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REPORT ON GAZELLE ENGINE SEVENTH STAGE COMPRESSOR BLADE FAILURE

by

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SUMMARY

Following a failure of a seventh stage compressor blade in a Rolls Royce Gazelle engine of a RAN Wessex helicopter, ARL was requested to investigate the cause and mode of failure. This report details the investigation and presents a number of conclusions and recommendations which deal with the cause of the failure. It also discusses new assembly methods which could alleviate future rebuild problems.

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ANNEXES

1. INTRODUCTION

Following a failure of a seventh stage compressor blade in Rolls Royce Gazelle Mk 165C - GA 2033 in a RAN Wessex Helicopter on 3 November 1985, ARL was requested to undertake an investigation into the mode and cause of failure; Reference 1 details the initial communication. Subsequent contacts with both SAMR and DNAE indicated that ARL's role was to include a directive as well as the normal ad hoc investigative function. This departure from the normal investigative role was due in part to problems which had existed with build standards of the engine and to previous compressor blade failures which had occurred in Gazelle engines albeit whilst in service with the Royal Navy. Immediately after the incident Rolls Royce (East Kilbride) offered the services of an Engine Metallurgist to carry out an on-site investigation; this offer was accepted by SAMR and a report of that investigation is given in Reference 2. Details of ARL's actions and progress as previously reported are given in References 3 and 4. This report brings together those actions and attempts to resolve a number of outstanding problems in regard to the blade failure and build configuration of the engine.

2. EARLIER BLADE FAILURES

7th Stage Compressor Blade Root Failure in the Gazelle engine is a known problem and has been well documented by Rolls Royce. The cause of failure has been largely attributed to an "incorrect" assembly of the blade into the compressor disc which allows an excessive clearance between the blade and the disc at the top most fir tree root (or upper land) Figure 1, and the possible resonance of the 7th stage blade, at 1st flap frequency, coincident with a sixth engine order at a compressor speed of between 89-100%. Figure 2 gives the Campbell diagram for the Gazelle 7th stage rotor blades. The interpretation of the methods of assembly of the blades into the disc has been the subject of numerous communications between Rolls Royce, SAMR and HdeH; ARL has provided SAMR with advice on various aspects of this matter (Reference 5) which will not be further discussed here. It is important to realise that the assembly procedures are defined to produce an interference fit between the upper fir tree root land and the compressor Disc. Failure to achieve this fit will allow high levels of vibratory stress to be transmitted to the fir tree root section of the blade rather than concentrated in the aerofoil section. The presence of these high stress levels will eventually lead to blade failure. The failure process can be hastened by stress raisers such as scratches, machining marks, incorrect copper plating or material defects, in the blade fir tree root.

It should be noted that the driving force initiating blade failure had not been identified in earlier investigations; it could have been due to flutter or associated with mechanical or aerodynamic excitations.

3. FAILURE INVESTIGATION

3.1 Initial Investigation

Following the blade failure, the engine was returned to Hawker de Havilland (HdeH) Sydney where a defect investigation was commenced. In the first instance the compressor casing was removed and an inventory of damage undertaken. Having identified a broken blade in the seventh compressor stage a disassembly and rebuild of the first 7 stages of the compressor was carried out to identify any loose blades or blades which could have failed the light gap check. Because of damage to the remaining four stages it was not possible to carry out a satisfactory rebuild procedure on these stages. The process, of necessity, involved stripping and cleaning the PL94/Molykote 106 sealer and PL110 paint from the blades and discs but did not involve the removal of the copper plating from the fir tree roots. Details of this part of the investigation are available in the HdeH defect report Reference 6. ARL observers were present for part of this period but were not directly involved and did not materially contribute to the investigation. A summary of the more important aspects of the rebuild are given in Table 1. Of particular interest are the number of blades which were found to be loose in the disc and those that failed the light check. It should be noted that at this initial stage it was not possible to assess if the blades had always been loose or had been loosened due to the passage of broken blades through the compressor. This aspect is discussed by Rolls Royce in detail in Reference 2 and will be addressed later on under the section on Mechanical Aspects.

3.1.1 Rolls Royce Investigations

Details of the Rolls Royce investigation are given in Reference 2. In brief, Rolls Royce concluded that the blade failure occurred in vibratory fatigue from multiple origins located in axial blade broaching scores exaggerated by copper plating in the second serration root radii on both sides of the blade. It also considered that a top serration gap had existed between the disc and the blade run out (upper land) allowing fatigue stresses to be transmitted to the lower part of the fir tree root. Whilst not disputing that high cycle fatigue was a contributory factor in blade failure and conceding that some evidence does exist for suggesting that some blades were loose in some discs, it cannot be agreed that such categorical statements can be made about the failed blade. It should be noted that only the lower section of the failed blade was available after engine strip down, and at the time of the Rolls Royce investigation neither the PL94/Molykote 106 had been removed from the fir tree root surface nor had the blade root been sectioned. The Rolls Royce conclusions appear in part to be based on inference from previous failures in Gazelle compressors.

3.2 ARL Investigation

The ARL investigation, requiring activity by ARL and other centres, was coordinated by Aero Propulsion Division; it commenced on the completion of the Rolls Royce metallurgist's initial report. A first action was to arrange for Aircraft Materials Division ARL to examine the fracture surface of the broken blade and to carry out a sectioning of the root section. This procedure was adopted so that an independent assessment of the blade failure could be obtained. In addition a number of the "loose" blades still coated with "sealer" and paint were forwarded to the Aircraft Materials Division for assessment of coating condition/depth and blade condition.

Concurrent with the metallurgical examinations of the failed blade, a number of complementary actions by ARL, MRL, Rolls Royce and HdeH were initiated in order to establish comprehensively the cause and mode of blade failure. The total programme encompassed:

a. Metallurgical Aspects
   i. Failed Blade
   ii. Examination of loose blades
   iii. Copper Plating Process

b. Mechanical Aspects
   i. Blade/Disc Design
   ii. Build Procedures
   iii. Engine Vibration Characteristics

4. METALLURGICAL ASPECTS

A metallurgical examination of the failed blade and the associated disc rim was undertaken at ARL whilst investigations of the copper plating process used at HdeH was undertaken at MRL.

4.1 Failed Blade

The only section of the failed blade which was available was that part directly held by the fir tree dovetail of the disc. Visual examination of the fracture surface indicated high cycle vibratory fatigue emanating from both leading and trailing surfaces of the blade root section. As the outer surface of the blade fir tree was extensively coated in cured PL94/Molycote 106, a dry lubricant with an epoxy base, it virtually precluded an examination of the outside surface for any signs of stress concentrators in the blade or its copper plating. A preliminary assessment of the failed blade by Aircraft Materials Division ARL is given in Reference 7 and Annex A. A comparison of the ARL and Rolls Royce findings indicates a dichotomy of views in that ARL state that the fatigue failure was initiated from a microscopic inclusion on the blade/copper plate surface and not from multiple origins located in a single axial stress raising feature (a score on the blade surface) as had been suggested by Rolls Royce. Subsequent sectioning of the failed blade root (Reference 14 and Annex H) confirmed the initial findings of the ARL - Aircraft Materials

Division in that the sectioned blade did not reveal any flaws in the blade surface or the copper plating. However metallographic examination of the surface of the sectioned blade did indicate an unusually large number of inclusions in the blade material. A check on previous blade failures indicates that a large percentage of previous failures were associated with blades forged from the PJ material batch, that is 7PJ when used as seventh stage compressor blades.

Further metallurgical investigations, detailed in Annex H, into the material composition and structure of the failed 7th stage blade indicated that:

a. The blade failure was initiated at a small inclusion in the 7PJ material. Sectioning in the vicinity of the inclusion was unable to locate or identify any defect in the copper plating which could have initiated a fatigue crack as had been surmised by Rolls Royce in Reference 2.

b. The etched macro structure of the failed blade was markedly different to that of other blades including other 7PJ batches, in that there was evidence of a distinctly banded non-homogeneous structure. The complex banded structure or striations of the failed blade, described in detail in Annex H, is an atypical microstructure which may have resulted from anomalous heat treatment. Details of material specifications, manufacture, forging, heat treatment and inspection procedures are given in References 16 and 19. Whilst the materials specification details inspection procedures and sample sizes (typically two blades/500 forgings or "set" - not necessarily a complete material batch) it does not detail consequential/rejection procedures to be used if any of the two blades fail to meet the specifications. In this investigation it must be assumed that the two sample blades taken from the "set" from which the failed blade emanated did not fail the inspection criteria. Notwithstanding this the possibility must exist that other PJ blades from that set could display the same features. As total batch sizes of PJ, AZ etc material are not known it should not be concluded that the whole PJ batch (consisting of possibly many 500 blade sets) is suspect. (It is known, Reference 19, that 3633 blades carrying 7PJ identifier were produced, whilst an unknown number of other compressor blades for other stages was manufactured from the remaining part of the PJ batch). However until more precise data are available from Rolls Royce, the SAMR decision to remove all 7PJ blades from Gazelle compressors currently being built is endorsed. It is believed that the resulting metallurgical structure, of the failed blade, would lead to an increased variability of the material mechanical properties and in particular fatigue strength of the blade, and could be conducive to accelerated failure.

c. A comparison of metallographic sections taken from samples of 7PJ blades and from blades from batch 7AZ shows that there is a significant difference in inclusion size and number between the failed blade batch 7PJ and that of the 7AZ. The 7PJ batch contained a greater number of large inclusions (up to 30 micron) and has a greater number of inclusions overall; the observed increase in size and nature of inclusions would increase the probability of an inclusion initiating a blade failure.

From data presented on batch 7PJ and detailed in ANNEX H it is recommended that Rolls Royce carry out a metallurgical examination, including etching of other Gazelle failed blades and in particular those of batch 7PJ.

4.1.1 Disc rim/blade fir tree root interface

Vibration of a 7th stage compressor blade held loosely in the compressor could, depending on amplitude of vibration and flexibility of blade, be indicated by fret marks or indentations on the compressor rotor disc rim/blade interface, i.e. section x-x in Figure 1. Surface examination at ARL of this area did not indicate any marks on the blade or disc. As the aluminium bronze blade would have been relatively soft in comparison to the stainless steel disc, the lack of marks or indentations should not been used to conclude that the failed blade was not loose in the disc, or a light gap was not present between the blade upper fir tree root land and the disc.

4.2 Examination of Loose Blades

During assembly of the compressor the rotor blades are press-fitted into the disc, light checked and subsequently coated with PL94/Molykote 106 to seal against corrosion and then coated in an Aluminium enamel PL110; the whole assembly is then cured at temperatures up to 200°C. Reference 8 details this process. Notwithstanding the controls used during this complex process, subsequent to engine failure two blades were found loose in the seventh stage, and even more in the last four stages. Table 1 and Reference 6 gives details of strip and rebuild. If it is assumed that the blades were loose from first assembly and not knocked loose (see section 5.2.3) during the failure process or assembled with a light gap then the condition of these blades is of particular significance in that if there had been a gap at the upper fir tree root land then some evidence or indication of incipient cracking could be present in the blade surface. Rolls Royce addressed the degree of blade looseness in Reference 2 by stating that very little contact could have occurred between the disc and the upper land because of the large quantities of PL94/ Molykote 106 and even PL110 paint which were present on the blade upper land.

At the time of the Rolls Royce investigation, Rolls Royce were unable to examine in detail or measure the sealant thickness on the loose blades; photographs of two of the loose blades (12 and 59) taken from the 7th stage compressor disc are given in Figures 3a and 3b. Prior to microscopic examination of the blades the surface distribution and thickness of the PL94/Molykote 106 layer was measured using a "mechanical" surface traversing procedure. Full details of the measurement method are given in Annex G. In summary it was found that a continuous layer of sealant varying in thickness from .01 mm to .05 mm ($^{4}/_{10}$ of 1 thousandth of an inch to 2 thousandths of an inch) was present on both surfaces of the fir tree upper lands of blade No. 12. Due to the complexities of measuring the sealant thickness and distribution, and the need to examine the copper plating of at least one of the loose blades, only one blade was kept for sealant examination. For both blades the sealant was removed using citric acid. Considerable experimentation was required, using a variety of "solvents", before a method was developed to remove the baked PL94/Molykote 106 without affecting the copper plating. The stripping procedure used by Rolls Royce in Reference 2, sulphuric acid, would certainly have damaged the sub sealant copper plating. Subsequent micrographic examination of the copper plating of both blades 12 and 59 from the seventh stage did not reveal any defects in the copper plating, eg nodules, nor was there any evidence of incipient cracking in the copper plating or blade base material. The direct corollary of the finite and continuous layer of sealant is that a light gap, albeit very small, must have been present during the initial build of the compressor disc; the implications of a light gap on stresses in the blade root and fatigue life of the blade are addressed in Section 5.1 on Blade/Disc Design.

4.3 Copper Plating Process

Visual and microscopic examination of a number of blades taken from the 7th to 11th stage Gazelle compressor blading by Rolls Royce (Reference 2) indicated that the copper plating on a number of the blades was poor, with numerous copper nodules and re-entrant cracks being visible, see for example Figures 7 and 11 - 14 of Reference 2. Previous investigation on Royal Navy Gazelle seventh stage blade failures, Reference 9, has indicated that cracks in the base blade material can develop from re-entrant areas in copper plating, and can eventually result in blade failure. As an overall check on the procedures used by HdeH in the copper plating process, samples of plating solution and copper anode were taken from the HdeH plating bath, together with inspection reports for its condition over the last 12 months. These have been examined at MRL, who also investigated the reverse cycle plating process, as specified in Reference 10, to assess its suitability as a method for generating smooth plated surfaces. Preliminary and final MRL Reports are enclosed at Annex B and I respectively. In general the MRL investigation confirmed the Rolls Royce findings in that for the blades removed from the failed compressor, the copper plating was found to be rough and nodular. At high magnifications it was clear that some nodules had formed into folds in the surface and in one particular case formed a crack. Poor adhesion of the copper plating was also observed such that in areas the copper plating could be peeled off the surface of the base metal. Contrary to the above observations, some tests on specimen blades, plated by HdeH under controlled conditions at the request of ARL as a trial of the process, indicated that, with the exception of one blade, with limited nodular growth, good plating can be achieved. Following this preliminary examination MRL conducted a trial of the copper plating procedure used by HdeH and as described in the specification of Reference 10. The MRL results indicated that whilst the copper layer deposited was fine grained and free from nodules, it lacked any substantial depth. Modifications to the periodicity of the reverse cycle plating times increased the thickness of the layer without detriment to the quality of copper plating.

Contacts between MRL and HdeH regarding these tests revealed that there were a number of serious problems in the HdeH plating/metal finishing area, Annex I gives full details of the MRL investigations and their consequent recommendations. HdeH were not plating to their own specification (Reference 10), and due to the size of the plating bath and the sensitivity of the indicating instrumentation HdeH had little control over the current density being applied during the plating process. It was also found that on occasions the plating solution was not at the recommended strength. In addition to the problems with plating it was observed that the copper plate stripping procedures were not being carried out in accordance with the HdeH specification. Conversely the recommended Rolls Royce recommended stripping method, whilst adequate for removing copper, left an oxide deposit on the aluminium bronze base material. Poor cleaning of the blades subsequent to stripping, it is believed, has been partially responsible for the lack of adhesion of the copper plating. Modifications to the RR stripping and cleaning process to incorporate a cyanide dip has resolved this problem.

In the more critical area of nodule formation during copper plating, discussions between MRL and HdeH have resulted in a modified specification for copper plating being defined. This new procedure involves a more accurate control of the overall plating process, including new instrumentation, and hence more control over current plating density. The procedure has been investigated by MRL and trialled at HdeH. The results have shown that a modified reverse cycle process based on a 35 second plating, 7 second deplating cycle would give an adequate deposition of copper. However as the plating bath ages, due to oxidation of cyanide, the carbonate level builds up and it is imperative that cyanide is added on a regular basis. Under these tighter controls fine grained and smooth copper deposits could be produced provided a low current density of the order of 2.5 amps/decameter was used and the carbonate levels kept below 100 grams/litre.

As part of the investigation into assembly/build methods HdeH were also requested to trial methods for selectively copper plating the upper lands of a number of seventh stage blades. It was proposed that by this means, and provided insertion loads were not exceeded, that a more reliable method of providing an interference fit could be obtained. This aspect of the investigation, including the effect of interference fits on disc/blade stresses, are given in Section 5.2.2.

5. MECHANICAL ASPECTS

In this section of the report an assessment is made not only of Gazelle blade design methods and engine build procedures but also of the aerodynamic and vibrational characteristics of the engine as a whole.

5.1 Blade/Disc Design

The blade/disc design-assembly procedures for the Gazelle compressors are unusual in that in contrast to most other compressors the blades must be inserted into the disc with a given preload and then checked to ensure that the upper land of the blade fir tree root is bedded into the rim of the disc using a light check. Reference 8 gives full details of this complex process. The rationale for this procedure is that, as well as locating the blade in the disc prior to locking and machining, it is required to overcome a deficiency in the original Napier design which leads to the requirement of an interference fit at the rim to prevent excessive vibratory stresses being experienced at the upper fir tree root section which would otherwise result in fatigue failure of the blade. A stress analysis of blade/disc interface has been carried out at ARL.

The results of the ARL stress analysis are given in Annex J and Reference 21. The analysis which was carried out using a PAFEC finite element program investigated stress levels in the blade fir tree root especially at section y-z-y of Figure 1 when there was a gap and no gap at positions x-x. The effects on stress levels of:

- Centrifugal loads
- Gas bending loads
- Friction (at fir tree contact surfaces), and
- Vibration loads as generated by a $\pm$ 1mm displacement at the blade tip were considered.

In the analysis the reference steady state load case was taken to be that at a maximum engine speed of 19900 RPM. At this condition a nominal stress at section y-z-y of 84 MPa (ie 5.44 tsi) direct stress and bending stress due to fir tree restraint, as opposed to gas bending and vibration loads, was calculated. For the same restraints a peak-concentrated-stress of 343 MPa (22.2 tsi) is generated in the radius of the fir tree serration at y. The theoretical stress concentration factor of over 4 is consistent with the geometry of the fir tree serration. Under these loading conditions a gap or extension of the blade at x-x of 9 microns (.00035 inch) was produced. The effects of typical values of friction and gas bending increased the peak stresses by only 8% and 12% respectively. To determine the effects of blade vibration on fir tree root stresses at y, the theoretical peak concentrated stresses due to an arbitary 2.0 mm peak to peak blade tip displacement were compared for different bending restraint cases. For simplification two restraint cases are presented here:

A. clearance at x-x such that bending of the blade (displacement of the tip) does not cause contact at either of the upper land faces x-x or x^1-x^1, and

B. the condition of alternate zero gap at x-x and clearance at x^1-x^1 as the blade is subject to bending back and forth due to vibrations.

C. an additional case of zero gap or interference at both x-x and x^1-x^1 surfaces is considered in Annex J and Reference 21.

The effects of bending or blade vibration on peak stress, in cases A and B above, were assessed in two ways:

a. by superposition of separately calculated centrifugal and bending stresses, and

b. by direct simulation/computation using the PAFEC program.

The latter case, whilst more representative of the physical situation, involves a number of assumptions regarding root fixing, friction and contact faces. Details of both methods are discussed in Annex J and Reference 21.

In summary it can be shown that the combined peak stresses, as predicted by the direct simulation procedure, gives values for cases A and B of 594 MPa (38.5 tsi) and 486 MPa (31.5 tsi) respectively. The condition assumed for case B is for minimal interference at the upper fir tree lands, consistent with just passing the light gap check. Any increased interference would certainly reduce the estimated value of 486 MPa. The minimum difference in peak stress which can be expected for blades with and without a light gap is 108 MPa, and whilst this level is smaller than had at first been expected, the 22% change in concentrated stress is indicative of a larger percentage change in nominal stress levels; the consequent effect on blade fatigue life is critically dependent on the position on the S/N (Stress/No of cycles) Fatigue Life Curve for the blade material, and the actual blade tip deflection (taken as $\pm$ 1 mm in this analysis). A smaller deflection would necessarily mean lower peak stresses, and hence greater blade fatigue life.

The PAFEC direct simulation results also indicate that to maintain a gap at either shoulder (x-x, x^1-x^1) during vibration/bending of the blade tip to $\pm$ 1 mm then a minimum gap of 25 microns (.001 inch) must exist at static conditions, depending on blade dynamic response and friction effects. Any clearance above this value will not affect the peak stress levels in the blade fir tree root, as relaxation of stresses due to interference or contact at the shoulder could not occur.

Interpretation of these results in terms of estimates of blade fatigue life at the blade root fixing is complex, especially in light of the lack of specific S/N data on the HIDURAX 1/12A Aluminium Bronze blade material, and knowledge of actual blade tip deflections during vibration. The Rolls Royce (Napier and Sons) design criterion was based on a direct centrifugal stress level equivalent to 18.75% of the .1% proof stress. This limit would presumably have been derived from photo elastic analyses and would have been assessed as including sufficient margins for "service" factors of blade vibration.

As mentioned above little data were available to assess the fatigue life of the blade fir tree root and its fixture. Fatigue life based on centrifugal loads alone (0-MAX RPM-0) is likely to be greater than 10^7 cycles, more than adequate for low cycle loading. However blade resonances at blade frequencies of (1750-1950 Hz) equivalent to a 6th engine order forcing function coincident with engine speeds between 89 and 100% (Figure 2) would obviously reduce blade fatigue life to very short times if the vibration was of sufficient amplitude. The effect of blade root fixing, gap or no gap at the upper land will also influence the fatigue life.

The results of the stress analyses for ± 1mm blade tip displacement indicate that case B (no clearance) would have a greater cyclic (fatigue) life than that for case A in which a gap of at least 4 microns (.00016 inches) exists at the upper land. The reduction in fatigue life due to the gap cannot presently be estimated, however if the blade material (which typically does not show a fatigue limit) was operating on a relatively flat section of the S/N curve then the 22% change in stress levels could cause a considerable reduction in fatigue life. The addition of stress concentrators in the fir tree root, either as cracks in the copper plating or inclusions in the base metal will also generate higher local peak stress, again reducing blade fatigue life, although of diminishing fatigue life impact. It can therefore be concluded that the existence of a gap at the blade fir tree root upper land in excess of 25 microns (.001 in) (of the order of the limit of the light check) would result in higher combined peak stresses in the blade and could impose severe limits on the blade fatigue life.

The above result is in contradiction to the results derived by Rolls Royce in experimental tests, Reference 22, in which Gazelle compressor blades with varying gaps at the blade fir tree root upper land were vibrated until failure cocurred. These tests indicated that blade failure would only occur in the blade fir tree root if the upper land gap was greater than 75 microns (.003 inch). However the ARL results confirm, in part, the Rolls Royce assembly procedures which are designed to eliminate any gap at the blade fir tree root upper land: current inspection procedures would certainly not tolerate a 75 micron or .003 inch gap at either shoulder x-x or x^1-x^1.

5.2 Build Procedures

As mentioned earlier Reference 8 details blade/disc build methods as a series of steps involving "loaded insertions", copper plating and light checks as a means of achieving an interference fit. An examination of the insertion processes which are both tiresome and complex indicates that it is possible for blades to be inserted into the disc with very small preloads, ie loose, and yet show no indication of a gap at the upper land of the fir tree root, provided the blade/disc root profiles have close tolerances. Conversely insertions with excessively high preloads cannot guarantee a zero light gap fitment, and on many occasions may produce a light gap at the upper land. As such the build procedure including copper plating does not necessarily ensure a correct fit. Great reliance must be placed, at present, on the light check procedure; this aspect of the process has been semi-automated by HdeH by use of a times 20 shadowgraph enabling more consistent results to be obtained.

5.2.1 Light Check

A typical example of the shadowgraph is given in Figure 4. It is to be noted that neither this check (nor the RR visual check) can ensure that contact is present and maintained along the complete surfaces of the upper land. Dirt, oil or hair can give a false indication. ARL, using a simulated fir tree root/disc gauge with gaps ranging from ½ - 3 thousandth of an inch, checked the sensitivity of the shadowgraph process. Results of these tests given in Figure 5 show that .0005 of an inch gap can be relatively clearly indicated. However minor movements or obstacles in the light path would impair this reading and imply that there was no gap at the interface. These results indicate that the light check procedure, whilst instituted by Rolls Royce as a simple method for assessing blade to disc contact, is by no means a foolproof and failsafe procedure, and should be treated with circumspection.

5.2.2 Light Check Alternative

Numerous alternatives to the light check have been proposed; these range from measuring vibrational characteristics and generating holographic images of the blade whilst fitted to the disc to assess the "looseness" of fit, to selectively copper plating the upper lands of the blade or "gluing" the blades into the disc.

