURING OF HANKS

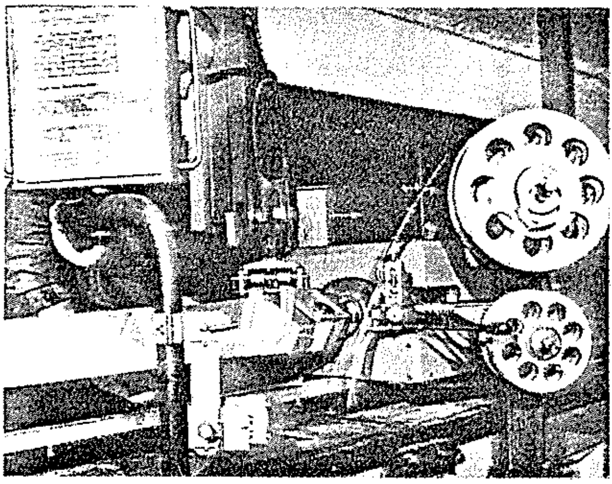

FIG. 13 : TORSION BOX WINDING

FIG. 15 : ACOUSTIC CHECK

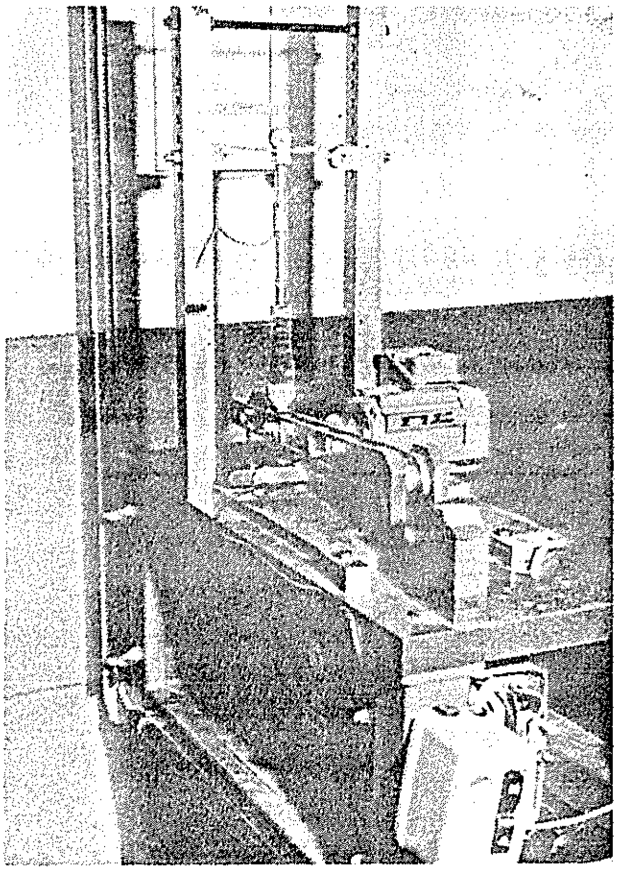

FIG. 14 : SPECIMEN BENDING TEST

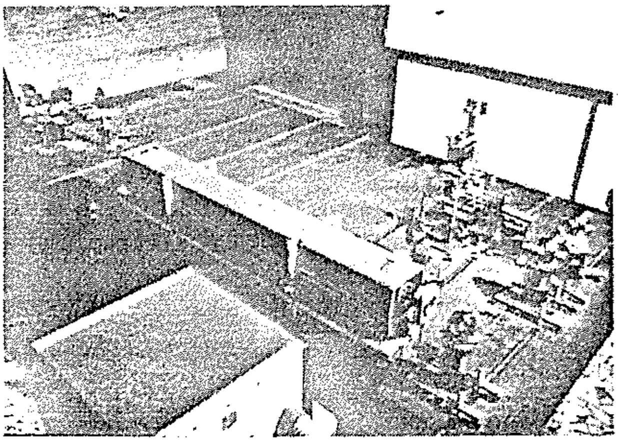

FIG. 16 : LASER HOLOGRAPHY INSPECTION

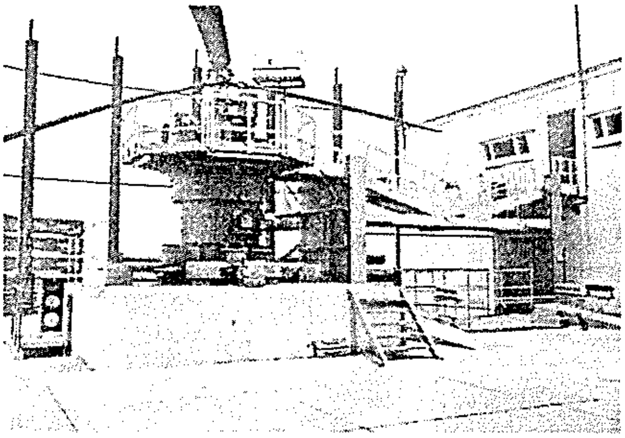

FIG. 17 : DYNAMIC SETTING RIG