(a) Use of Vibrational Characteristics

Measurements at ARL, Annex C, of vibrational characteristics of the seventh stage compressor blade have shown first flap frequency variations of up to 10% for blades as assembled into the disc. These results confirm the Rolls Royce findings of Reference 11 which indicated natural frequency of blades varying from 1734 - 1873 Hz for blades fitted with varying insertion loads and interference fits.

An initial study of blade vibrational characteristics and its mounting constraints was carried out at ARL Annex D. This study indicated that, notwithstanding the large range in natural frequencies for blades supported independently, a general property of blade fixture was that the blade frequency decreased by up to 80 hertz as a light gap at the upper land was introduced.

On the basis of these initial findings an investigation was undertaken to develop a blade build checking procedure, ultimately for use on the shop floor, which could discriminate between blades which were or were not directly supported at the blade fir tree upper root land. Full details of the investigation and procedures as they were developed are given in Reference 25. In summary the procedures, which have been implemented on three complete disc assemblies with some degree of success, involve the following steps:

i Marked (numbered) uncoppered blades are inserted, one at a time, into a reference fixture designed to enable fully supported - no light gap - blade frequencies to be measured.

ii. Having identified each blade's individual natural frequency the blades are assembled into the compressor disc as per the procedures given in Reference 8. In this process the blades are inserted within given preloads, copper plated if necessary and finally light checked.

iii. The frequency of each of the individually numbered blades is rechecked, whilst assembled in the disc and its value compared with that determined in "i" above.

iv. Deviations in frequency levels (i - iii) above specified limits would be used as a rejection criterion for re-assessment of a light gap at the blade fir tree root upper land.

Complete results for the three discs assembled by HdeH and tested by ARL are given in Reference 25. Typical data for one of the 7th stage discs is given in Figure 6 and Table 2. In summary, the results show that contrary to original expectations there was a broad band of frequency differences (FD) (see iv. above) and that a fixed or specific (80 Hz) rejection criterion, as had originally been surmised, could not be utilized. The original hypothesis for a fixed frequency difference was based on tests in which the gap at the upper land was created by removing part of the disc rim, giving an obvious and consistent gap: no account was made at the time for possible partial contacts in this area. The data in Table 2 indicate frequency differences of between -1 to -105 Hz. With such a large range of FD's it can be argued that all but the zero frequency difference blades had been installed in the disc with at least minor light gaps or some degree of freedom to move at the interface of the blade fir tree root upper land and the disc. It is to be noted that it was not possible to correlate the respective values of FD with the blade insertion pressures ($r = .02$ for the blades tested). Examination of blades with FD's of magnitudes greater than 80-100 Hz (from zero) using the shadow graph method indicated that in all cases contact was present for at least the outer 50% of the land as was required by the assembly procedures of Reference 8 - see Figure 4. Thus removal and refitment of any of these blades would appear to be futile. However, as indicated in Section 5.2.1 dirt, hair etc could obscure light transmission at this interface, and reassembly with increased copper plating may enable a more "correct fit" to be achieved, provided insertion loads are not exceeded. To further investigate the hypothesis that the blades were only partly held at the fir tree root upper land interface a number of supplementary tests were carried out. Preliminary work at ARL on holographic interferometry, see (b) below -"Static Stiffness Measurement", had suggested that movements/deflections of the blade root due to varying gaps could be assessed and correlated with the number of interference fringes. To support this contention, that a number of blades, although passing the light check, were not firmly supported, holographic - deflected/undeflected - images of all the blades were obtained. These results are summarised in Table 2 in terms of number of fringes per blade and can be compared with their respective blade frequency differences. It can be seen that quantitatively there is general agreement between the number of fringes observed and the magnitude of the frequency differences with the correlation coefficient (r) for these data points being greater than .8. Whilst these results are not wholly conclusive in that there are a few contentious points in the data they do support the supposition that a large number of the blades are not held in the disc as firmly as would be implied from the light gap check. However, as stated above, there does not appear to be any real means for overcoming this problem other than perhaps fixing the blades in the disc with adhesive or by "welding". As a more absolute check on the effects of root fixings on the measured frequency differences a number of blades (5, 7, 11, 27, 32, 56) were removed from the disc and retested for resonant frequencies after a positive albeit artifical light gap had been created at the blade/disc interface by removing copper plating from the blade fir tree root upper land. By this method the blade would obviously be unsupported. The results of these tests are also given in Table 2. The limited data indicate that the frequencies for the blades which were nominally "loose" only increased by a small amount whilst those that were originally "tight" showed a significant increase. From these tests it can be postulated that blades with frequency differences greater than 75 Hz are not located rigidly in the disc even though they satisfactorily pass the light test: these blades consequently warrant further inspection. A further check on blade root fixing restraints was achieved by observing the effect of heat on installed blades and the respective change in frequency differences. The criterion used, as established in (d) below, was that only a small change in FD would occur, with heating, for blades installed with a light gap whilst for those which were initially "tight" a much greater change in FD would be measured. Tests were carried out on four blades, two of which were thought to have a minor light gap (1 and 68) and two more firmly held (8 and 61). The results are given in Table 2 indicating that for blades 1 and 68 only a small increase in FD resulted (33 and 23 Hz) on heating whilst for blades 8 and 61 the change was much greater (46 and 63 Hz). These results add further evidence to the contention that ranges of blade constraints are present in the assembled disc which are not able to be identified by the current light check procedure. In summary, and notwithstanding the fact that a specific and absolute frequency difference between "tight" and "loose" blades could not be discerned, it is believed that both the vibration and holographic interferometry procedures are capable of being used (FD $<$ -75 Hz or number of fringes greater than five) to discriminate between blades which are not rigidly/firmly assembled into the disc. However, both tests are very complex and require operator skills which would not normally be found on the shop floor. ARL personnel had numerous difficulties in interpreting etched numbers on the blade platforms and consequently in obtaining consistent data for all blades in the disc; for example, data are only presented for 52 blades out of a disc of 61 blades. In addition, it is not possible to determine if the degree of fit which would be achieved by using the above criteria is warranted; comment by Rolls Royce should be solicited.

(b) Static Stiffness Measurement

The variation in ("loose/tight") frequencies measured in "a" above are a direct result of the different mounting constraints on the blade fir tree root within the disc, and the consequent deflection/vibration of the blade and its platform. On this basis it can, with reasonable confidence, be hypothesized that if a blade is installed with a gap at the blade fir tree root upper land as against a blade which is more rigidly held at the blade platform then the former will deflect more when it is loaded. Measurement of this deflection, albeit very small, could be used to determine the fit of the blade in the disc. Investigatory work carried out by the Structures Division at ARL has used Laser Holography to indicate the varying degrees of deflection of the blade and hence fit (or light gap) of the blade in the disc. Annex K and Reference 24 describe the procedures as developed. In the most simplistic form the procedure involves the construction of an interferometric holographic image of the deflected-undeflected blade. A movement of a deflected, "loose", blade generates a series of interference patterns or fringes, whilst a fixed blade (one without a light gap) shows little if any fringe effect. Figure 7 gives a comparison of blades which appear to be assembled with and without a light gap. This particular holographic technique is still in its formative stages and requires development if the fringe patterns are to be correlated with the size of gap at the blade fir tree root upper land interface. However it is believed that the method including the use of pulsed lasers has considerable potential as an investigative tool and could possibly be used as an in situ, compressor blade/disc, inspection device as well as for assembly purposes on the shop floor.

(c) Selective Plating

Selectively plating the upper fir tree lands of the seventh blade row has been investigated by HdeH in response to an ERF (NBE 077 DIR RAN 1807 Issue No. 22) but some difficulties have been experienced in providing an adequate mask at the lower sections of the blade to prevent copper deposition on the lower fir tree root areas. HdeH in Reference 20 indicated that trials had been carried out with wax and latex as a maskant. Both were unsuccessful. Following consultations with MRL, HdeH suggested that an alternative procedure of over plating with subsequent chemical strip back may offer some merit. At present this proposal is not being pursued due to the lack of control in estimating the resultant copper layer.

Complementary to the HdeH trials ARL has studied the effects of interference fits at the upper land on stresses in the blade root and disc rim. A summary of these results are given in Annex J and Reference 21 where it is shown that high stresses are present in the blade root section. Excessive interference due to poor selective plating could overstress the blade if insertion loads are not controlled. This conclusion is supported in part by Rolls Royce in Reference 12 where they state "No objection to selective plating as long as insertion load limits maintained". Notwithstanding the above comments it may be still difficult to judge if the light gap has been eliminated and an interference fit exists. In a related exercise ARL has investigated the effects of a sequence of copper plating and rolling on the profile of the fir tree root. This investigation was carried out to confirm comments made in Reference 13 which suggested that coppered blades once rolled showed a deflection at the top face/land ranging from .001 - .002 inch depending on the number of times it had been rolled. Hence the more the blade has been rolled the less likely it would be able to be assembled with an interference fit at the upper land, even though the insertion loads were high. The ARL tests, Annex E, on a limited number of blades, whilst not conclusive tend to confirm the Rolls Royce findings. On this basis it is recommended that fir tree root rolling should be kept to a minimum. It should also be realised that a high insertion load does not necessarily imply an interference fit at the critical top land.

(d) Use of Adhesives

As long as it is impossible to ensure an interference fit by means of a physical (light) check, other more radical solutions must be considered. One such solution is the use of high temperature, high compressive "glues" such as Araldite or Loctite to "cement" the two surfaces together. It is estimated that the maximum temperatures in the region of the seventh compressor stage during normal engine operations are of the order of 140-170° (depending upon engine speed) and should be within the range of modern high temperature adhesives. To test this theory a section of disc with varying gaps at the blade/disc interface was used to investigate the strengths of a range of high temperature "glues". Following discussions with ARL staff specimen disc sections were impregnated with a selection of adhesives. These were:

i ESP 108 - Permabond single part epoxy.

ii. Epicote 828 or Ciba-Geigy GY 250 resin/Ciba-Geigy HY 217 hardener - (High Temperature Epoxy with a curing time in excess of 25 hrs), and

iii. Cold curing galvanising paint.

The test specimens were instrumented with thermocouples and heated with hot air to a temperature in the region of 60°C - 140°C depending on the glue used. The effectiveness of the adhesives in maintaining a bond between the blade and disc was assessed by periodically monitoring the natural frequency of the blades (in the disc) as the heat was applied. A softening or breakdown in the adhesive bond would be accompanied by a reduction in blade frequency, consistent with the results described in "a" for blade fixtures with and without a light gap. As a control for these tests two specimens impregnated with PL94 and Molykote 106 were also tested. Both these sealants are cured at temperatures of up to 150°C and as they had on occasions been found at the blade disc interface they may have acted as a vibration damper or inhibitor, thus alleviating the effects of a light gap. A further control to these tests was to investigate the effect of heat on blade resonant frequencies when blades were installed in a disc with and without a light gap, and when one was held rigidly at its base.

A summary of the test results are given in Table 3. Interpretation of these results are complicated by the fact that both 6th and 7th stage blades were used and have different fundamental frequencies. However the blade fixtures are similar in both cases, and the resonant frequency of the longer 6th stage blades is known to be less but of similar characteristics. Hence it is believed that trends and thus indicative conclusions can be obtained provided differences or changes in natural frequency (with application of heat) are used as against absolute values. Using these qualifications on the data for heating the blades to 140°C it can be inferred that:

- a decrease in blade frequency by up to 20 hertz (due to expansion of blade length) occurs as the blade is heated,
- blades held in disc without support of glues exhibit frequency decrement of the order of 60 hertz, of which, up to 20 hertz could be attributed to lengthening of the blades,
- blades held in the disc using, PL94, Molykote 106, ESP108 and galvanising paint, albeit with "large" light gaps, showed a very rapid fall off in natural frequency, at temperatures of 60 - 80°C, indicating that the "glue" joint had failed at relatively low temperature, and
- blades held in the disc using the high temperature epoxy exhibited a significantly different behaviour in that whilst there was a decrease in the natural frequency of the blade it was much less marked than that for the alternative glues used. In fact the measured frequencies were part way between those for the blade held rigidly at its base, and blades "freely but correctly" assembled into the disc, indicating that the epoxy was, to a degree, providing a dampener, and compensating for the effects of the known light gap.

From these limited tests and initial conclusions, it is believed that high temperature epoxy adhesives could well provide a means for overcoming the deficiencies of the light gap; however, these glues are difficult to use and would require a combination of vacuum impregnation and/or paradoxically wet assembly with the disc, once minimum light checks had been ascertained, to be satisfactorily used in service. The most appropriate method for using a high temperature adhesive such as CIBA GEIGY GY250/HY217 is as a substitute for the PL94/Molykote 106 dry lubricant-sealer, provided its use in service is satisfactory to both Rolls Royce and RAN (DNAE/SAMR) from an airworthiness standpoint. The use of high temperature "glues" should not preclude normal overhaul/repair of engines - compressors as the adhesives can be softened by heating to temperatures in excess of 250°C or stripped using, ARDROX 26HT, EPOSOLVE 299 or DECAP provided the strippers do not react or modify the base disc or blade material. Further investigation into the above proposal should be undertaken.

Stemming from the tests carried out to determine a light check alternative, and especially from the results for heating a blade whilst fixed in the disc, either with an adhesive or simply in accordance with current build procedures, an alternative installed checking procedure can be postulated. This method is based on the result that the frequency difference for "loose" blades (ie those with a light gap) decreases by the order of 20-30 Hz on heating whilst the frequency change of "tight blades" would be of the order of 45 or greater. However, (again) due to the uncertainty of the root fixing (partially loose-tight) there could be an overlap in the frequency differences. The advantages of this method is that blades do not have to be numbered individually, its major disadvantage is in the heating of the blades and disc and in determining the frequency difference. Further consideration should be given to developing this method as a final go-no-go checking procedure.

5.2.3 "Loose Blades"

As mentioned in Section 4.2 an examination of blade fit during the HdeH defect investigation, Reference 6, indicated that there was a large number of loose blades in the seventh to eleventh stages. It had been suggested that as the debris from the seventh and eighth stages passed through the compressor, an increasing amount of damage or loosening of blades would have occurred.

This hypothesis is discounted in part by Rolls Royce in Reference 2 where comments were made of the large surface layers of PL94/Molykote 106 sealer and even some PL110 paint present on the fir tree root upper land. These extensive regions of paint and sealer were confirmed by ARL (Section 4.2) in the course of metallurgical examination of the loose blades. An assessment of the thickness of the sealant layer was made on blade No 12 using a mechanical traversing method at the Department of Defence's Ammunition Factory Footscray. Full details are given in Annex G. In brief a continuous sealant layer varying in thickness from .01 mm to .05 mm was measured on both surfaces of the fir tree blade root upper land, indicating that for this blade at least it must have been assembled with a light gap at the upper blade fir tree land surfaces. Separate tests at ARL were carried out to test the impact/loose blade hypothesis. A sixth stage compressor disc (steel) assembled with aluminium bronze blades with 2 lobes per fir tree root as in the seventh stage was progressively impacted. The tests were carried out for a range of loads and for blades with and without a light gap. In the testing some blades were cracked but in no case was a blade loosened or light gap created or closed. Details of the tests are given in Annex F. The ARL results have been supported by unreported tests carried out by Rolls Royce and by their engineer's memory, Reference 12 which states "no recall of blades being knocked "slack" in disc as a result of blade failures elsewhere in compressor pack".

Whilst undoubtedly there is some concern about blades being found loose in the disc subsequent to the compressor failure, and recognising that the ARL impact tests (Annex F) to check on the hypothesis that loosening occurred during failure were not statistically significant, it should be noted that loose blades do not necessarily imply high blade stress levels. As mentioned in Section 5.2, on insertion loads, a compressor could be built without a light gap yet assembled with only minimal insertion loads. The major criterion for the build standard of Gazelle compressor is that the blades should be fully supported at the blade fir tree root upper land ie there should be no light gap at this interface. Notwithstanding the above comments, the conclusion must be drawn that assembly with loose blades ie those without a preload did occur. Every effort should be made to improve the build procedures and prevent its reoccurrence.

5.2.4 Resume on Build Procedure

From the tests carried out during this investigation and the evidence examined by ARL it must be concluded that on occasions the build procedures for the Gazelle compressor were not implemented to the desired standards. It is clear from the measurements made on the sealant thickness of blade 12, and the impact tests on the blades, that this particular blade was assembled into the compressor disc with a light gap at the blade fir tree root upper land, and could even have been loose in the disc at the same time. In addition, photographs presented by Rolls Royce in Figures 15 and 16 of Reference 2 clearly indicate that a continuous layer of dry film lubricant was present on at least two blades of the tenth stage indicating that a light gap must have been present at the upper blade-land interface. It is recognised that the Gazelle compressor build procedures demand a considerable degree of concentration for extended periods; this is compounded in the case of the RAN Gazelle as current overhaul instructions require all 11 compressor stages to be assembled to the same light check criteria. Advice from Rolls Royce, References 17 and 18, and interpretation of Royal Navy overhaul procedures indicates that only stages 7 and 8 of the compressor are required to be assembled using the light check method. It must therefore be assumed that the blade/disc design deficiency is only manifest in these two middle stages. Because of the level of effort required in this checking process, and with the added complexities of the proposed vibrational check procedures detailed in Section 5.2.2, it is considered that maximum effort should be applied to the most critical areas, ie the 7th and 8th stages.

5.3 Engine Vibrational Characteristics

As detailed in Section 2.0 earlier seventh stage compressor blade failures had been attributed to high cycle fatigue thought to be a result of incorrect blade assembly, material defect and an engine generated vibration associated either with blade flutter or a resonance, the latter being a result of a forcing frequency coincident with first flap mode of vibration of the blade. Rolls Royce were approached regarding flutter boundaries for the Gazelle engine/compressor but due to the age and ancestory of the engine, (it was designed by Napier Aero Engines in the early 1950's), very little design information was available; analysis of this data is given in Section 5.3.2. Evidence for the latter mode of failure, blade resonance, is given in the Campbell diagram, Figure 2, for the seventh stage where first blade flap resonance occurs at sixth engine order in a compressor speed range of 89-100% N_1, and by comments of Reference 12 which state that "within the Gazelle engine there are 6 struts in the inlet air intake casing and 6 outlets in the main support plate to the combustor and these tend to produce a strong forcing influence through the compressor". Whilst not disagreeing with this comment it does appear unlikely, due to the location of the seventh stage with respect to the inlet and outlet section of the compressor, that a sixth order so generated could have a large effect on the blade unless there was a strong aerodynamic or acoustic coupling within the engine. To investigate the possibility of a sixth order engine frequency being present a vibration survey of a RAN Gazelle engine was carried out over a range of operating speeds and inlet guide vane angle settings and hence bleed valve schedules. A detailed report on the vibration survey is given in Reference 15. The results in general indicated that a significant sixth engine order was present but only at low "g" levels. Figure 8 gives a typical survey. Further tests show that the magnitude of the vibration is relatively insensitive to variable inlet guide vane angle. From the level of the vibration it is doubtful if blade failure could have been initiated by a mechanical excitation. The remaining sources of excitation as mentioned above are aerodynamic coupling or blade flutter. The possibility of induced vibrations from bleed valve slots located in the sixth stage stator row has been discounted as the bleed slot/hole-blade number is not a multiple or sub multiple of 6, and the fact that the bleed valve is nominally closed at speeds above 85% N_1 which is below the critical speed range for 1st flap resonance as indicated in Figure 2.

5.3.1 VIGV and Bleed Valve Settings

In the course of setting up the Gazelle engine, surge margin checks are regularly carried out. A rescheduling of the variable inlet guide vane (VIGV) system is permitted to give the required surge margin provided engine speed and exhaust gas temperature limits are not exceeded. It should be noted that many engines are very susceptible to variations in blade geometry as the non standard flow conditions can initiate blade flutter. From tests carried out at Rolls Royce Reference 11 where VIGV schedule was grossly changed, only small variations in blade stress levels were observed. Notwithstanding these comments there was still a need to examine blade flutter boundaries and their relationship to VIGV (Bleed Valve) settings. The operation and setting of these components on engine GA-2033 has been checked by HdeH under an ERF: both items were found to be within the specified overhaul manual limits.

5.3.2 Blade Flutter Boundaries

As mentioned earlier blade flutter can impose serious limitations on engine/compressor operations. These limitations can be greatly increased if variable geometry is used in the compressor stator rows. As the Gazelle is fitted with variable inlet guide vanes (VIGV) unscheduled variations of the VIGVs could impose serious vibration loads on the compressor blades due to self induced blade flutter. Under these conditions blade failure can occur in the course of minutes, especially if there is a misscheduling of the VIGV system due to incorrect setting up during initial build. This was not the case in Gazelle 165C-GA2033, however the possibility did exist that the 7th stage blades could be flutter prone at normal operating conditions. Whilst both the Rolls Royce and ARL tests, References 11 and 15 respectively, did not indicate the presence of blade flutter, (the compressor was not specifically instrumented to indicate its presence) there was a need to assess the blade flutter boundaries for the 7th stage compressor blades. Following requests to Rolls Royce, details of the flutter boundaries of the Gazelle 7th stage compressor blades were sent to ARL. These boundaries are given in Figure 9 in terms of the engine operating line with respect to the 7th stage cascade choke line and the stall line or twice minimum drag envelope. This presentation is typical of the procedures used in the late 1950's to assess flutter boundaries. It owes its development in part to the work of Carter, Reference 23, in which the boundaries are related to the cascade maximum and critical Mach Numbers. Figure 10 defines these boundaries in terms of flutter free and flutter prone areas. As can be seen from Figures 9 and 10, the nominal operating line of the Gazelle engine (for the 7th stage) is well within the flutter free boundary for all engine speeds, even when the compressor as a unit is choked. From this type of analysis it is not possible to determine the effects of misscheduling the VIGVs on blade flows and consequently blade flutter, however effects of changes to VIGVs would be more marked in the first and second stages. The fact that the Rolls Royce and ARL tests of References 11 and 15 which carried out experiments with gross misscheduling of the VIGVs did not overtly encounter flutter can be indicative of the fact that the occurence of flutter is not a significant problem for the 7th stage compressor row, and maybe for the whole compressor. It should be noted that the flutter assessment techniques used for the Gazelle are not representative of current aero engine practice; the problem is much more complex than analysis by simple cascade theory. However due to the age of the engine, and lack of specific component data it is not possible, nor in this case warranted to establish the boundaries more accurately.

6. CONCLUSIONS AND RECOMMENDATIONS

Following the failure of a seventh stage compressor blade in Rolls Royce Gazelle engine MK 165C - GA2033, a detailed investigation has been carried out into both the metallurgical and mechanical aspects of the mode and cause of failure. In particular it was concluded that:

- The compressor blade failed due to high cycle fatigue initiated at a minor discontinuity (inclusion) in the blade material, and not at a crack or score in the blade fir tree root copper plating as had been surmised by Rolls Royce.
- The failed blade exhibited an atypical microstructure: this could have reduced the fatigue life of the blade.
- The 7PJ material batch from which the failed blade was manufactured exhibited an unusually large number of inclusions in comparison to other blade batches.
- One blade in the failed 7th stage disc and 2 blades in the 10th stage, as indicated by layers of ingressed sealant, were assembled with a light gap at the blade fir tree root upper land.
- No evidence exists to indicate that the failed blade was incorrectly assembled into the disc.
- The copper plating on a number of compressor blades in Gazelle engine showed signs of nodular growth and incipient cracking. In the case of the failed blade there was no evidence that plating defects were a cause of the failure.
- The Hawker de Havilland plating, stripping and cleaning procedures, for processing Gazelle compressor blades, were not being carried out to specification. This was most evident in the area of plating current density and formation of carbonates in the plating bath, that is ageing of the bath.
- The design procedures of the 7th and 8th stage compressor blade/disc assemblies requires "unusual" build methods to minimise stress levels in the blade fir tree roots.
- The shadowgraph modification designed by HdeH is a major advance on the build procedures laid down (by Rolls Royce for Stages 7 and 8) in terms of operator repeatability but it is not fail safe in ensuring an interference fit: the presence of oil, dirt or only partial contact can be sufficient to allow a faulty blade fit to be accepted by the operator and inspector.
- The peak stresses in the region of the upper serration of the blade fir tree root, of a correctly assembled blade/disc, are of the order of 486 MPa (31.5 tsi). These stresses can be increased by up to 22% that is to 594 MPa (38.5 tsi) if a gap greater than 4 microns (.00012 in) exists at the blade fir tree root upper land. This gap is far less than the 75 micron (.003 in) gap indicated by Rolls Royce experiments for failure to occur in the blade fir tree root section. It is however much more in line with the resolution and requirements of the light gap check.

● Due to lack of fatigue data on compressor blade material no estimates can presently be made on overall fatigue life, however it must be stated that the blade stresses are already high even for a correctly assembled blade. The 22% increase in stress would seriously reduce blade fatigue life especially if it were on the flat section of the S/N curve: it would make the blade very susceptible to even low levels of vibration.

● More positive methods for assembling the blade into the disc are required, noting that high preloads cannot ensure assembly without a light gap, and that repeated rolling of blade fir tree roots profiles may distort the fir tree profile such that a light gap is inevitable on assembly.

● A number of methods for improving the blade assembly procedures were investigated, these included:

- Selective copper plating of fir tree roots,
- "Gluing" or "cementing" of the blades in the disc,
- Installed/uninstalled blade frequency (vibration) checks, and
- Interferometric laser holography to determine relative movement of the blade platform when assembled with and without a light gap.

Of the four methods investigated all showed some promise, albeit with varying degrees of acceptability. The first method was rejected primarily because of manufacturing difficulties associated with obtaining a uniform and repeatable layer of copper plating on the upper blade fir tree roots. Failure to ensure consistent plating could result in overstressing of the blade/disc due to excessive interference on insertion of the blade into the disc. The viability of the second method (gluing) depends essentially upon the relative softening points of the glues used, and the fact that high temperature expoxies are invariably difficult to apply and may require excessive uring times. Preliminary results have shown some promise and warrant further investigation as it appears to provide the most failsafe method (to date) of installing, a blade in the disc.

The latter two methods investigated, which were essentially high technology inspection procedures, were basically similar in that whilst not positively confirming the existence of a light gap the procedures do indicate that varying degrees of fit are evident even when a gap is not indicated by the light check. However, because of the variation in fit that is possible neither method can be used rigorously as a rejection criteron, in addition due to the complexity of equipment and skilled manpower needed to operate it the procedures may not be cost effective in providing a control on the blade fit. An alternative vibration checking procedure based on heating the installed blade to approximately 140°C and determining the difference between resonant frequencies when hot and cold could be used to indicate degree of fit at the blade root but requires development. Frequency differences of less than 30 Hz implies that a light gap could be present at the blade fir tree root upper land interface whilst frequency differences greater than 45 Hz would imply a satisfactory fit.

● No evidence exists for concluding that loose blades found in stages 8 - 11 were a result of impact loads caused by debris from the 7th stage passing through the compressor. Limited tests were unable to loosen blades which were originally firmly fixed in the disc.

● Despite extensive studies the source of the vibration or driving force which induced the fatigue failure of the seventh stage could not be resolved. However in tests it was possible to isolate a Sixth Engine Order (EO) vibration within the engine albeit at low "g" levels. The 6 EO vibration could have emanated from the 6 struts at the compressor inlet or the 6 combustion chambers or an aerodynamic coupling of the two.

● Blade vibration resulting from bleed band or variable inlet guide vane misscheduling and/or blade flutter of the seventh stage compressor blades could not be substantiated as the driving force for the vibration.

In light of the above conclusions the following recommendations regarding assembly and operation of the Gazelle engine are made:

● Rolls Royce should be requested to carry out a metallurgical examination of the PJ compressor blade material batch and should be asked to comment on its acceptability as a blade material for the Gazelle compressor. In the meantime the SAMR decision to exclude blades manufactured from batch PJ in future Gazelle compressor builds of the 7th stage is endorsed.

- HdeH should in consultation with MRL, adopt the new plating/stripping/cleaning procedures, as detailed in Annex I of this report for the processing of new and old Gazelle compressor blades.
- Blade fir tree root rolling, to modify copper plating thicknesses, should be restricted to a maximum of two passes through the rollers per plating process.
- RAN (DNAE and SAMR) in consultation with Rolls Royce, as the engine contractor, should consider the use of high temperature adhesives in place of PL 94/Molykote 106 as a blade/disc sealer for the seventh and eight stages of the compressor. Wet assembly of blades into disc after passing preload and light check should be investigated.
- If the above recommendation on the use of high temperature adhesives is not adopted then a blade vibration check procedure based on limits established for heating a blade when installed in the disc should be investigated as a final go-no-go check after the light check/shadowgraph inspection procedure has been carried out.
- Rolls Royce should be asked to comment on varying degree of fit observed during vibration check on installed blades.
- An in situ method for assessing blade fir tree root upper land clearances/gaps using pulsed lasers and interferometric holography to determine relative blade platform displacements should be further investigated (outside the auspices of this investigation) at either ARL or an alternate establishment with expertise in laser holography.
- Blade fir tree root upper land/disc light gap checks (together with vibration/frequency method and or holography tests if developed) should only be carried out on the seventh and eighth compressor stages of Gazelle engine.

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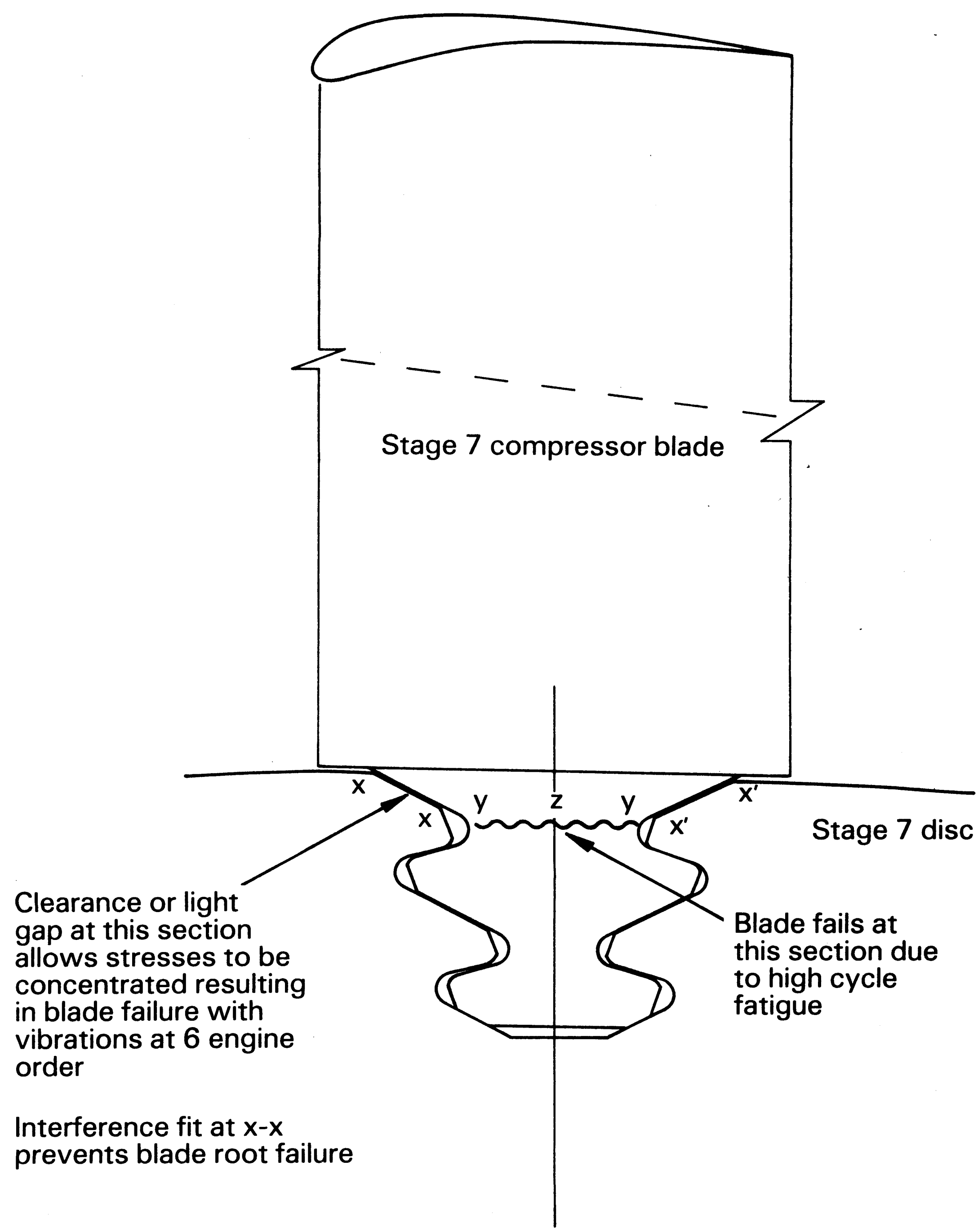


FIG 1 BLADE AND DISC SEGMENT
ROLLS ROYCE GAZELLE INVESTIGATION

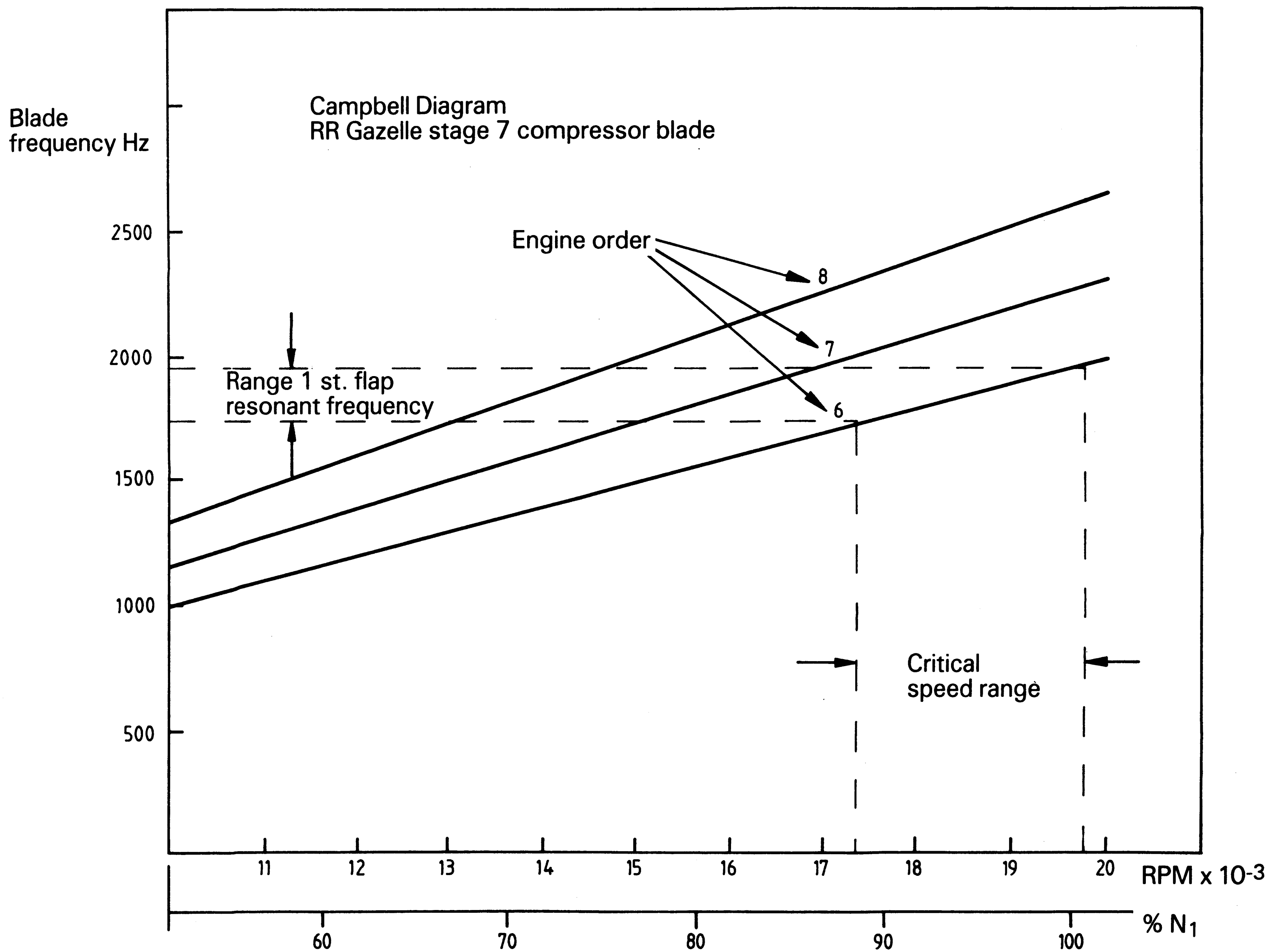


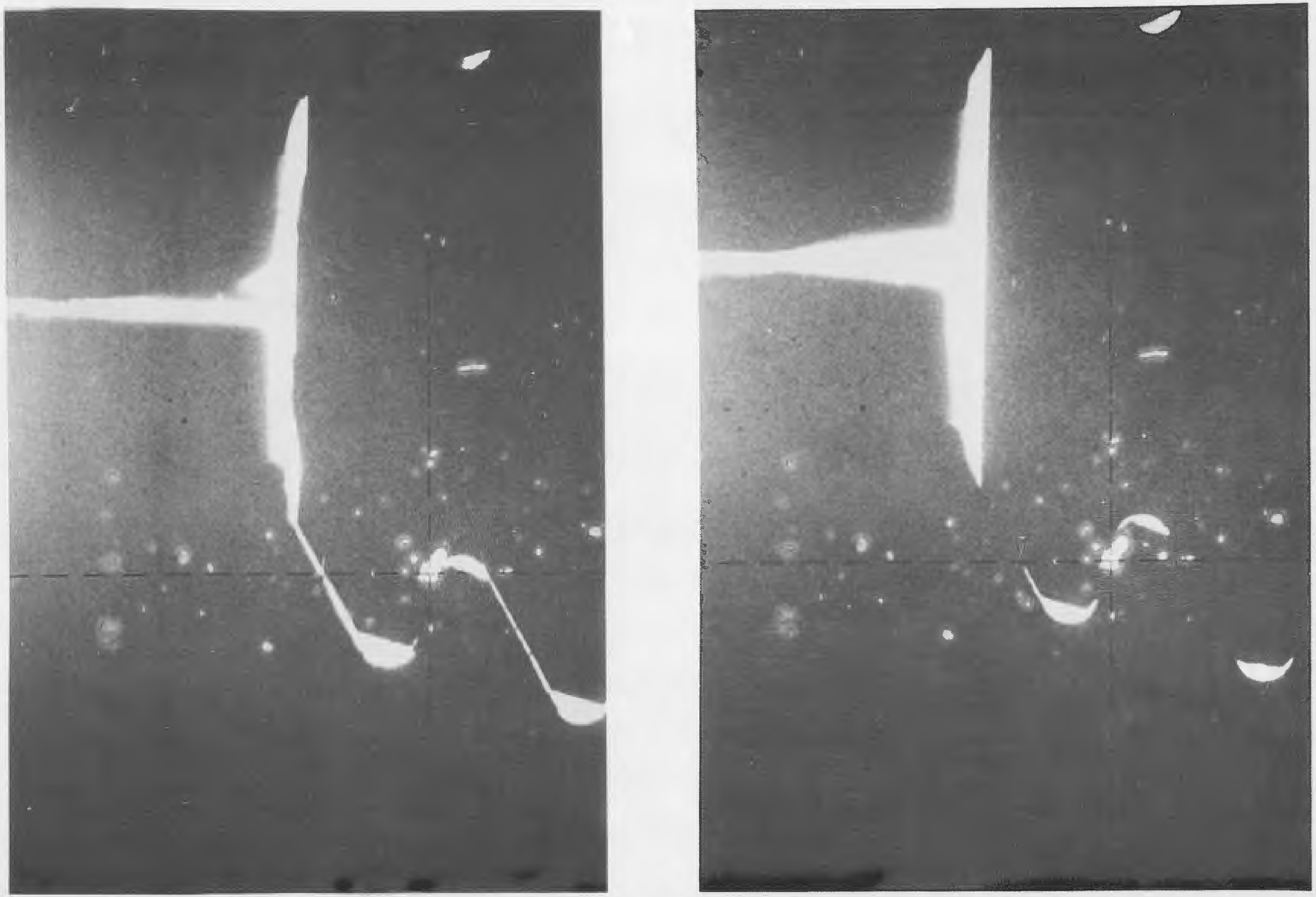
FIG 2 CAMPBELL DIAGRAM: RR GAZELLE STAGE 7 COMPRESSOR ROTOR BLADES

COMMERCIAL-IN-CONFIDENCE

FIG 3A HEAVY LAYER OF SEALANT ON UPPER LANDS OF LOOSE BLADE NO 12

FIG 3B HEAVY LAYER OF SEALANT ON UPPER LANDS OF LOOSE BLADE NO 59

COMMERCIAL-IN-CONFIDENCE

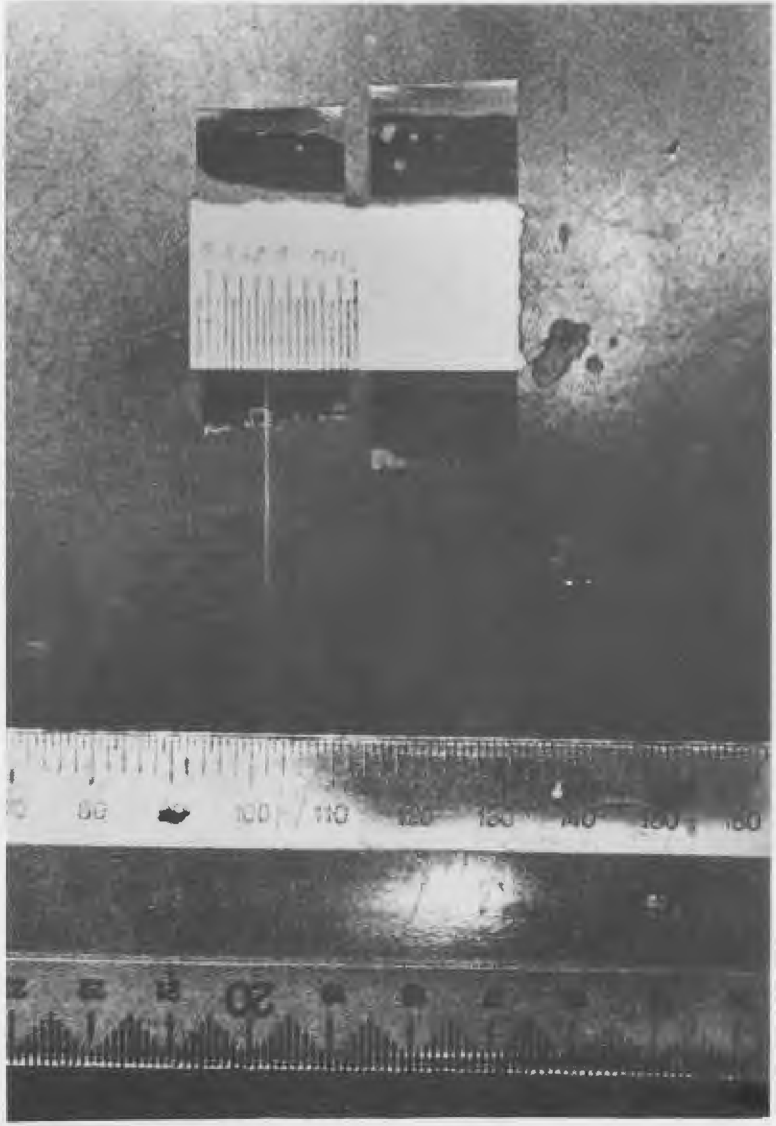


Unacceptable

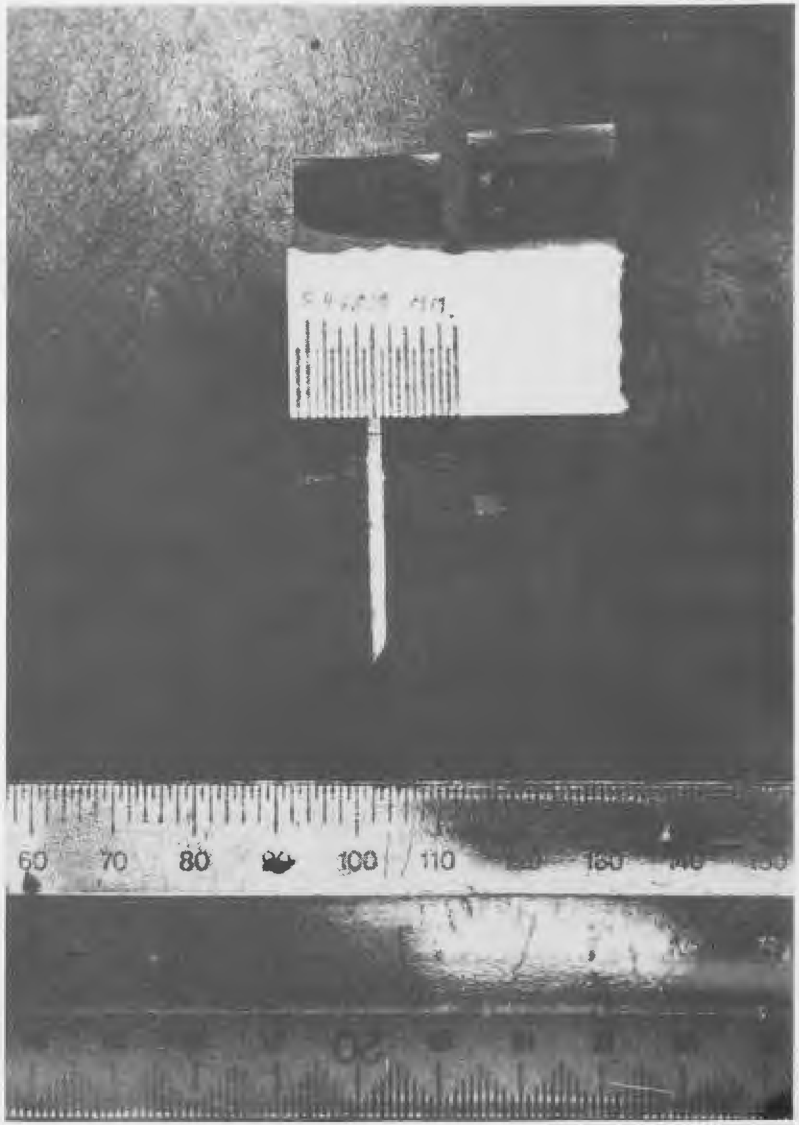
Acceptable

FIG 4 EXAMPLE OF SHADOWGRAPH RESULTS DURING BLADE/DISC BUILD

COMMERCIAL-IN-CONFIDENCE



.0005 in. gap



.0025 in. gap

FIG 5   ARL SIMULATED FIR TREE ROOT/DISC GAUGE RESULTS
FROM Hde H TIMES 20 SHADOWGRAPH

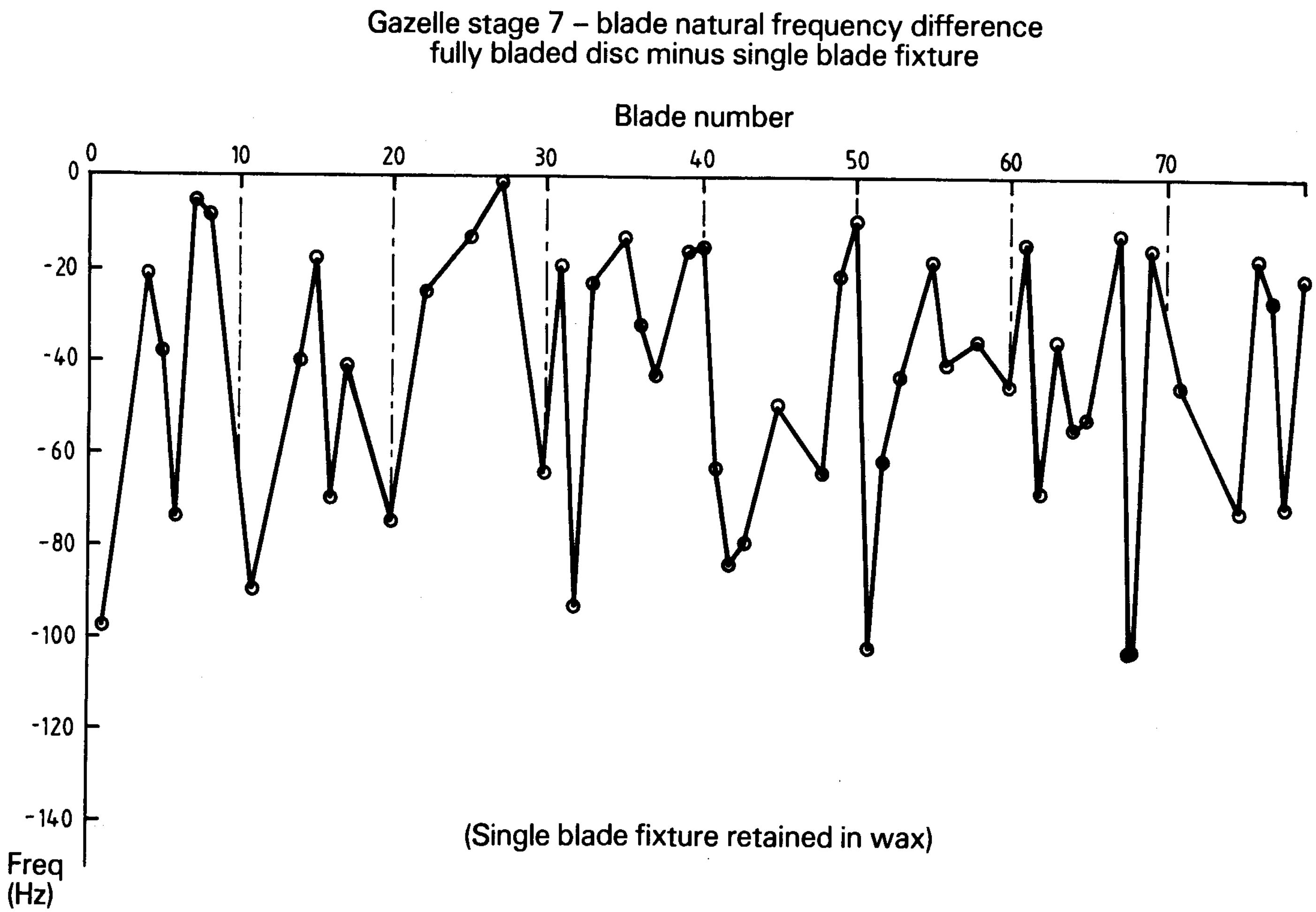
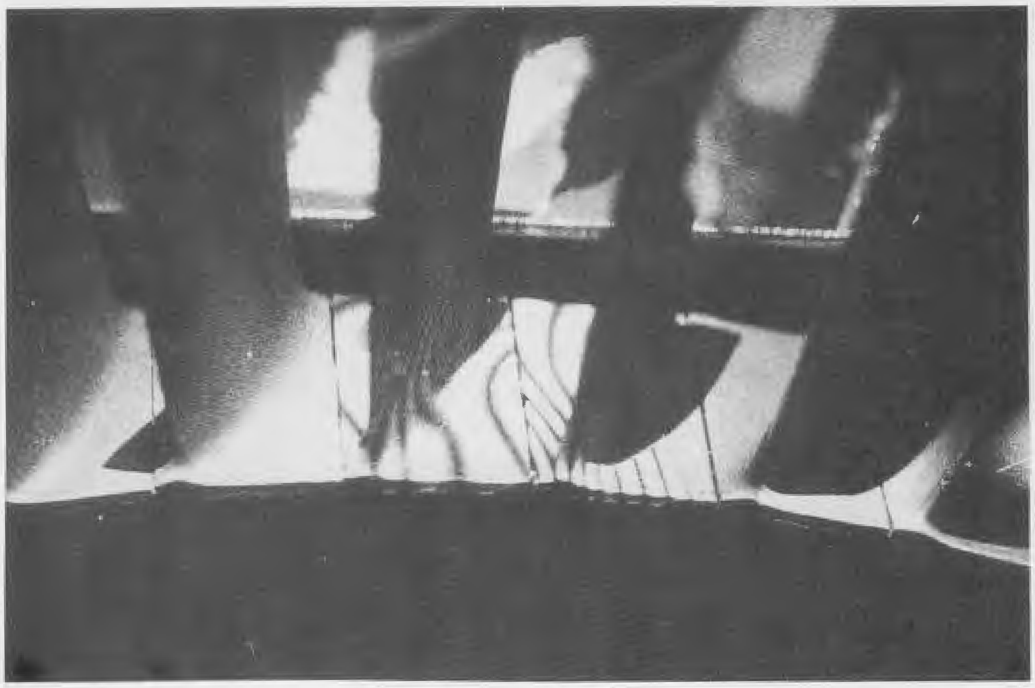