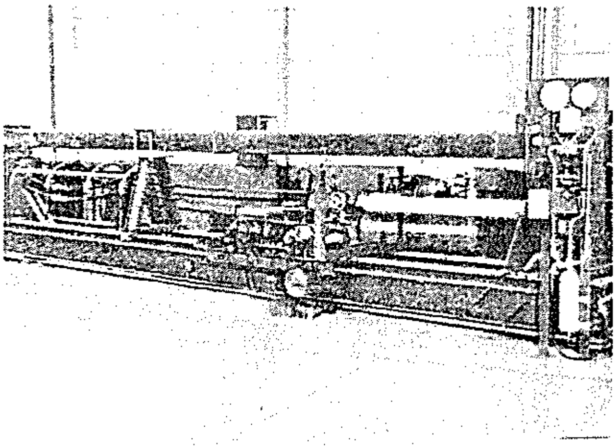

FIG. 18 : FATIGUE TEST ON BLADE SECTIONS

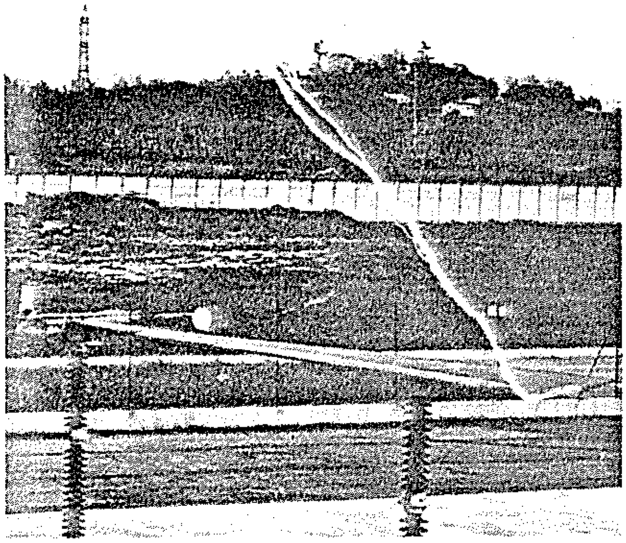

FIG. 19 : LIGHTNING TEST

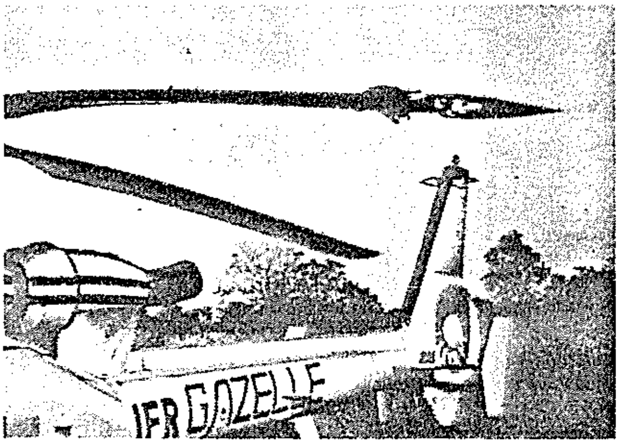

FIG. 20 : SA 341 GAZELLE AFTER IMPACT WITH PRIVATE AIRPLANE

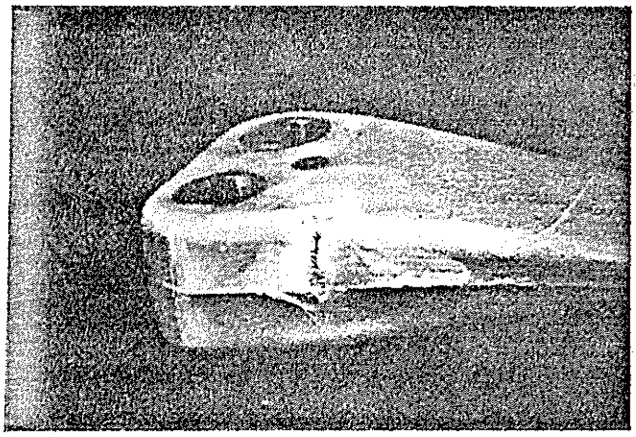

FIG. 21 : VULNERABILITY TEST