FIG 6 STAGE 7 DISC – BLADE FREQUENCY DIFFERENCES



"No gap"

- Blade with gap at blade fir tree root upper land
- Platform movement indicated by number of fringes dark lines

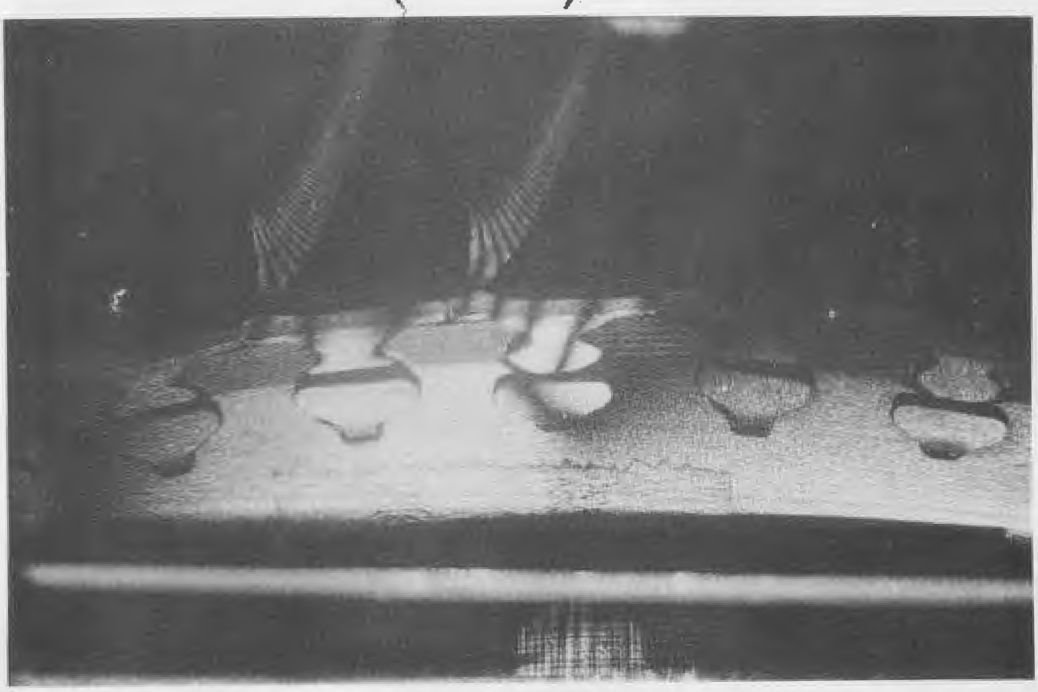


FIG 7 INITIAL RESULTS OF LASER INTERFEROMETRIC HOLOGRAPHY ON BLADES ASSEMBLED INTO DISC WITH AND WITHOUT GAPS AT BLADE FIR TREE ROOT UPPER LAND

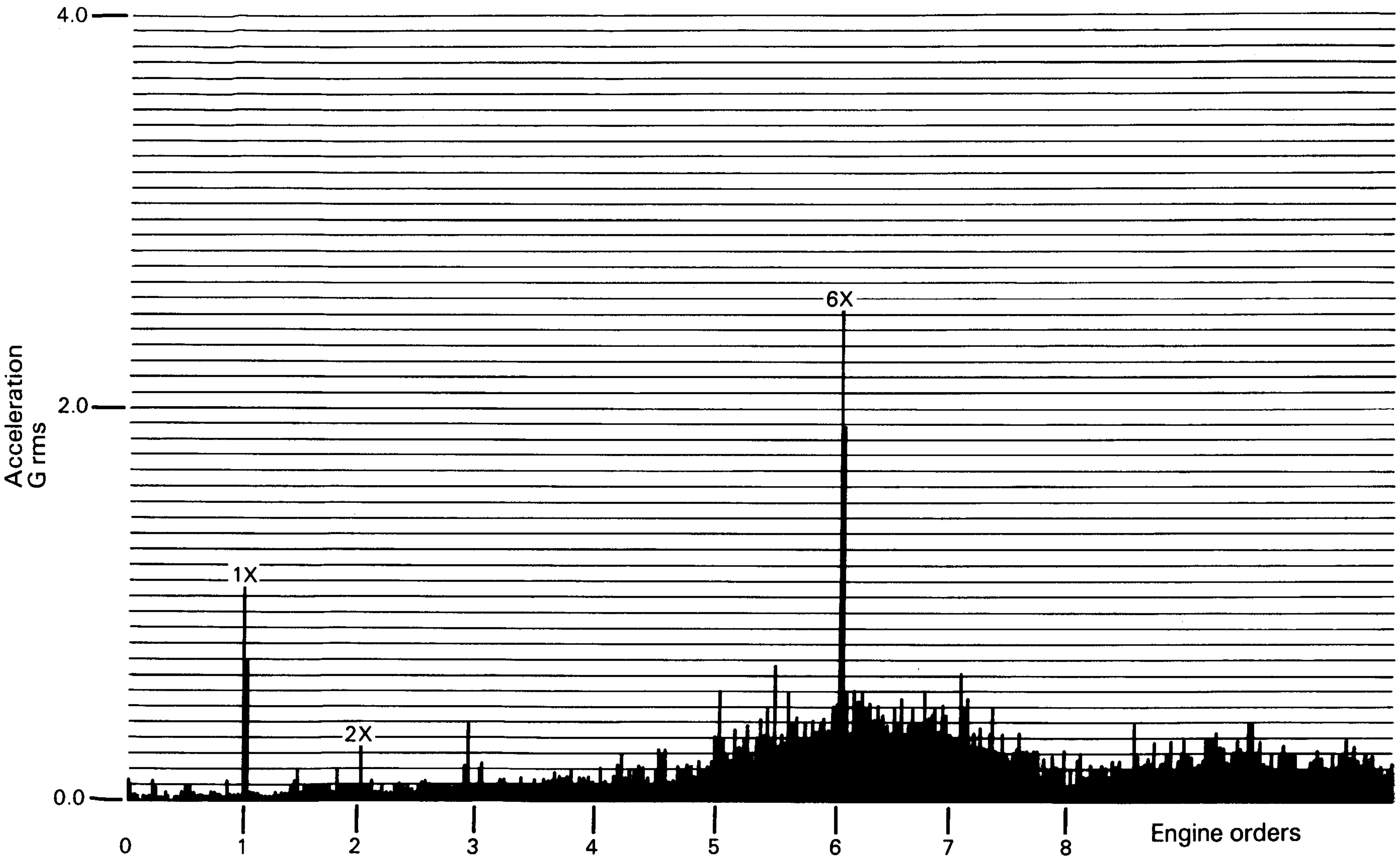


FIG 8 VIBRATION SIGNATURE
OF ROLLS ROYCE GAZELLE ENGINE

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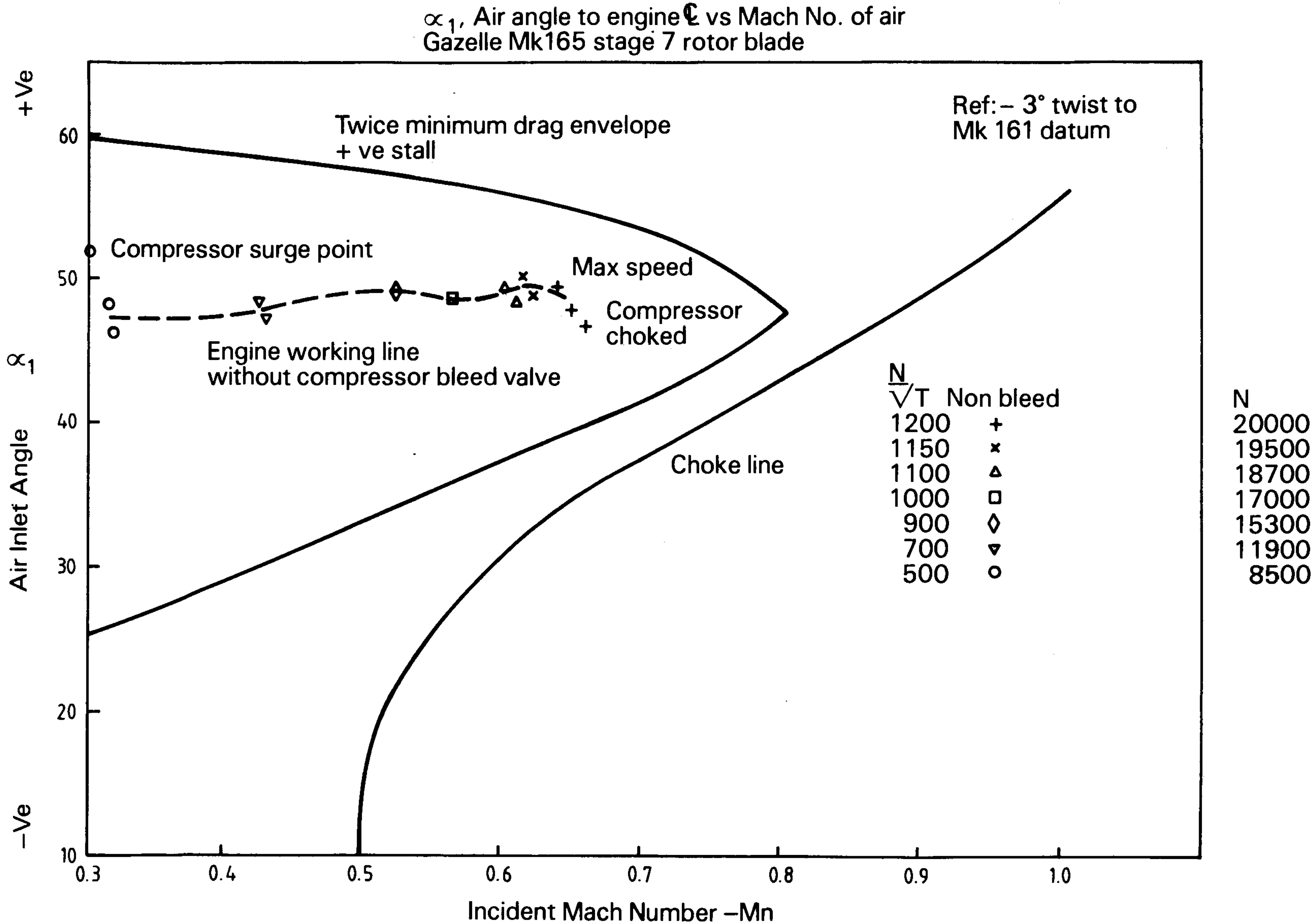

FIG 9 GAZELLE 7TH STAGE COMPRESSOR BLADE ROW FLUTTER BOUNDARIES AND ENGINE OPERATING LINE

COMMERCIAL-IN-CONFIDENCE

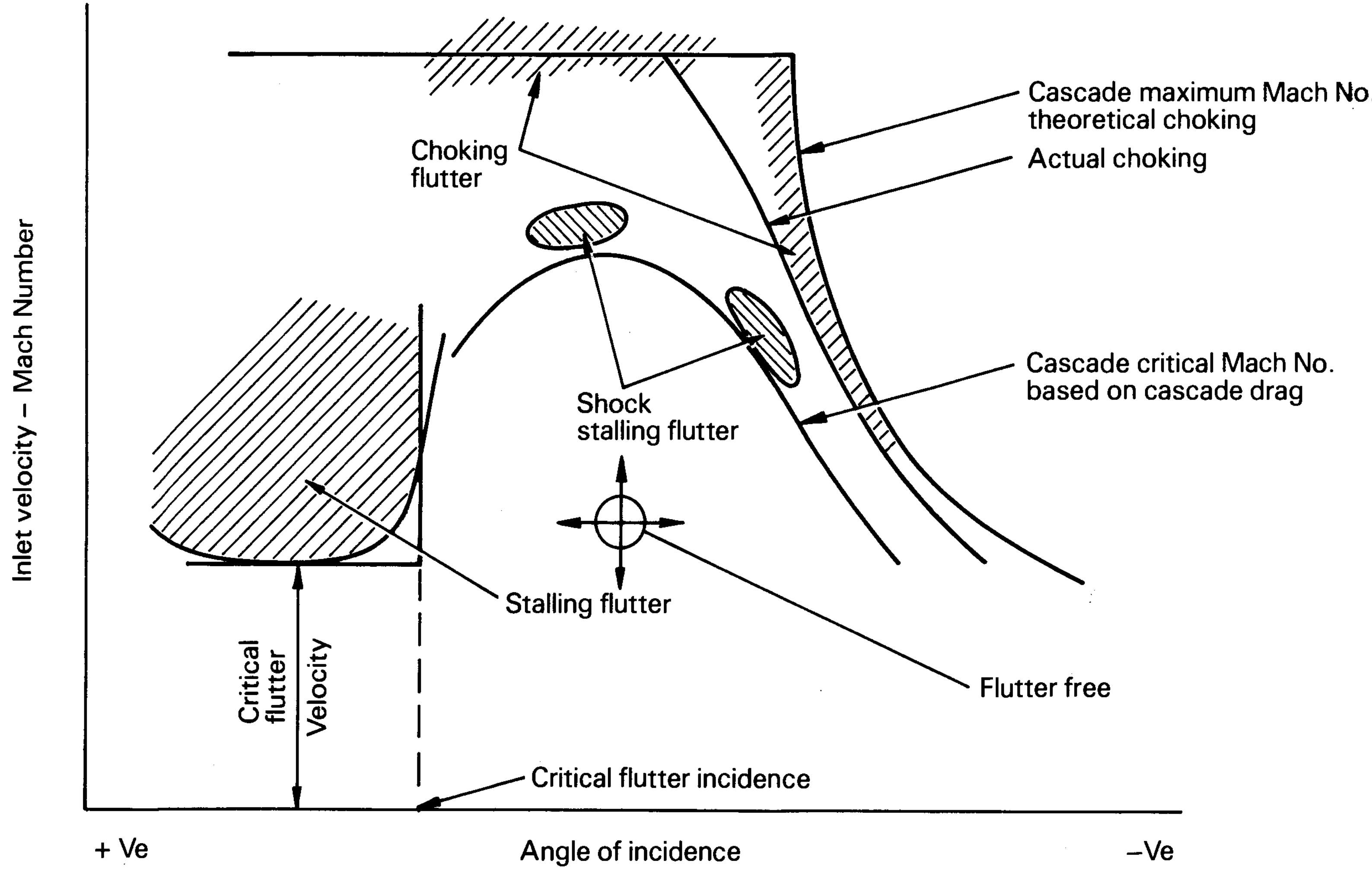

FIG 10. IDEALIZED FLUTTER STRESS CONTOURS FOR A CASCADE BLADE (REFERENCE 23)

COMMERCIAL-IN-CONFIDENCE

STAGE NUMBER	1	2	3	4	5	6	7
NO. OF BLADE/STAGE	27	33	39	43	49	61	61
FAILED INSERTION TEST	8	20	6	7	34	9	8
FAILED LIGHT CHECK	2	0	0	11	29	8	8

TABLE 1
GAZELLE MK 165C – GA2033

SUMMARY OF SALIENT POINTS DURING COMPRESSOR REBUILD

Blade No.	Insert. Press.	Freq Diff	No of Fringes	GAP-FD (△ F)*	Blade No.	Insert. Press.	Freq Diff	No of Fringes	GAP-FD (△ F)*
1	115	-98	6	(-33)	41	1.50	-63	3	
2					42	65	-84		
3					43	135	-79	4	
4	110	-21	1		44				
5	70	-38	3	-96	45	120	-49	6	
6	60	-14	4		46				
7	140	-5	1-2	-75	47				
8	125	-8	2	(-46)	48	95	-64	4	
9					49	65	-21	3	
10					50	120	-9		
11	130	-90	7	-98	51	70	-102	7	
12					52	145	-61	4	
13					53	75	-43	3	
14	100	-40	4		54				
15	100	-18	2		55	65	-18	1-2	
16	100	-70	6		56	135	-40	4	-70
17	65	-41	2		57				
18					58	120	-35	2	
19					59				
20	150	-75	4		60	140	-45	2-3	
21					61	70	-14	1-2	(-63)
22	120	-25	2		62	75	-68	4	
23					63	110	-35	2-3	
24					64	65	-54	4	
25	95	-13	1		65	80	-52	7	
26					66				
27	125	-1	1	-80	67	100	-12	2	
28					68	70	-105	6	(-23)
29					69	135	-15	2	
30	125	-64	7		70				
31	85	-19	1		71	120	-45	4	
32	135	-93	4	-90	72				
33	80	-23	2		73				
34					74				
35	100	-13	1		75	135	-72	5	
36	100	-32	3		76	135	-17	2	
37	135	-43	1		77	95	-26	3	
38					78	140	-71		
39	125	-16	2		79	140	-21	1	
40	90	-15	2		80				

TABLE 2 SUMMARY OF BLADE VIBRATION DIFFERENCES FOR SEVENTH STAGE GAZELLE COMPRESSOR DISC

*(△F = FREQUENCY HOT – FREQUENCY COLD)

ROOT FIXING		ROOT TEMPERATURE	CHANGE IN BLADE * FREQUENCY	BLADE STAGE
BLADE RIGIDLY CLAMPED AT PLATFORM		120 - 140°C	-20 Hz	SIXTH
BLADES ASSEMBLED INTO COMPLETE DISC	"TIGHT" NO-GAP	120 - 140°	-45 → -65 Hz	SEVENTH
	"LOOSE" LIGHTGAP		-20 → -30 Hz	
BLADE GLUED WITH COLD GALVANISING PAINT		60 - 120°C	-100 Hz	SIXTH
BLADE GLUED WITH SINGLE PART EPOXY		60 - 120°C	-100 Hz	SEVENTH
BLADE GLUED WITH PL94/MOLYKOTE 106		80-120°C	-100 Hz	SIXTH
BLADE GLUED WITH HIGH TEMPERATURE EPOXY		120 - 140°C	-40 → -45 Hz	SEVENTH & SIXTH

TABLE 3 EFFECT OF HEAT ON BLADE RESONANT FREQUENCY FOR BLADES HELD WITH DIFFERENT ROOT FIXING METHODS

(* FREQUENCY HOT - FREQUENCY COLD)

ANNEX A

PRELIMINARY FINDINGS - GAZELLE ENGINE 7th STAGE COMPRESSOR BLADE FAILURE

1. The remains of a broken 7th stage compressor blade from a Gazelle Mk 165C engine (SN GA2033), were passed to Aircraft Materials Division, ARL, from Aero Propulsion Division for examination (Ref A). SAMR had requested (Ref B) that ARL determine the mode and causes of the failure. This report sets out the findings to date, with respect to the blade failure.

2. The piece of the component supplied for analysis represented the majority of the fir-tree section of the blade; this had been retained in the compressor disc after failure. The blade had broken at the first fir-tree serration immediately beneath the blade land. Examination of the fracture surface of the broken blade (Fig 1)* revealed two separate cracks. One of the cracks (labelled A, Fig 1) had initiated in the root of the fir-tree serration on the leading side of the blade, and grown inwards towards the centre of the blade, approximately parallel to the blade land, as well as along the length of the root of the serration itself. The other crack (labelled B, Fig 1) initiated in the fir-tree serration root on the trailing side of the blade, and had then grown in a similar manner to the crack on the leading side. Final failure of the blade occurred by overload of the reduced cross-sectional area of the fir-tree.

3. At higher magnification, progression markings were clearly distinguishable on both crack faces (for example, at arrows P, Fig 2) indicating that, in both cases, crack growth had been by fatigue. The crack which had initiated on the leading side of the blade (Crack A, Fig 1) had penetrated to a greater depth (about 1.8 mm) than the crack on the trailing side (approximately 1.1 mm). Each crack face exhibited a heat-tinted zone of crack growth over the final stages of crack propagation (typically at arrows T, Fig 1). At higher magnification the tinting was not a continuous band, but a series of distinct dark and light bands (for example, at arrows T, Fig 2), consistent with fatigue crack growth under environmental and/or loading conditions which were varying significantly. Engine cycling (start-up to shut-down) is a likely source of such changing conditions, although at this stage, the exact source of blade loading is not known. If engine cycling is assumed to be responsible for the alternating bands on both fracture faces, then crack propagation from initiation to failure took place during a series of engine operations.

4. The initiation sites for both cracks are indicated by arrows O and S, figure 2. While no distinctive characteristics were revealed at these origins by the optical microscope, examination using the scanning electron microscope (SEM), at high magnification, revealed some interesting features. An inclusion (at arrow I, Fig 3) approximately 1.6 microns in diameter was found at the origin of the crack on the leading side of the blade (at arrow O, Fig 2). This inclusion was located very close to the surface of the blade at the root of the fir-tree serration. The chevron pattern or "river"-marking, on the blade fracture surface (arrows C, Fig 3) points to this inclusion as the origin of cracking for the crack on the leading side of the blade. X-ray micro-analysis of the particle indicated that it contained both iron and aluminium which are elements normally present in the blade material. The initiation site of the cracking on the trailing side of the blade had suffered secondary damage (ie. subsequent to the blade failure) and the cause of cracking could not therefore be determined.

5. The absence of observable fatigue striation detail between the distinct progression marks (arrows P, Fig 2) on both crack faces prior to the heat-tinted zones, suggested that the crack driving stresses were relatively low and that the number of fatigue cycles was high (ie. high cycle, low stress fatigue). These facts would be consistent with the contention (paragraph 3) that crack propagation from initiation to failure had taken place during a series of engine operations.

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* Figures and References mentioned in the Annexes refer to respective Figures etc contained in the Annex unless specifically stated as applying to main body of the report.

6. The occurrence of two similar fatigue cracks growing from opposite sides of the blade towards each other, indicates that cracking occurred under reversed-bending loading; however, such loading need not have been symmetrical about zero load.

7. It is concluded from this initial analysis of the failure of the 7th stage compressor blade from Gazelle Mk 165C engine SN GA 2033 that:

(a) the blade had broken as a result of the initiation and propagation of two separate fatigue cracks from the roots of the first fir-tree serrations under the blade land;

(b) the majority of fatigue cracking was of the high cycle, low stress type;

(c) crack propagation occurred under reversed-bending loading;

(d) the crack on the leading side of the blade initiated at a small inclusion (ie. at a point origin);

(e) crack propagation from initiation to failure probably occurred over a number of engine operations;

(f) final failure of the blade occurred by overload of the reduced cross-sectional area of the fir-tree.

8. While this report is concerned mainly with the interpretation of the fracture-surface features of the broken blade, two further observations are considered worthy of mention:

(a) In addition to the failed blade, a large number of blades from engine SN GA2033 were examined, including all those from the disc containing the failed blade. It became clear from this examination that the quality of the copper plate on many blades was poor. Specifically, a nodular copper structure was exhibited, to varying degrees, on many blades examined. It should be noted that Ref C, paragraph 3.11 requires that the "...copper plating shall be smooth, ..., free from nodules and other defects which are detrimental to the utility, form, fit or function of the part". While it is not inferred, at this stage of the overall investigation, that there is any direct relationship between the quality of the copper plate and the 7th stage blade failure described above, the possibility of such a relationship should be further investigated.

(b) The investigation has been hampered, to a degree, by the presence of a strongly adherent molybdenum disulphide coating on the external surfaces of the blades examined (see for example arrow M Fig 2), particularly in the fir-tree region. Considerable effort has been spent in trying to develop a method to remove this compound without also damaging the copper plate or the blade material itself (the blades are manufactured from aluminium-bronze, a copper-based alloy). While none of the methods employed was completely satisfactory in meeting this latter criterion, the best method developed involved the use of a 50 percent citric acid solution in conjunction with an ultrasonic cleaner.

REFERENCES

A. Discussion with Mr D.E. Glenny (Aero Propulsion Division, ARL), 26 November 1985.

B. SAMR Telex 214, 7 November 1985.

C. MIL—C—14550B, "Copper Plating (Electro-Deposited)", Amendment 1, 4 December 1984.

D. Annex A A/Mats Division Ref: M76/85/SRL — BM2/47 of 21/3/86.

FIG 1 THE FRACTURE SURFACE OF THE BROKEN 7TH STAGE COMPRESSOR BLADE FROM GAZELLE MK165C ENGINE SN GA2033. IN THIS PHOTOGRAPH THE LEADING SIDE OF THE BLADE IS AT THE TOP. TWO CRACKS ARE VISIBLE ON THE FRACTURE SURFACE. THE CRACK LABELLED A HAS INITIATED IN THE ROOT OF A FIR-TREE SERRATION ON THE LEADING SIDE OF THE BLADE, WHILE THE CRACK LABELLED B HAS ALSO INITIATED AT THE ROOT OF A FIR-TREE SERRATION, BUT ON THE TRAILING SIDE OF THE BLADE. A REGION OF HEAT-TINTED CRACKING IS VISIBLE ON BOTH CRACK FACES TOWARDS THE FINAL STAGES OF CRACK GROWTH (TYPICALLY AT ARROWS T; SEE ALSO FIG. 2). THE REGION OF THE FRACTURE SURFACE LABELLED D REPRESENTS THE MATERIAL OF THE BLADE EXPOSED WHEN THE COMPONENT FAILED IN OVERLOAD.

Magnification: 15.

FIG 2 ENLARGED VIEW OF A PORTION OF THE TWO CRACKS ON THE FRACTURE SURFACE OF THE BLADE SHOWN IN FIG. 1. FATIGUE PROGESSION MARKS ARE CLEARLY VISIBLE ON BOTH CRACK FACES (FOR EXAMPLE AT ARROWS P). THE BANDS OF HEAT-TINTED CRACK-GROWTH (NOTED IN FIG. 1) ARE REVEALED, AT THIS MAGNIFICATION, TO BE A SERIES OF DARK AND LIGHT ZONES (ARROWS T). THE INITIATION SITE OF THE CRACK ON THE LEADING SIDE OF THE BLADE IS INDICATED BY ARROW O, WHILE THE INITIATION SITE FOR THE CRACK ON THE TRAILING SIDE IS ARROWED S. MOLYBDENUM DISULPHIDE CAN BE SEEN IN THE AREAS INDICATED BY ARROWS M.

Magnification: 23

FIG 3 HIGH MAGNIFICATION SCANNING ELECTRON MICROSCOPE PHOTOGRAPH OF THE ORIGIN (ARROWED 0, FIG.2) OF THE CRACK ON THE LEADING SIDE OF THE BLADE. THE FRACTURE SURFACE OF THE CRACK IN THE BLADE MATERIAL IS LABELLED F. THE FRACTURE SURFACE OF THE COPPER PLATE IS LABELLED E, WHILE THE BOUNDARY BETWEEN THE COPPER PLATE AND THE BLADE MATERIAL IS ARROWED D. AT THE TOP OF THIS PHOTOGRAPH, LABELLED M, IS THE MOLYBDENUM DISULPHIDE COATING ON THE (NORMALLY) EXTERNAL SURFACE OF THE BLADE (IN THIS CASE THE ROOT OF THE FIR-TREE SERRATION). THE "RIVER" PATTERN OR CHEVRON MARKINGS (AT ARROWS C) ON THE BLADE FRACTURE SURFACE POINT TO AN INCLUSION, ARROWED I, AS THE ORIGIN OF THE CRACK ON THE LEADING SIDE OF THE BLADE. THE INCLUSION IS APPROXIMATELY 1.6 MICRONS IN DIAMETER.

Magnification: 1600

ANNEX B

GAZELLE ENGINE COMPRESSOR BLADE FAILURE — PLATING INVESTIGATION

PRELIMINARY REPORT

1.0 INTRODUCTION

Your request C2/202 of 13 December for assistance in evaluation of copper plating procedures used to plate compressor blade roots is proceeding. This report is to advise of results of the investigation so far completed.

2.0 BACKGROUND

The compressor blades are manufactured from nickel aluminium bronze. To enable a tight locking of the compressor blades into the rotor, the fir tree roots of the blades are copper plated to give a deformable spacer between the blade and the rotor. A Rochelle copper cyanide plating solution is used.

The plating procedure is described in Hawker de Havilland Process Specification No HPS 1.03.07. Appendix 1 (ETI 3/115/7) lays down the procedure for compressor blade roots using periodic reverse current plating.

It is understood that blades are plated with 25 m copper on the blade root and then fitted to the rotor. Blades which are too tight to fit are rolled as described in Appendix 2 (ETI/115/7). If they still fail to fit, the copper plating is stripped according to the specification procedure, Paragraph 10.12, and the blades replated. Blades with too great a clearance are returned to the plating bath for further plating. This procedure is repeated until a satisfactory fit is obtained.

3.0 EXAMINATION

Initially three 7th stage compressor blades were sent to MRL for examination.

Examination of these blades showed:-

1. The copper plating on the blade root surface was very rough and nodular. On the root contact surfaces the nodules had been flattened by the fitting of the blades to the rotor.

2. At high magnification (SEM) the nodules had formed folds in the surface and in one blade a crack had formed at the base of the folds. (This blade was returned to ARL for further metallurgical examination).

3. Poor adhesion of the copper plate was observed on one blade. This had occurred on the blade face rather than on the fir tree root. In the failed area the copper plate could be peeled off the surface easily.

4. The copper coating was stripped off one blade using the Rolls Royce stripping procedure. After removal of the copper the blade was found to be heavily tarnished with a black oxide deposit, presumably formed as a result of the stripping. The oxide could not be removed with 10% hydrochloric acid. Severe scrubbing with pumice was necessary to remove the deposit.

5. A further six samples of compressor blades (plated by Hawker de Havilland to Spec. HPS 01.03.07 App. 1) were sent to MRL for examination. These experimental blades had been copper plated with a range of time delays during preparation, the idea being to simulate actual preparation in the plating shop. The effect of all the surface preparation methods tried was similar - all blades had a fine grained copper deposit with little or no nodule production.

4.0 EXPERIMENTAL

A series of trials have been conducted at MRL using the standard Rochelle cyanide copper plating solution and procedure in Specification HPS 1.03.07 and Appendix 1 (ETI/115/7) on flat specimens of nickel aluminium bronze. Our results to date show:-

1. Using parameters laid down in ETI/115/7 for periodic reverse plating (ie. 30 sec. cathodic, 20 sec. anodic 20% duty cycle), very little copper was deposited. The coating, while very fine grained and free from nodules, was unsatisfactory because of lack of thickness.
2. A change in the periodic reverse cycle produced a much better result. A 10 sec cathodic and 2 sec anodic cycle (80% duty cycle) produced a fine grained, nodule-free deposit at the predicted thickness.
3. Conventional plating procedures (not using periodic reverse cycling) produced fine grained copper deposits on nickel aluminium bronze samples. However, some nodules and high spots were observed at corners and sharp edges.
4. This work is continuing.

5.0 COMMENTS

1. The examination of the 7th stage compressor blades showed that the copper plating was poor. Bad noduling of the copper plate had occurred. Examination at high magnification indicated that folds between nodules could be a source of stress concentration. One crack was detected in a critical area at the base of the nodules.

2. Adhesion of the copper plating to these blades is suspect. It indicates a failure of the cleaning procedure, possibly related to difficulties of removing any oxide film formed if stripping had been carried out during fitting (ref. our Examination 4 above). A special procedure may be required to ensure that the oxide film is removed prior to replating.

3. A variation in fitting procedure is suggested which could save considerable time and effort. The blades that are overplated could be chemically stripped to remove only the minor amounts of copper required to achieve a satisfactory fit. Chemical stripping is suggested as this would remove the copper coating evenly.

4. The experimental series of blades plated at Hawker de Havilland showed that fine grain deposits can be produced under properly controlled conditions when processed according to HPS 1.03.02.

5. However, further work is required to resolve the different results obtained by MRL and Hawker de Havilland in working to the same plating specification.

6.0 CONCLUSIONS

1. The copper plating observed on the 7th stage compressor blades is of poor quality. Nodule formation on the deposits has given rise to sources of stress concentration in critical areas.

2. Adhesion of the copper plating to the nickel aluminium bronze is suspect, and a review of the cleaning procedures after copper stripping is required.

REFERENCES: A. ANNEX B. MRL Metallurgy Div Ref: 64/18/8 M9/5/10 of 7/4/86.

ANNEX C

SURVEY OF GAZELLE MK 165C STAGE 7 COMPRESSOR BLADE NATURAL FREQUENCIES

1.0 INTRODUCTION

This Annex describes measurements carried out at ARL on some seventh stage Gazelle compressor blades. The measurements were made on static blades held in two types of blade fixtures. The purpose of the measurements was to:

a. Establish if the blade natural frequencies were similar to those of RN Gazelle engines as reported in Reference 11 of the main report.

b. Establish what difference in natural frequency occur with and without a clearance at the blade/disc interface.

c. Establish the blade-to-blade variation of natural frequencies for a complete set of seventh stage blades fixed in a disc.

2.0 METHOD

Two types of blade support were used in these tests, these are described below.

2.1 Single-blade fixture

This fixture was built from a segment of a stage 7 disc (see Figures 1 and 2). The disc was slit radially from the fir tree root, so as to enable a blade to be easily removed or inserted, and then tightly clamped in a circumferential direction. The clamping was to simulate the 60-150 lbf insertion pressure specified for blade assembly in the disc.

Excitation for the blade was provided by an air-jet impinging near the tip of the blade. The air-jet could be expected to be a source of random excitation, containing significant energy in the required frequency range (approx. 1,800 Hertz).

The response of the blade was measured using a Kaman Sciences KD 2310-1U eddy-current probe. This probe was chosen because of its high sensitivity (10-70 mV per thousandths of an inch) and its insensitivity to clearance between probe tip and measurement surface (up to 0.040 in being permissable), and its suitability for use with non-ferrous materials. Analysis of the blade response was made using a Bruel and Kjaer type 2034 frequency analyser.

The blade fixture used in these test is shown in Figure 1. It is a modification of that initially designed, in that the fixture support length was increased and the components bolted together to eliminate structural vibrational modes which were close to the blade fundamental frequency in bending.

2.2 Bladed-disc fixture

In order that the natural frequencies of blades as assembled in a stage 7 disc could be compared, a fixture (Figure 3 and 4) was constructed using a complete seventh stage disc.

The blade excitation and measurement were as for the single-blade fixture, described above.

3.0 RESULTS

3.1 Single-blade fixture

For this fixture three tests were carried out, all with varying degrees of clearance/interference at the blade/disc interface. The results of the tests for the fundamental bending mode of the blade are given in Table 1.

ANNEX C (cont.)

TABLE 1

Test No.	Fundamental bending frequency Hz	Comments
(a)	1784	No apparent platform clearance.
(b)	1784	Platform had interference fit on top face of disc.
(c)	1712	Clearance between blade platform and disc 0.004 inch.

From Table 1 it is apparent that the effect of introducing clearance between the blade platform and the disc is to lower the fundamental bending frequency by 72 Hz.

3.2 Bladed-disc fixture

For these tests the blades were assembled into the disc complete with their locking tab and coatings of PL 94/Molykote 106 and PL 110. The results of the tests are given in Table 2.

TABLE 2

Blade Number	Fundamental Frequency Hz	Blade Number	Fundamental Frequency Hz
1	1956	31	1924
2	1816	32	1912
3	1820	33	1828
4	1820	34	1800
5	1884	35	1896
6	1760	36	1856
7	1856	37	1888
8	1856	38	1812
9	1772	39	1880
10	1836	40	1912
11	1836	41	1884
12	1812	42	1948
13	1872	43	1948
14	1772	44	1756
15	1888	45	1808
16	1896	46	1900
17	1840	47	1824
18	1860	48	1908
19	1856	49	1912
20	1916	50	1788
21	1912	51	1860
22	1880	52	1864
23	1892	53	1840
24	1856	54	1840
25	1892	55	1964
26	1904	56	1748
27	1880	57	1996
28	1900	58	1920
29	1864	59	1904
30	1912	60	1788
		61	1948

ANNEX C (cont.)

From Table 2 it can be seen that the variation in frequency between blades is considerable. The highest frequency is 1996 Hz, and the lowest 1748 Hz, the difference then being 240 Hz.

4.0 DISCUSSION

The blade natural frequencies measured here are similar to those found in RN Gazelle Engines, Reference 11 of the main report, where blade frequencies between 1734 and 1873 were measured.

As would be expected, the introduction of clearance beneath the blade platform lowers the fundamental bending frequency. This is because of the decrease in stiffness, and also the small increase in effective mass for this mode.

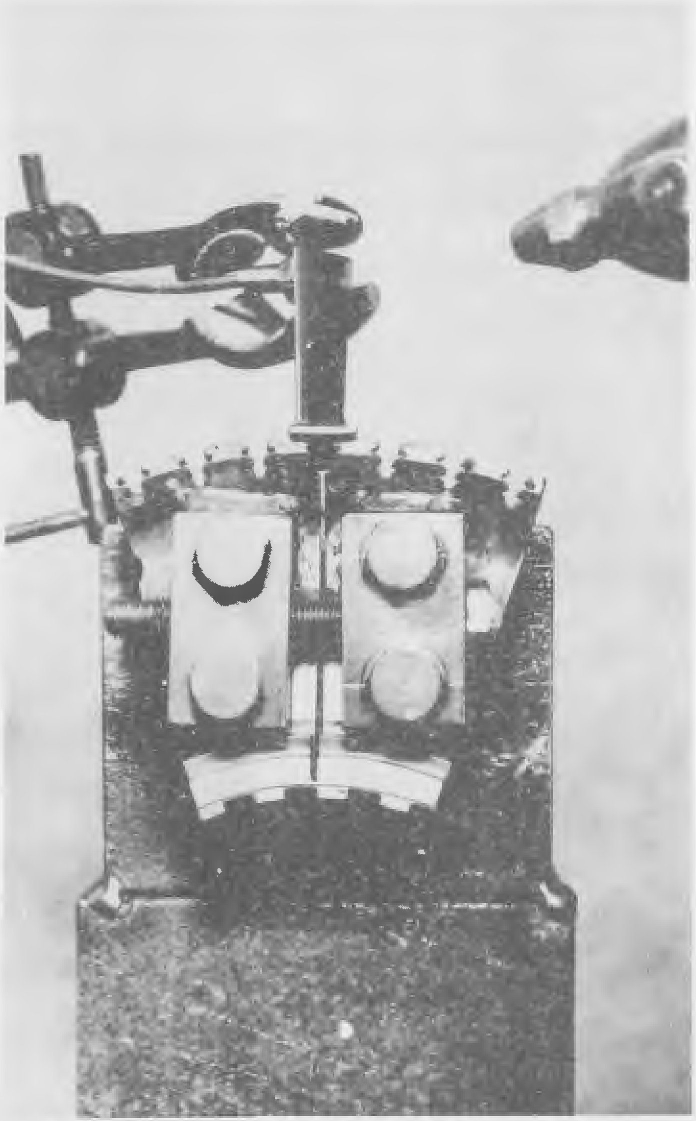
The scatter in natural frequencies between blades in a disc assembly appears too great (for this example 240 Hz) to use this measurement as an indication of those blades which may have platform clearance. However, if the blade frequencies of assembled blades are compared with their own individual frequencies, determined prior to insertion, then a viable clearance checking technique could be developed.

5.0 CONLUSIONS

(a) The fundamental bending natural frequency of Stage 7 compressor blades held by the RAN is similar to those of the RN.

(b) The existence of clearance beneath the blade platform of a Stage 7 compressor blade will lower the fundamental bending natural frequency by 72 Hz.

(c) The natural frequencies of the 61 blades in a typical disc assembly was found to range from 1756 Hz to 1996 Hz, a variation of 240 Hz.



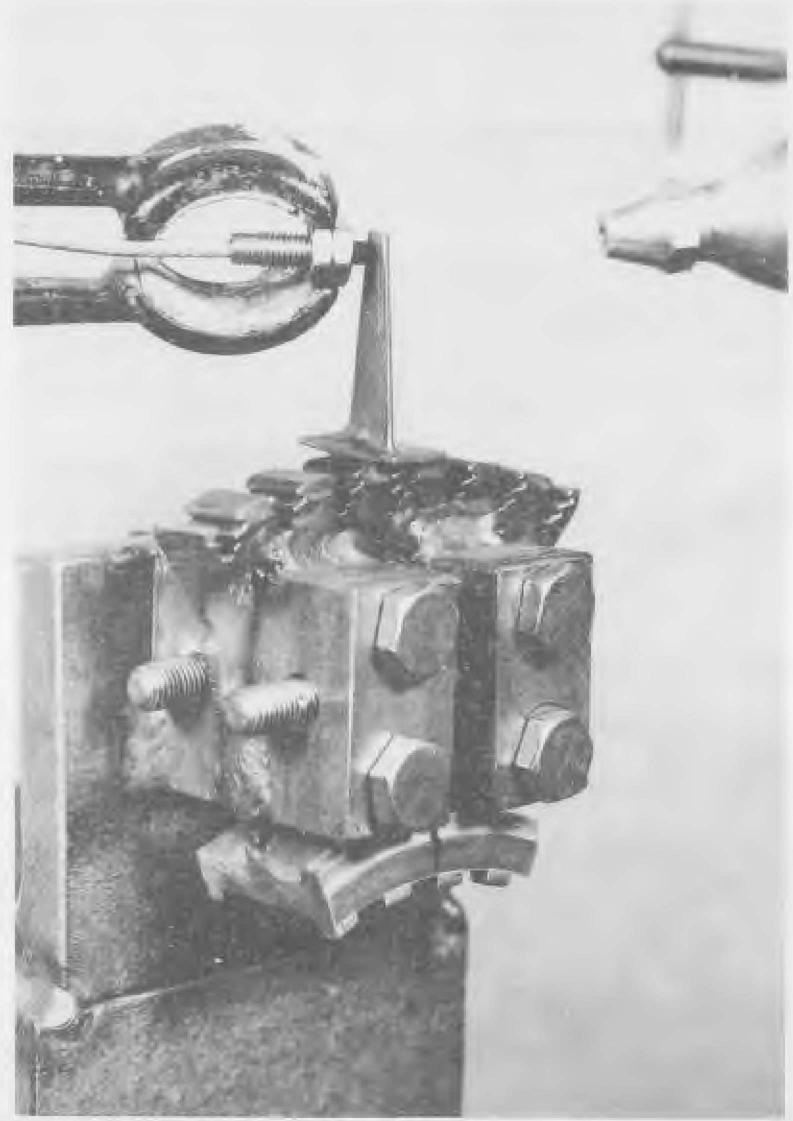


FIG 1 AND 2   SINGLE BLADE FIXTURE

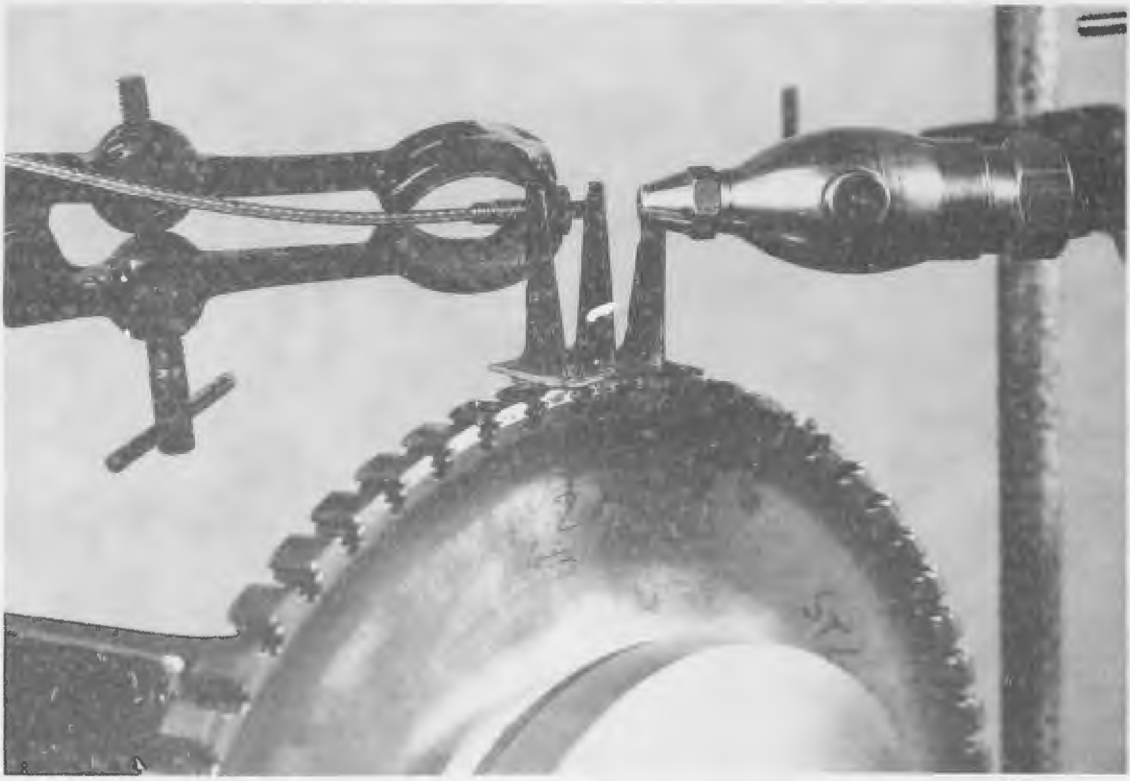


FIG 3. TESTS FOR BLADE FREQUENCY AS ASSEMBLED INTO DISC

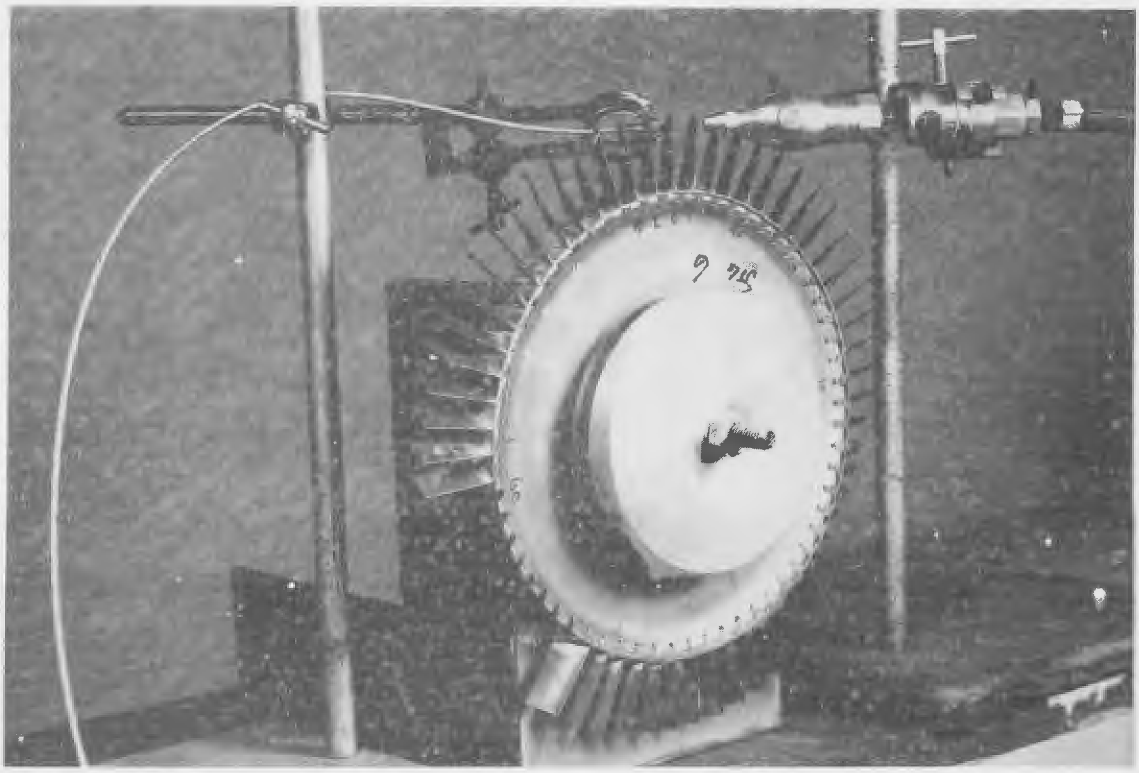


FIG 4. PARTIAL ASSEMBLED DISC DETERMINATION OF BLADE FREQUENCIES

ANNEX D

INVESTIGATION INTO THE USE OF GAZELLE COMPRESSOR BLADE NATURAL FREQUENCY MEASUREMENTS TO DETECT BLADE/DISC PLATFORM CLEARANCE

1.0 INTRODUCTION

This annex details tests carried out to confirm the possibility of detecting blade/disc platform clearances by observing changes in the natural frequency of a given blade when initially measured in a reference fixture and then measured in the compressor disc. In earlier tests Annex C it was shown that the scatter in natural frequency of a set of blades was considerably higher than the changes in frequency of a particular blade when held in a rotor disc with and without clearance at the blade/disc interface.

However it was also shown that the blade frequencies increased by up to 5.0% or 80 hertz when the light gap at the blade/disc interface was reduced to zero.

From these observations it was postulated that if the natural frequency of a given blade was determined in a reference jig or fixture (of known tightness and clearance) then deviations from this value, when the blade was assembled into the disc, could be used to assess the degree of fit of the blade in the disc.

2.0 METHOD

The equipment and instrumentation used in these tests is similar to that of Annex C. However for this investigation stage 6 compressor blades were used in lieu of stage 7 as at the time of the tests there was only a limited supply of stage 7 blades. As the fir tree root dimensions of the 6th and 7th stage blades are identical, the conclusions should be equally valid for both 6th and 7th stage blades. It should be noted however that the fundamental bending natural frequency for the stage 6 blade is lower than that for the 7th stage blade, ie. 1400 - 1500 Hz compared to 1750 - 1950 Hz respectively.

In this investigation the following test procedure was used:

a. Four stage 6 blades (a randomly selected sample) were inserted one at a time into the single-blade test fixture Figure 1. In this jig each blade had a clearance of at least 0.004 inch below the upper blade fir tree platform or land. The fundamental bending natural frequency of each blade was then measured using the method described in Annex C.

b. The sixth stage compressor blades were then inserted into a segment of a 7th stage disc such that two blades had a significant clearance at the upper land, achieved by machining the disc rim, whilst the remaining two blades were araldited into the blade disc to ensure zero gap at the interface. (Previous unreported tests at ARL had demonstrated the effectiveness of using araldite (at room temperatures) to achieve an interference fit at the rim). The disc segment was then mounted into a fixture such that the blades could be excited by an air jet and their respective frequencies determined.

c. The 4 blades were then removed from the disc segment and step a. repeated.

d. Following step c. above, step b. was repeated.

e. The procedure of step a. was repeated but this time with a new sample of four randomly selected stage 6 blades.

f. Following step e., step b. was repeated for the new set of blades but this time using a complete disc assembly, Figure 2, rather than the disc segment used previously.

3.0 RESULTS

The results for steps a, b, c, d, e and f. are summarised in Table 1, whilst a collation of the respective frequency differences obtained from the single blade fixture and the disc/disc segment fixture are given in Tables 2, 3 and 4. The results from these latter tables indicate that (data

ANNEX D (cont.)

(b-a), (d-c) and (f-e)) the fundamental frequency of the blade held in the disc with an interference fit has been increased by up to 58 hertz whilst that for the blades with a platform clearance has been reduced by as much as 30 hertz. In total a difference between unsupported to supported (light gap to no light gap) blade frequencies of the order of 42 to 78 hertz was recorded. These results are comparable to the results of Annex C for the 7th stage blades where a difference in frequency levels of up to 72 hertz was observed.

It should be noted that transferring of a blade from the "reference" single-blade fixture to a position in the disc/disc segment which also has a clearance or light gap results in a lowering or reduction in the respective blade frequencies. It is believed that this reduction is due to the "softer mounting" of the disc/disc segment when compared to the rigidity of the single-blade fixture; the reduction in blade frequency is also evident for the blades with no clearance at the upper lands ie. the araldited blades. Notwithstanding these latter comments it can be seen from these limited tests that it is possible to identify whether the blade is supported at the blade platform by an analysis of the change in blade frequencies. However before this experimental procedure can be used definitively on the shop floor some further investigations and comments should be made. In particular some comments on the lack of repeatability in the single-blade fixture (steps a and c) is required. The reason for the difference is not obvious at first but it is believed to be associated with a varying degree of contact of the lower blade fir tree roots when reinserted into the single-blade fixture. In the present tests it was not possible to reproduce consistent blade insertion loads or contact surfaces. However it is believed that the level of repeatability is within the limits necessary to identify blades which are assembled without an interference fit ie. with a light gap at the upper blade platform.

TABLE 1

Test	Blade No.	Fund. Bending Frequency Hz	Comments
(a)	1	1374	
Single-blade clearance	2	1490	) all blades have
Fixture	3	1500	) under platform
	4	1380	
(b)	1	1354	platform clearance
Disc segment	2	1484	" "
	3	1536	platform interference
	4	1422	" "
(c)	1	1380	
Repeat Single-clearance	2	1498	) all blades have
blade fixture	3	1518	) under platform
	4	1394	
(d)	1	1350	platform clearance
Repeat Disc	2	1476	" "
Segment	3	1542	platform interference
	4	1426	" "
(e)	1	1410	
Single-blade clearance	2	1404	) all blades have
fixture (new	3	1482	) under platform
blade set)	4	1456	
(f)	1	1390	platform clearance
Disc (new blade	2	1398	" "
set, complete	3	1536	platform interference
disc)	4	1514	" "

ANNEX D (cont.)

TABLE 2
Results of Test (a) subtracted from Test (b)

Blade Number	Freq. Diff. Hz	Comments
1	-20	) platform clearance
2	-6	) in disc
3	+36	) no platform clearance
4	+42	) in disc

TABLE 3
Results of Test (c) subtracted from Test (d)

Blade Number	Freq. Diff. Hz	Comments
1	-30	) platform clearance
2	-22	) in disc
3	+24	) no platform clearance
4	+32	) in disc

TABLE 4
Results of Test (e) subtracted from Test (f)

Blade Number	Freq. Diff. Hz	Comments
1	-20	) platform clearance
2	-6	) in disc
3	+24	) no platform clearance
4	+58	) in disc

4.0 CONCLUSIONS

The results of tests on a small sample of sixth stage Gazelle compressor blades has shown that it is possible to identify blades in a disc which have been assembled with a clearance at the fir tree upper platform. The degree of fit or interference, for each blade, is determined by making a comparison of its individual blade frequency as measured in a reference, single-blade, fixture and then as installed in the actual disc.

However, before the procedures can be used on the shop floor further testing will be required to assess the overall repeatability of the process. Details of these tests and proposed production/shop floor procedures are given in Annex K.

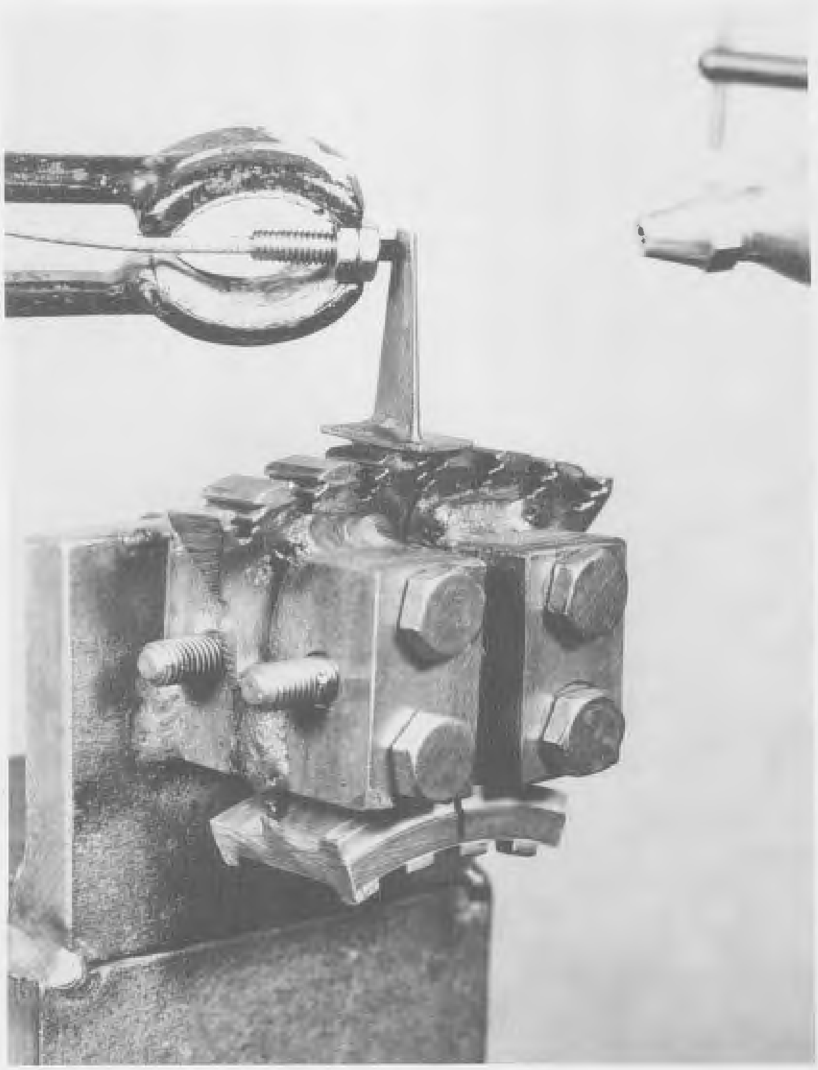


FIG 1. SINGLE BLADE – FREQUENCY TEST FIXTURE

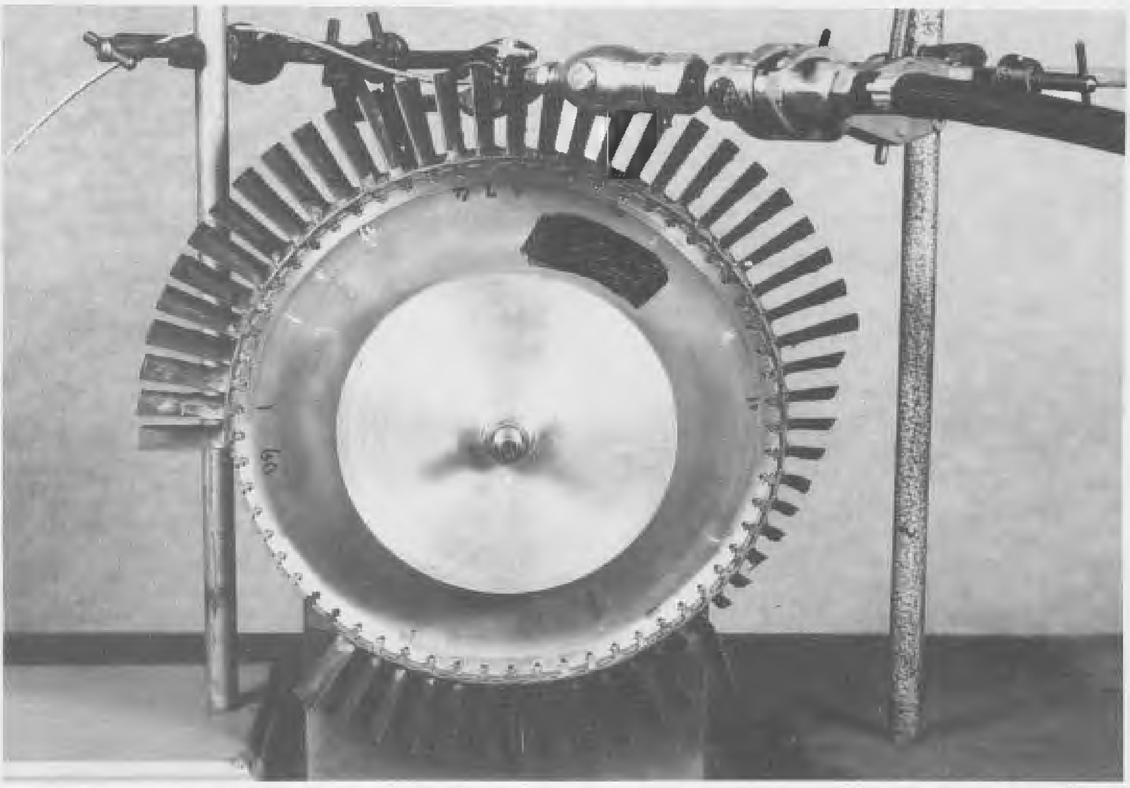


FIG 2. PARTIALLY ASSEMBLED BLADE/DISC FOR DETERMINING BLADE FREQUENCIES

ANNEX E

BLADE FIR TREE ROOT PROFILES, AS FORGED, COPPERED AND ROLLED

1.0 INTRODUCTION

Following an analysis of reports from previous blade failures in Gazelle 7th compressor blades, particular attention was directed to Reference 13 (of the main report) in which it was concluded that blades which were close to form except at the top faces were generally short of material; this shortage of material at this top face also tended to produce clearance on assembly. In addition it was shown that blades which were copper plated and had been rolled exhibited a deviation at the top face (land), this deviation increasing as the number of passes through the rollers increased; deviations as high as .0025in were noted. These deviations cannot be minimised by high insertion loads. To confirm these conclusions a comparison of new, coppered and rolled blades was undertaken on a number of 7th stage Gazelle compressor blades.

2.0 METHOD

Four new unrolled seventh stages compressor blades, two of which were uncoppered, were checked against 20X master fir tree root profile in the metrology sections at Commonwealth Aircraft Corporation and Hawker de Havilland. Following dimensional checks the coppered blades were rolled whilst the uncoppered blades were plated to give copper deposits of approximately .002 in and then rolled. Dimensional checks of the four blades were then repeated. HdeH ERF 18 (NBE 077-IR RAN 1807.) gives full details of specified procedures. It was anticipated that these tests, whilst not statistically significant in themselves would confirm the tests reported by Rolls Royce in Reference 13 of the main report.

3.0 RESULTS

The inital results obtained on the X20 shadowgraph by HdeH and CAC were in general agreement, however, for the second set of measurments HdeH did not detail specific deviations from the master drawing, rather measurments were only made across the Napier/Rolls Royce specified A B C points required for inspection of forming tool, see Figure 1. A typical shadow graph analysis against the master profile is given in Figure 2. A summary of the measurements made by CAC and HdeH for the 4 blades is given in Table 1, specifically for the position of the blade upper land with respect to the master drawing.

In summary the results for blades 1 and 4 before and after rolling indicate that in both cases the top land had moved approximately .001 in. away from the nominal surface during the rolling process. The results for blades 3 and 4 are more difficult to interpret in that a full comparison with the master drawing was not made after the copper plating and before rolling. From the CAC data it is apparent the plating and rolling process increased the root dimensions overall by approximately .002 in. Whilst comparison of the respective BC dimensions before and after rolling suggests that the rolling process squeezed and reduced the copper plating layer by .001 in ($\Delta B/5$, $\Delta C/5$). It is estimated from the HdeH figures that at least .0025 in of copper had been deposited. The rolling process had redistributed about .002 in of copper plate.

4.0 CONCLUSION

The measurements made on the four test blades indicate that the rolling process effectively redistributes the copper plated on to the fir tree root surface. There are however, concerns that the redistribution is not uniform and that more material is removed from, or blade surface deformed, in the region of the blade upper fir tree root land. These trends are in agreement with the Rolls Royce results. If these results are mantained with successive rollings (as was shown in Reference 13 of the main report) then the upper land will continue to move away from its correct position; hence increasing the likelihood of producing a light gap at the blade upper land/disc interface. It is therefore recommended that the number of profile rollings be kept to a minimum. If rolling has to be carried out then consideration should be given to relieving the sides of the rollers (negative bias) in regions of the upper land. That is, remove material from the rollers such that the upper land of the blade is not rolled, or has only minimal rolling pressure applied to the surface. This technique would be equivalent to selectively plating of the upper land.

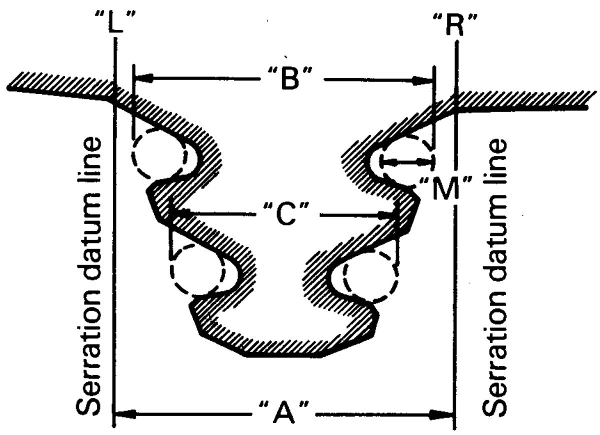
	BLADE 1		BLADE 2		BLADE 3		BLADE 4	
	L	R	L	R	L	R	L	R
C.A.C.	.0023	0	.0015	0	.002	0	.0030	0
HdeH	.0025	0	0	0	.001	0	0	0
HdeH a.	.2467		.2453		.2453		.2483	
b.	.242		.2106		.2106		.2136	
c.	.1574		.1559		.1560		.1595	
After Rolling	Δb = .005 Δc = .001						Δb = .0013 Δc = .0023	
C.A.C.	.002	-0.0015					.002	-.001
HdeH	–	–					–	–
HdeH a. b. c.	.2462 .2115 .1564						.2470 .2123 .1572	
After plating			Δb = .0129 Δc = .0126		Δb = .0124 Δc = .0127			
HdeH a. b. c.			.2557 .2230 .1685		.2557 .2230 .1687			
After Rolling			Δb = .002 Δc = .003		Δb = .0045 Δc = .005			
C.A.C.			.004	.002	.005	.002		
HdeH			–	–	–	–		
a. b. c.			.2557 .2210 .1655		.2532 .2185 .1635			

TABLE 1 SUMMARY OF '4' BLADE ROOT DIMENSIONS

Standard fir tree root
blade root

SK.No. 10122

Dimensions for tool inspection



Diameter of measuring wire "M" =.038″

"A" = "B" +.0347″
"C" = "A" – [.0889″ ± .000¼″]

Dimension "A" = .2465″ $^{-.0002''}_{-.0012''}$

For dimension 'C' the actual value of 'A' derived as shown above must be used.

Supersedes SK. No. 10024

D. Napier & Son Ltd.
Acton Vale, London, W3

FIG. 1 "ABC" DIMENSIONS FOR TOOL INSPECTION

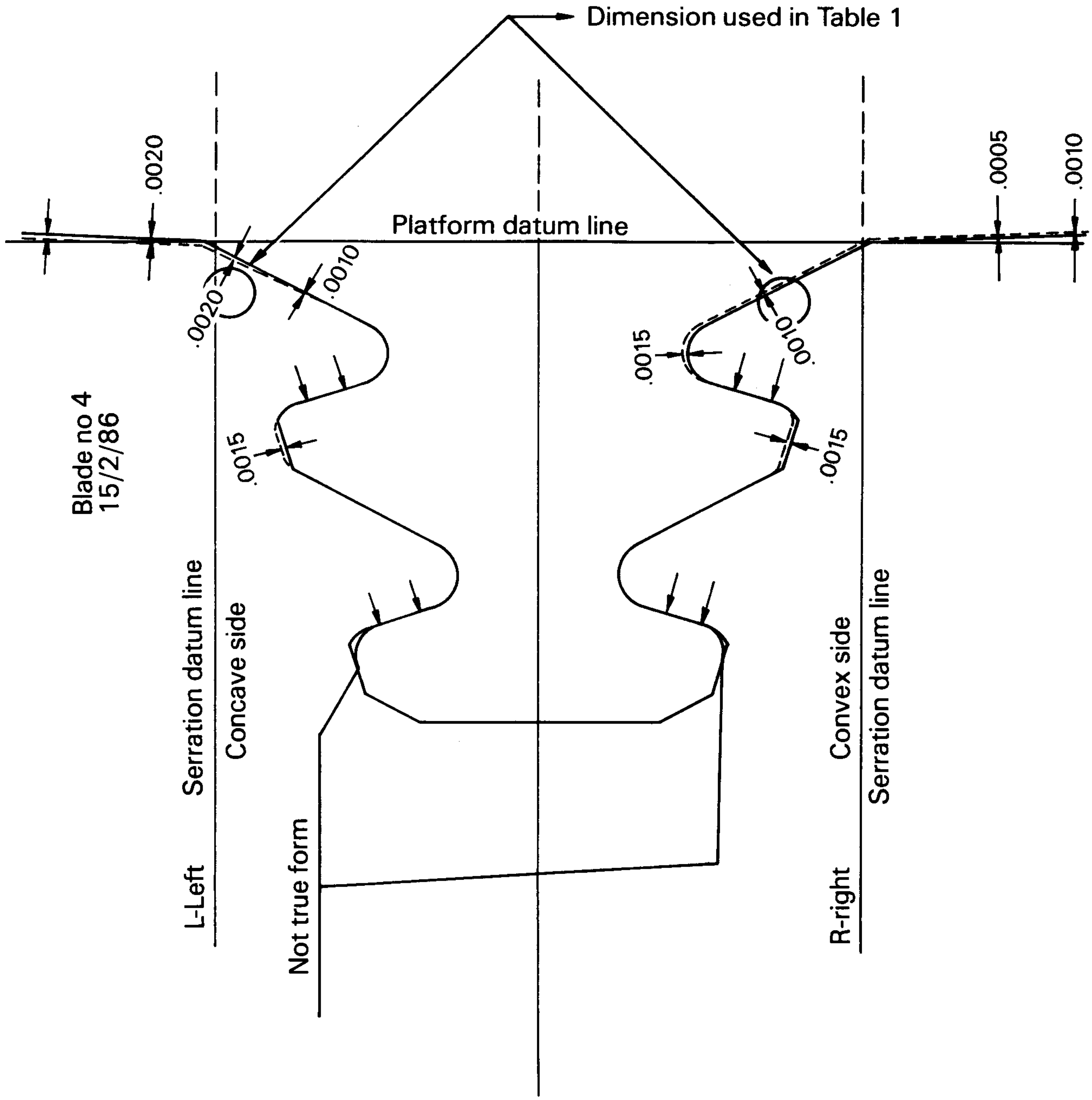


FIG 2 EXAMPLE OF BLADE PROFILE DIMENSIONAL CHECK

ANNEX F

IMPACT LOAD TESTS ON COMPRESSOR BLADES IN A GAZELLE MK165C

1.0 INTRODUCTION

The effects of blade fragments emmanating from the 7th stage compressor impinging on blades of the 7th stage and later stages of a Gazelle compressor were simulated by dropping a guided weight on to selected blades of a 6th stage Gazelle compressor disc. The blades, disc and root fixtures of the 6th stage closely resemble in design and materials those of the 7th and remaining stages and hence results obtained should be representative for these later stages.

2.0 METHOD

The complete disc, as removed from the failed engine, was firmly mounted on a support bracket with blades to be struck projecting horizontally and with their chord line also horizontal. The tips of some of the adjacent blades were removed to allow access for the falling weight; Figure 1 shows the system set up with the weight above blade. The weight or simulated fragment had a mass of 490 grams with a spherical striking surface of 12mm dia. it was arranged to strike the blade approximately 6mm from its tip. The blades selected for testing were Nos. 33, 34, 35, 36, 37 and 39; of these Nos. 35 and 36 had failed a light check test carried out during engine strip and rebuild subsequent to the engines failure. Table 1 and Reference 6 of the main report gives details of the rebuild. The existence of the light gap on blades 35 and 36 was confirmed at ARL prior to the impact tests; the remaining four blades appeared to be satisfactorily held in the disc. During the tests the weight was dropped 600mm for blades 34 and 35, and 1000mm for blades 33, 36, 37 and 39.

3.0 RESULTS

Examination of the six blades after the impact tests showed that despite considerable damage to all blades, some had been severely cracked, none of the blades were loosened in their root fixture, neither was there any change in the pre-existing light gaps. In the case of blades 35 and 36 which had shown light gaps, there was no change in light gap, even though the direction of impact, Figure 2, was such as to close the gap: notwithstanding this the blades themselves were severely distorted. A summary of the test results for the six blades is tabulated below.

Blade No.	Summary Result
33	Blade bent to touch No. 34 TE crack 6mm long 5mm from root.
34	Blade bent to within 2mm of No. 35.
35	Blade bent to within 3mm of No. 36.
36	Blade bent to touch No. 37.
37	Blade 38 removed before test. Blade 37 bent 8mm.
39	Blade 40 removed before test. Blade 39 bend 10mm. TE crack 6mm long 6mm from root.

4.0 CONCLUSIONS

Impact tests on 6th stage compressor blades, as fitted into a Gazelle compressor disc, has shown that even with high impact loads causing severe distortion and cracking to the blades it was not possible to loosen the blade in its root fixture or modify or create a light gap at the interface of the compressor disc and top most fir tree root blade land. It is believed that these limited tests show that it is most unlikely for impacts of foreign objects or blade fragments on the 6th, 7th and 8th stage blades and discs in the failed engine to have affected the fit of the blade root in the disc slot. Consequently it is most likely that the blades which were found to be loose or failed the light gap check during strip and rebuild were in that condition from initial assembly.

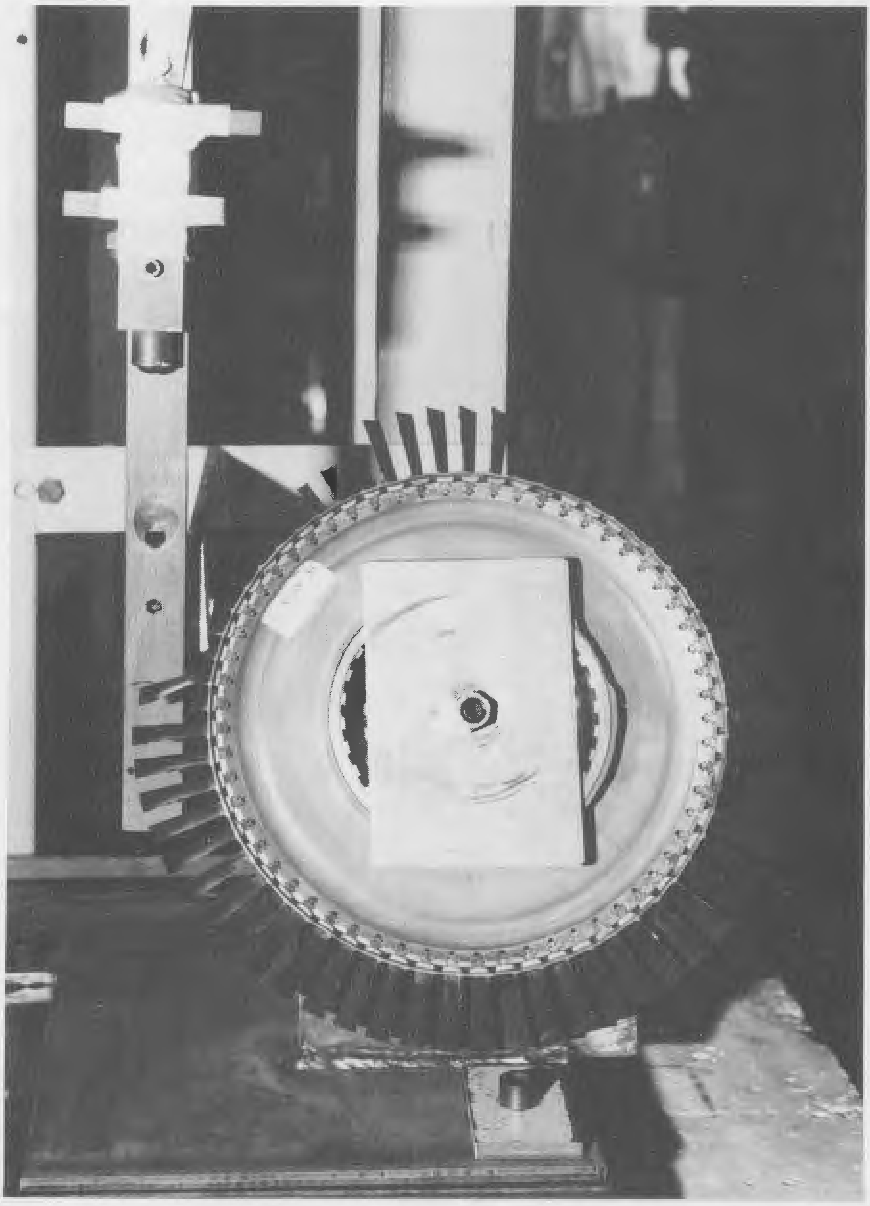


FIG 1 6TH STAGE DISC AND WEIGHT FOR BLADE IMPACT TESTS

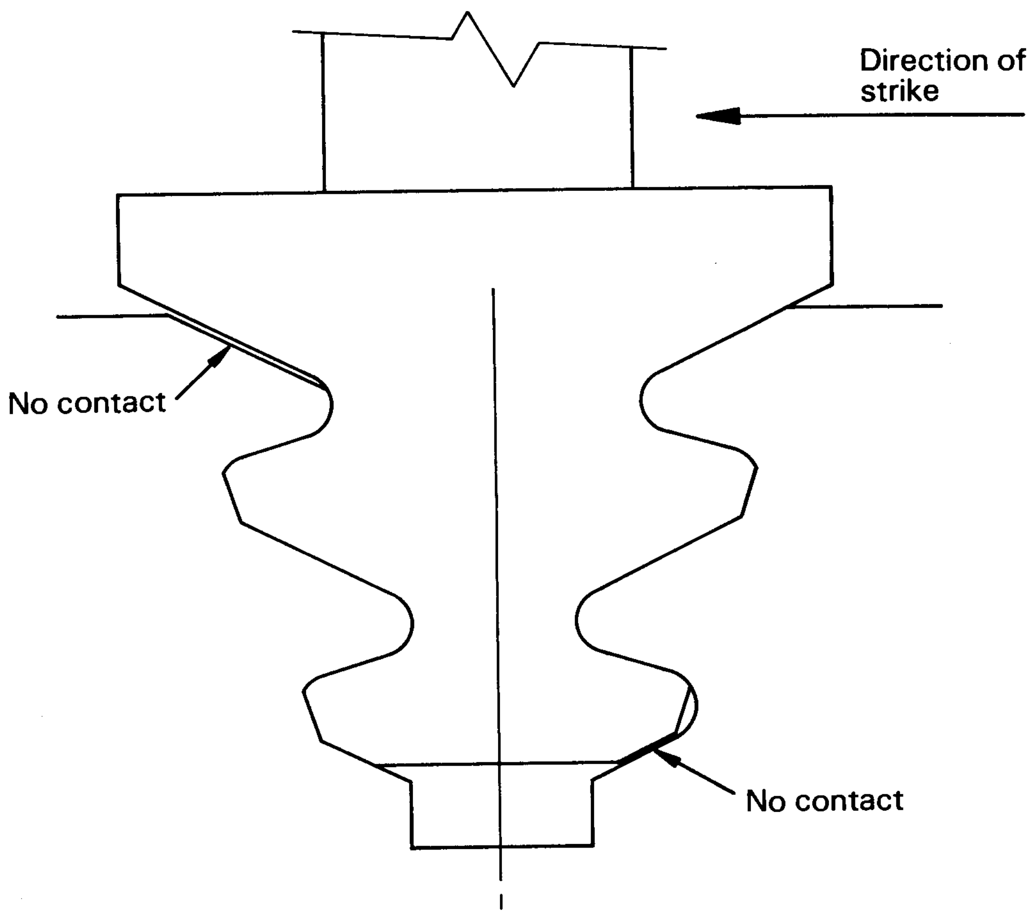


FIG 2 BLADE ROOT FITS FOR BLADES NOS 35 & 36

ANNEX G

"LOOSE BLADES" - SEVENTH STAGE COMPRESSOR DISC

1.0 INTRODUCTION

During the strip and rebuild of the compressor of RR Gazelle Mk 165C - GA2033 which was carried out by Hawker de Havilland subsequent to the blade failure, see section 3.1 main report, two loose blades (12 and 59) were found in the seventh stage compressor disc.

These two blades exhibited large quantities of PL 94/Molykote 106 sealant on the fir tree root blade upper land surface, that is in the region where there **should not be** a light gap. From the deposits it was obvious that at the time of initial build a substantial gap must have existed at this critical interface, however it was not known if any contact might have been present to satisfy the minimum requirements of the light check. Reference to Figure 4b of the main report indicates the minimum degree of contact which is considered to be acceptable, whilst section 5.2.1 details however small quantities of dirt, oil or hair can give a false indication of contact between the two surfaces. As a consequence it was a matter of some concern to determine if a gap could have been present at the initial build, and if so whether the blades would show some sign of cracking or failure at the blade root. It should be noted that these blades would have been subject to the same level of vibration which had caused the original seventh stage blade to fail.

Investigations into the condition of the "loose" blades centred on the following:

a. Estimation of thickness and area of contact of the PL94/Molykote 106,
b. Removal methods for PL94/Molykote 106 without damage to copper plating or incipient cracks in the copper plating, and
c. Examination of blade root for signs of cracking or fatigue failure.

2.0 THICKNESS AND AREA OF CONTACT OF PL94/MOLYKOTE 106

Following numerous discussions with the Metrology Section of Engineering Facilities ARL and contacts with engineering manufacturers, distributors of surface measuring equipment in Australia including CSIRO, CAC, Ammunition Factory Footscray (AFF) and AEL at DRCS it was finally decided to measure the sealant thickness and area by mechanical means using a ZEISS UMM500 COMPONENT MEASURING MACHINE at AAF. In the course of the investigation it had been hoped that a computerised optical system using self focussing light sources might have been "found" and used for non intrusive measurement - this was not to be so! An attempt was made to photograph the sealant layer under a scanning electron microscope, however the automatic exposure system could not cope with the electrical charge build up. To alleviate this problem a surface layer of carbon was deposited on the sealant layer; even then it was not possible to obtain a satisfactory quasi 3 dimensional photograph of the surface.

Because of the time delays involved in selecting a procedure for measuring the sealant thickness on the two blades and because it was imperative to check on the fir tree root condition of at least one of the blades it was decided to forego measuring the sealant thickness on one blade No 59. This blade was stripped of its sealant, PL 94/Molykote 106 using citric acid, see section 3.0, and examined for cracks, Section 4.0.

2.1 ZEISS UMM500 CMM

The measurement procedure used with the ZEISS UMESS measuring head of the ZEISS UMM 500 CMM consisted of setting up the blade surface or sealant layer to be contoured such that a number of parallel traverses could be made along the surface, first with the sealant in position and then with it removed. To enable the blade root to be removed from the measuring head and replaced such traverses across the surface could be repeated, it was necessary to provide a setting up or reference plane on the fir tree roots. This was achieved by machining the base of the fir tree root. Figure 1 shows a typical reference plane in contrast to a complete blade.

The surface of the sealant and the cleaned fir tree root were measured using ZEISS UMESS measuring head fitted with a .8 mm diameter ball. Seven traverses were taken at .2 mm

ANNEX G (cont.)

Pitch with readings being taken at spacings of .2 mm. The sequence of events is illustrated in Figures 2 and 3. Traverses were taken on both the rear and front faces as defined. Once the contour of the sealant had been measured the blade was removed from the jig, the sealant dissolved, surface cleaned and the blade reinserted into the jig using the machined reference plane to relocate it to its original position. The surface of the clean fir tree root was then measured. The arithmetic difference between the two sets of traverses was used to calculate the sealant or coating depth. Typical results for both rear and front faces are given in Figures 4 and 5 : it should be noted however that the effective depth of the sealant is given by d cos α where d is the vertical movement of the measuring head and α is the slope of fir tree root surface as defined in Figure 3.

3.0 DISCUSSION

As noted above Figures 4 and 5 give results for "d" the vertical depth of the sealant; data are presented for tracks 1 - 6 but are not plotted for track 7. During cross checking of the measured data, using results from the "as clean runs" it was determined that the fir tree root slope between traverses 6 and 7 was not equal to the nominal value of 28°. It was obvious that the seventh traverse was not on the fir tree root, the measuring ball was in the region of the intersection of blade platform and the fir tree root, see Figure 3 for a diagramatic representation. On this basis the readings for the seventh traverse were discarded.

Before discussing the results for the remaining six traverses and estimating the thickness and coverage of the layer of sealant some comments on the validity of the measurements are required. In particular the ability of a .8 mm traversing head to contour thicknesses at pitches of .2 mm needs to be examined. A geometrical representation of the measuring process is given in Figure 6a, from this figure it can be seen that it is possible for the size of the measuring ball and discontinuity in sealant layers to be such as to preclude a correct reading being obtained. In the example the traverse along 'b' is obviously in error. A simple criterion for maximum discontinuity which can be discriminated between any two traverses or measurements is developed in Figure 6b in terms of ball diameter, traversing pitch and measurement spacing. For this particular case with a ball diameter of .8 mm and pitch and spacings of .2 mm the nominal value for δ ref or δ ref vert is .0697 and .0785 mm (.0697/cos α where $\alpha = 28°$) respectively. That is provided the differences in layer depths between any two consecutive or side by side readings is less than .0785 mm (as measured vertically by the ZEISS UMESS head) then the readings are acceptable.

Examination of Figures 4 and 5, which plot sealant depth as measured vertically (δ v), shows that maximum sealant thickness is .0665 mm, (Track 1 Point 48 - Front face). Using the above criterion, for this value to be correct the indicated depth of sealant thickness on adjacent sides of point 48 must be greater than zero. In this case the maximum value of [δ b - δ a] is only .011 mm well inside the prescribed limits. Scanning the remaining data indicates that the maximum recorded value of [δ b - δ a] is .0397 mm (Track 6 points 48 - 49 on the Front face) again well inside the limit of .0785 mm. From these observations it is believed that the traces given in Figures 4 and 5 are a true representation of the depth and distribution of the surface layers of PL 94/Molykote 106.

Examination of the sealant layers in terms of thickness distribution on both front and rear faces indicates that the surfaces have a general coverage of at least .01 mm (4/10 of 1 thousandth of an inch) at positions 0 - 6 all tracks increasing to .05 mm (2 thousandth of an inch) at positions 40 - 50, again all tracks. A maximum thickness of .059 mm or about 2 ½ thousandth of an inch is indicated. The sealant is typically wedge shaped indicating that the blade could have been tilted as it was inserted into the disc.

From the tests carried out by ARL at Hawker de Havilland on the Light Check Method (Section 5.2.1) it is estimated that a gap of ½ of 1 thousandth of an inch could have been picked up. Therefore, provided the blade surfaces were clean and free from oil or dirt, the gaps as indicated by the depth of sealant given in Figures 4 and 5 should have been observed. However it is possible that poor focussing or location of blade/disc in shadowgraph could have obscured

ANNEX G (cont.)

The minor gaps. Notwithstanding the above comments it is highly likely, on evidence presented, that this blade had been assembled with a light gap from the initial compressor build. Whether the blade was loose in the disc is a matter of conjecture : the ARL impact tests ANNEX F did not address the situation of a blade with a light gap which was filled with sealer. A nominally fixed blade, under these circumstances, could have come loose when impacted.

4.0 CONCLUSIONS

The contour measurements made on the sealant deposited on one of the loose blades identified in the seventh stage compressor disc, indicated that for all intents and purposes a continuous film was present. The film whilst of varying thickness and extremely thin was sufficient proof, in this particular case, that a light gap must have existed between the disc and blade fir tree root upper land. From the thickness of sealant (.01 mm — .05 mm) the gap would have been observable on the HdeH shadowgraph, and should have been identified prior to assembly into the Gazelle compressor.

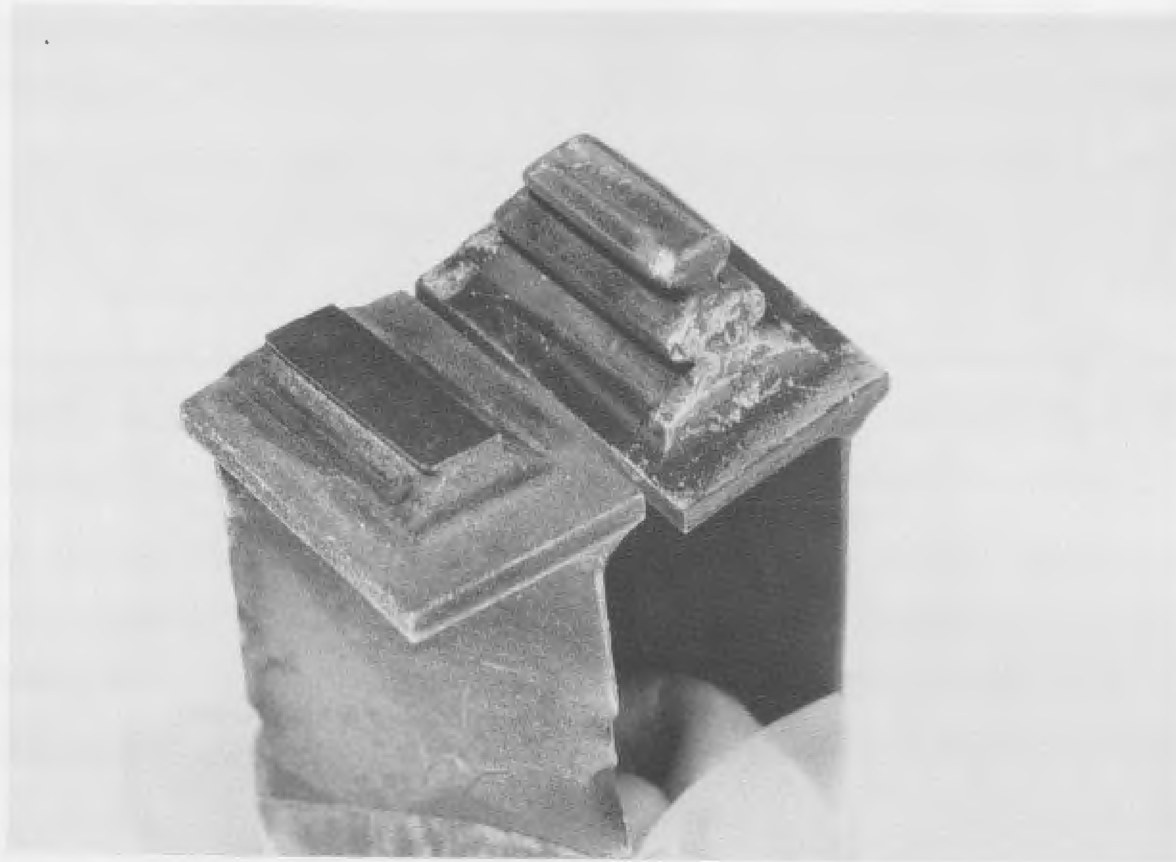


FIG 1 REFERENCE MEASURING PLANE FOR GAZELLE COMPRESSOR BLADE

COMMERCIAL-IN-CONFIDENCE

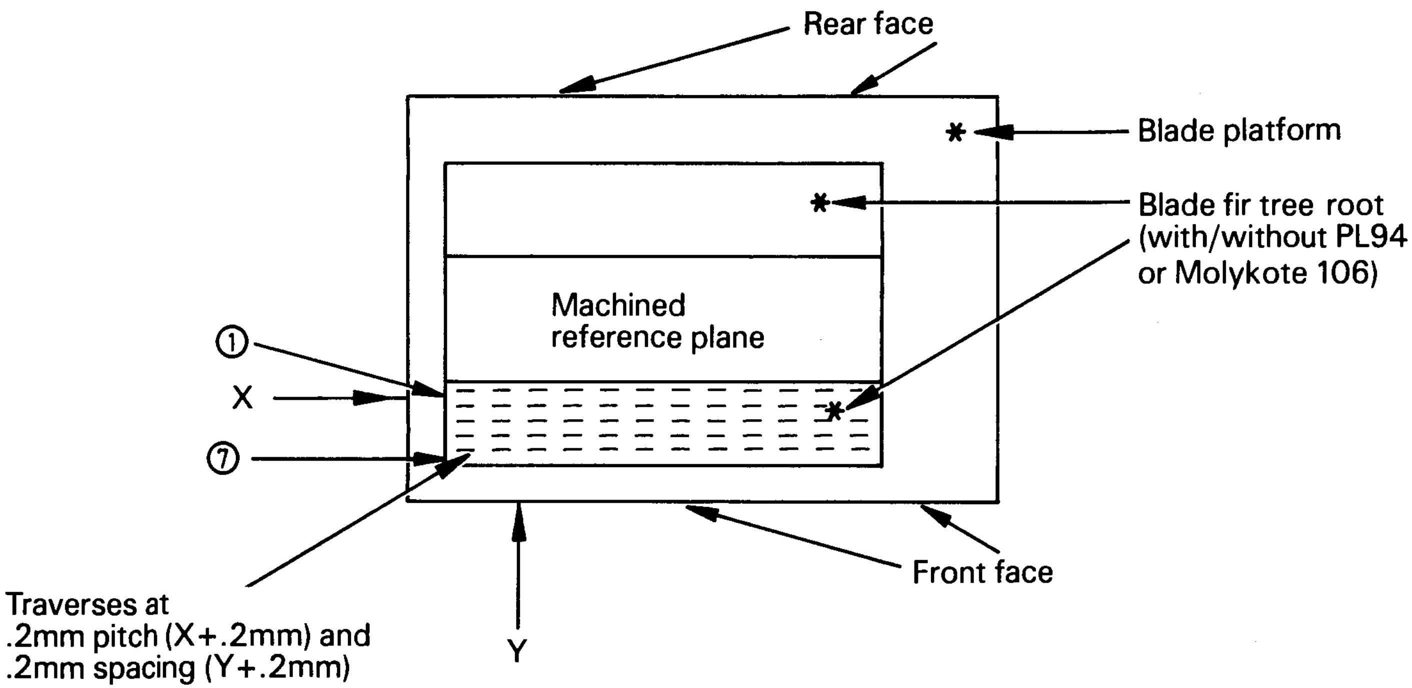


FIG 2 BLADE COATING MEASUREMENTS USING .8MM BALL ON ZEISS UMESS MEASURING HEAD

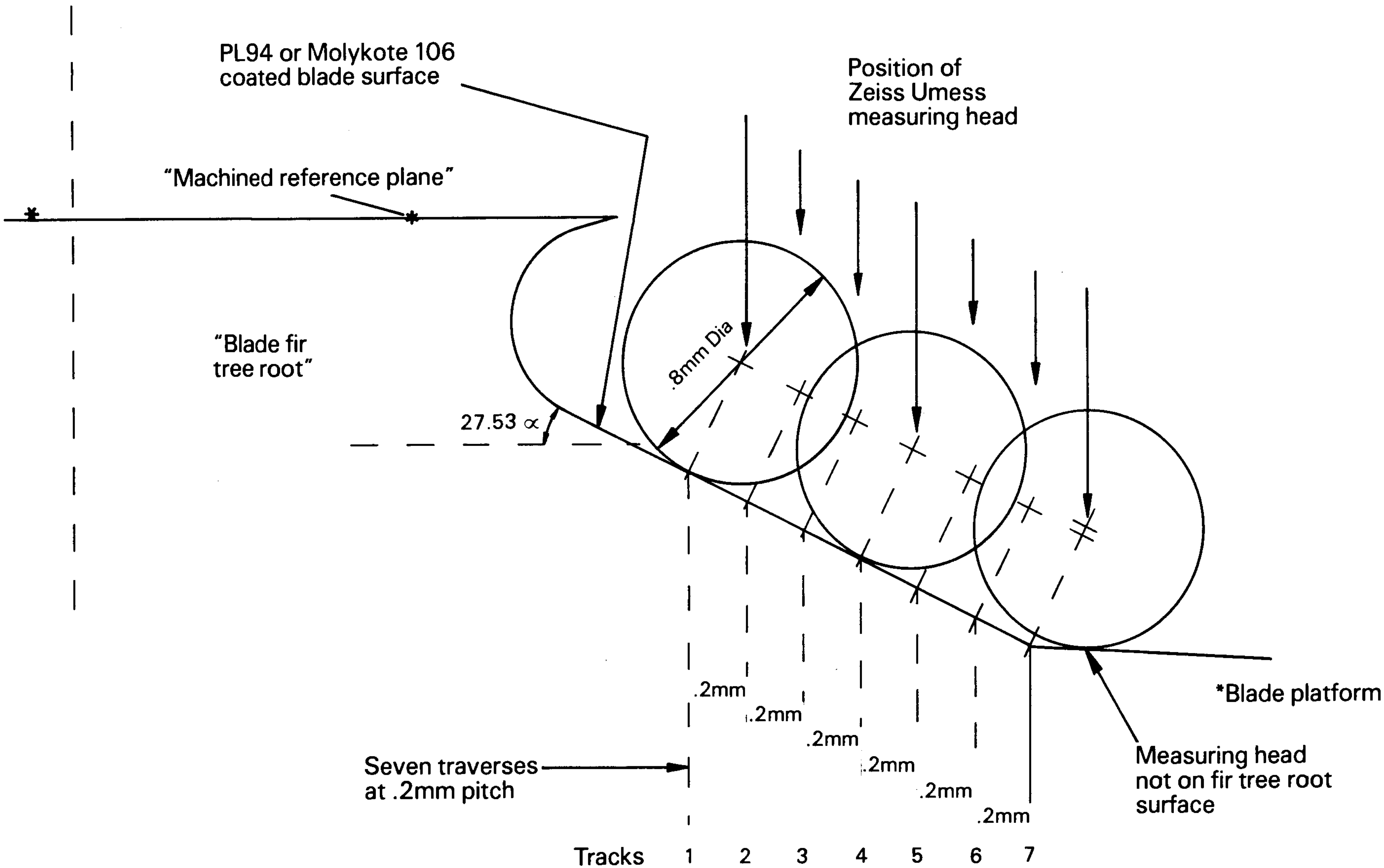


FIG 3 DETERMINATION OF BLADE COATING THICKNESS

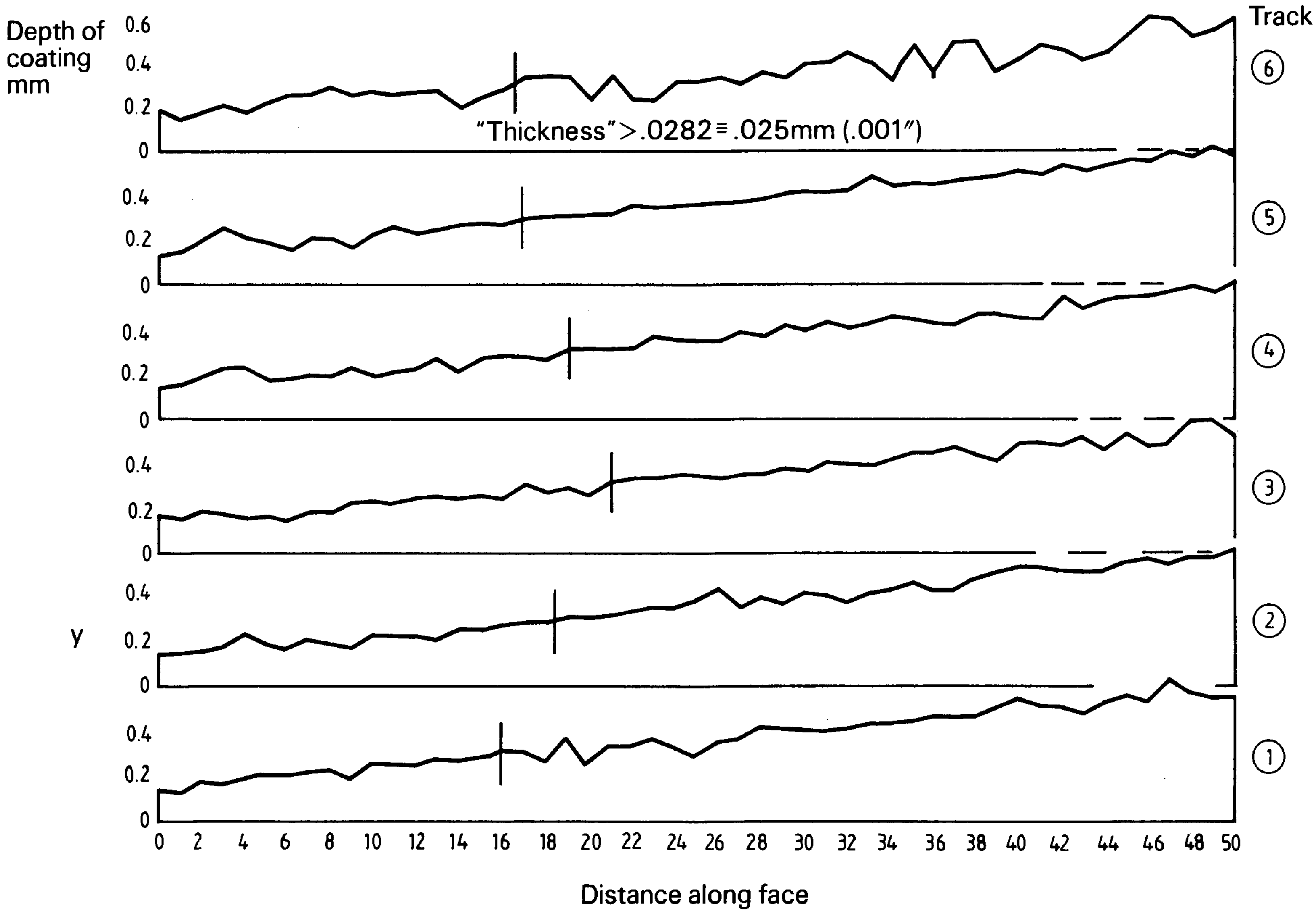


FIG 4 DEPTH OF SEALANT COATING: BLADE 12 REAR FACE

COMMERCIAL-IN-CONFIDENCE

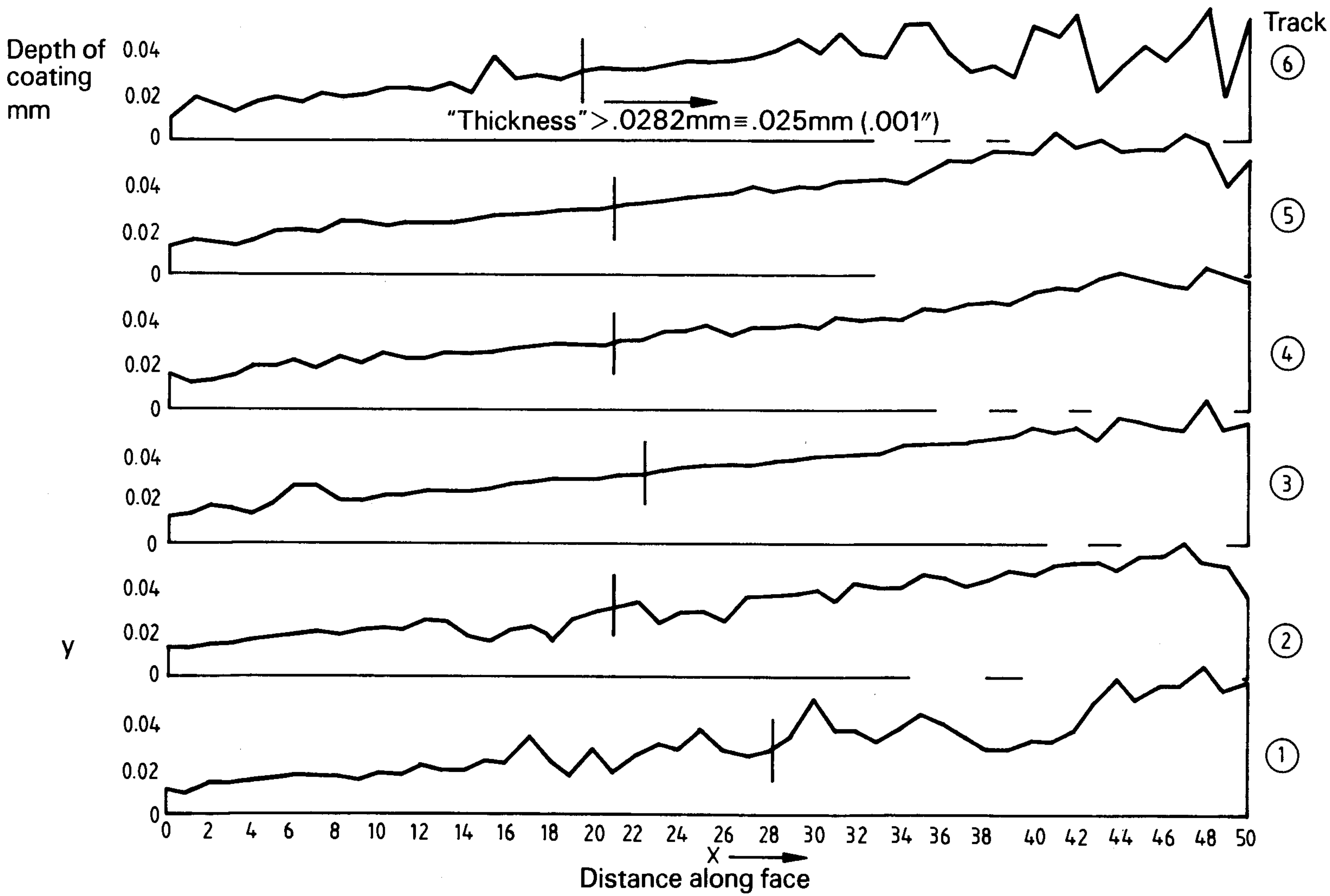
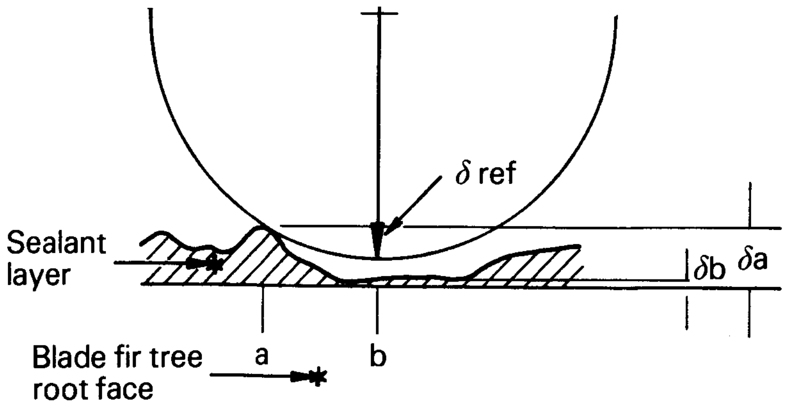


FIG 5 DEPTH OF SEALANT COATING: BLADE 12 FRONT FACE

COMMERCIAL-IN-CONFIDENCE

FIG 6A



$\delta a - \delta b > \delta ref$

ball will not touch layer at b

$\delta ref = r - r\cos\theta = r(1-\cos\theta)$
$\sin\theta = x/r$
$x = \dfrac{s}{\cos\alpha}$
$s = .2mm \quad \alpha = 27.533 \quad r = .4mm$
$x = .2255$
$\theta = 34.32^{\circ}\cos$
$\delta ref = .4(1-\cos 34.32)$
$= .0697$
$\delta v = .0697/\cos 27.53$
$= .0785$

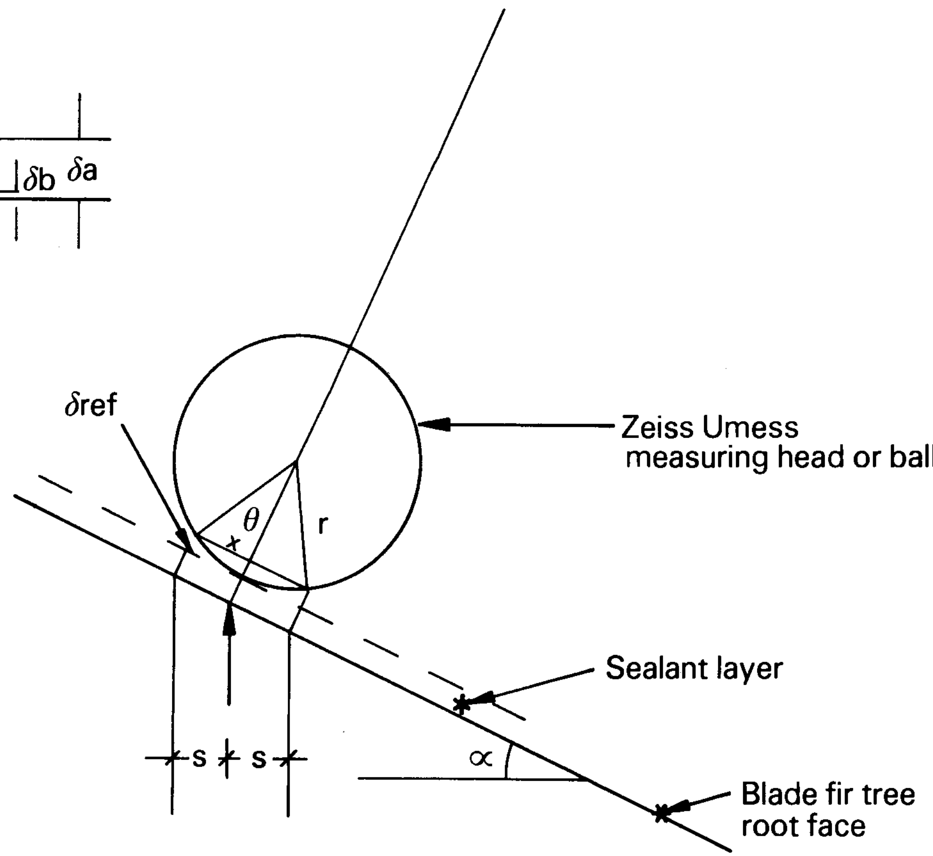


FIG 6B

r = Zeiss Umess ball radius
s=Distance between tracks
∝=Nominal blade fir tree root face angle

FIG 6. ANALYSIS OF TRACK WIDTH AND MEASURING DEPTH INTERMS OF BALL DIAMETER

COMMERCIAL-IN-CONFIDENCE

ANNEX H

FINAL REPORT (METALLURGICAL)
GAZELLE ENGINE 7th STAGE COMPRESSOR BLADE FAILURE

1. Reference A requested that Aeronautical Research Laboratories (ARL) determine the mode and causes of the failure of a 7th stage compressor blade from a Gazelle Mk 165C engine, SN GA2033. The initial findings with respect to the blade failure are set out in reference B. Briefly, it was found that the blade had failed in reversed-bending fatigue, cracking through the first fir-tree root beneath the blade land, and that the cracking had initiated at a small inclusion. This report sets out the findings of the metallographic examination of the failed blade and the final conclusions drawn concerning the blade failure.

2. Metallographic sectioning of the remains of the failed blade was carried out in the presence of a representative of Hawker de Havilland (Sydney). The main aim of this operation was to examine the copper plating adjacent to the primary initiation site (see Ref B) in order to determine the quality of the copper plating (reference C attributed the failure to '.... vibratory fatigue from multiple origins located in axial blade broaching scores exaggerated by copper plating in the second serration root radii ...The fatigue stressing was concentrated at the undesirable plating scores resulting in crack propagation and ultimate failure').

3. The blade was sectioned as close as practical to the primary origin and an attempt was made to polish up to the initiating inclusion (see Ref B); this proved unsuccessful. However figure 1 shows a polished and etched section from the failed blade, immediately adjacent to the primary initiation site and estimated to be within 0.2 mm of the initiating inclusion. A closer examination of the copper plate in this region did not reveal any evidence of gross plating defects which could have initiated cracking. Indeed examination of the etched microstructure of the copper plate close to the fracture surface revealed three layers of plate (arrows A, Figure 1), the boundaries between the layers ending sharply at the break in the copper plate (at arrow B, Figure 1).

4. It was noted (Ref A) that the failed blade was from a manufacturing batch designated '7PJ'. For comparison, a number of other blades from the disc containing the failed blade were also sectioned and polished for examination of the fir-tree region. Included in these other blades were examples from the 7PJ batch as well as blades from batches 7AZ and 7AAW.

5. Initially, metallographic sections of sample blades (including the failed blade) were compared in the unetched condition. It was noted that the failed blade, and the 7PJ blades in general, had a higher inclusion content. In particular, long stringer type inclusions (Figure 2) were seen in this batch but not in other batches examined.* The major dimension of these inclusions was aligned, approximately, with the length of the blade, ie. perpendicular to the fracture surface of the failed blade. In an attempt to quantify the observed apparent difference in inclusion content between batch 7PJ and other blade batches, an inclusion size and distribution analysis was performed on the failed blade and on a blade from batch 7AZ. The results of this analysis are represented graphically in Figure 3. In each case all observable inclusions were measured over an area of approximately 2.5 mm^2 of the blade cross-section in the fir-tree.

6. Comparison of the two graphs in Figure 3 demonstrates a significant difference in inclusion size and content between the failed blade and the blade from batch 7AZ. The parameter measured is the maximum dimension of the inclusions (DMAX), and the graphs show the (absolute) frequency of a particular particle size. The failed blade contains a greater number of larger inclusions (up to about 30 microns) and has a greater number of inclusions overall. Significantly the median (most frequent) particle size in each case is about 2 microns (the inclusion which initiated cracking in the failed blade had a diameter of about 1.6 microns). While

* This statement applies ONLY to the sample blades examined. The sample CANNOT be regarded as a statistically significant sample of all the blades in a particular batch.

ANNEX H (cont.)

noting that general conclusions regarding inclusions in blade batches cannot be drawn from the small sample examined, it is apparent that the failed blade and other blades examined from batch 7PJ, had a higher overall content than blades from other batches. The observed increase in the size and number of inclusions in the component would also increase the probability of an inclusion initiating a crack.

7. The etched macrostructure of the failed blade was markedly different to other blades and even to other blades from the 7PJ batch. Figure 4 shows the etched macrostructure of the failed blade while figure 5 shows the macrostructure of a blade from batch 7AZ (both at the same magnification). The failed blade exhibits a distinctly banded, non-homogeneous structure in comparison with the other blade (both blades were etched for a similar time in the same etchant). All other blades examined showed a similar macrostructure to that shown in figure 5. The banded nature of the failed blade macrostructure indicates a markedly varying metallurgical phase structure.

8. At higher magnifications the microstructure of the failed blade was complex (figures 6 & 7). The lighter etching bands (mottled grey, Figure 4) which was in the majority, consisted of an alpha matrix containing rounded particles and lamellae of kappa (see Figure 7). The darker etching stripes in figure 4, however, exhibited quite a different structure (Figure 8). These dark stripes contained a lighter etching phase which was apparently alpha phase with no kappa formation, and a darker etching phase which proved difficult to resolve even at higher magnification but was probably partially dissociated beta (ie. beta plus alpha and kappa). In comparison, the microstructure of other blades consisted entirely of an homogeneous alpha matrix containing kappa in the form of rounded particles and lamellae (see Figure 9). This structure is essentially similar to the lighter etching phase of the failed blade, although it was noted that the rounded kappa particles in the failed blade were generally much smaller than those in other blades.

9. While no specific details regarding the heat-treatment to which the blades were subjected were available, Reference D, paragraph 6, refers to '... tempering at 650°C for five hours...'. The microstructure seen in figure 9 ('other' blades) is consistent with these heat-treatment parameters, assuming the blades were initially subjected to a quench from a higher temperature (about 1000°C). This quench would result in an essentially all beta structure, while the subsequent temper, for a given temperature and time, would allow complete dissociation of the beta to form an alpha matrix containing the kappa precipitate. The long tempering time quoted - 5 hours - would allow substantial coarsening of the precipitate, which, again, is consistent with the observed microstructure of blades other than the failed blade.

10. It is clear from these observations that the failed blade exhibits a metallurgical structure which is anomalous in comparison with all other blades examined, including other blades from the same batch (7JP). While the exact reasons for the observed difference are not known, it seems likely that the heat-treatment applied to the blade was incorrect and, in particular, that the blade was tempered at an incorrect temperature or for insufficient time. Since no other blades from the 7PJ batch showed a similar microstructure to the failed blade, it is clear that the failed blade was not representative of the batch as a whole.

11. The observed variability in the microstructure of the failed blade would be likely to lead to increased variability in mechanical properties (including fatigue strength) throughout the blade. While the nature of this effect is unpredictable, it is known that the presence of the beta phase in these materials can result in a reduction in ductility compared to an alpha plus kappa structure of equivalent strength.

12. While the two anomalous features of the structure of the failed blade (ie. a higher overall level of inclusions and a widely varying microstructure) are not necessarily related (the inclusions would have been present in the original forging stock, while the variable microstructure is probably the result of the applied heat-treatment) their combined effect may have contributed to the blade failure by providing both the means for fatigue crack initiation (inclusions) and a structure which might display reduced resistance to fatigue crack growth.

ANNEX H (cont.)

13. Chemical analysis of the failed blade material was not possible due to the small amount of material available. However semi-quantitative analysis using EDAX, of a bulk section, indicated that the blade material probably conformed to the specification in reference D. All other blades examined, including those from the 7PJ batch, were analysed quantitatively and found to conform to this specification.

14. Hardness tests were performed on cross-sections of all blades examined, including the failed blade. Reference D specifies that blade forgings will have a hardness of between 180 and 255 Brinell-10kg (180 to 264 VHN-10kg). The failed blade had an average hardness of 245 Brinell (251 VHN). Other blades from the 7PJ batch had an average hardness of 201 Brinell (239 VHN). Blades from other batches exhibited an average hardness similar to the latter figure (eg. blades tested from batch 7AZ had an average hardness of 187 Brinell (225 VHN)). All blades tested had hardness values within the range specified in reference D. It should be noted that the hardness values represented here are for the bulk of the material ie. the variability of the microstructure of the failed blade would not necessarily be reflected in the recorded hardness values.

15. In reference B the main conclusions drawn regarding the failure of the 7th stage compressor blade from Gazelle Mk 165C engine SN GA2033 were:

(a) the blade had broken as a result of the initiation and propagation of two separate fatigue cracks from the roots of the first fir-tree serrations under the blade land;

(b) the majority of fatigue cracking was of the high cycle, low stress type;

(c) crack propagation occurred under reversed-bending loading;

(d) the crack on the leading side of the blade initiated at a small inclusion (ie. at a point of origin);

(e) crack propagation from initiation to failure probably occurred over a number of engine operations;

(f) final failure of the blade occurred by overload of the reduced cross-sectional area of the fir-tree.

16. As a result of further investigation into the failure, as described above, in particular with respect to the metallographic examination of the failed blade, the following additional conclusions can be made:

(a) No gross defects in the copper plate, of the type shown in reference C, were found in the vicinity of the crack initiation site in the failed blade;

(b) The failed blade, and other blades examined from the 7PJ batch, exhibited a higher level of inclusions in comparison to blades from other batches examined. This would increase the probability of an inclusion initiating a fatigue crack;

(c) The overall macro- and microstructure of the failed blade was markedly different from all other blades examined (including others from the 7PJ batch). In particular, the apparent presence of beta phase indicates that the failed blade was probably subjected to different heat-treatment conditions, and furthermore;

(d) the beta phase is known to have an adverse effect on ductility in these materials and the variation in microstructure of the failed blade is therefore likely to be associated with a variation of mechanical properties (including fatigue strength) throughout the blade cross-section;

(e) All blades examined were chemically analysed. There was no evidence that they failed to conform to the relevant specification;

(f) All blades were subjected to hardness tests and found to be within the range required by the relevant specification.

ANNEX H (cont.)

17. Finally, because of concern that the failure might have been a result, in part at least, of poor contact between the blade fir-tree and the disc fir-tree top land, ARL was asked (Ref E) to examine the failed blade* and the disc containing the failed blade for any metallurgical evidence to support this theory. No such metallurgical evidence could be found.

REFERENCES :

A. SAMR Telex 214, 7 November 1985.

B. ARL REPORT, "Preliminary Findings - Gazelle Engine 7th Stage Compressor Blade Failure", 21 March 1986.

C. Rolls Royce Ltd. report "Gazelle MK 165C, 7th Stage Compressor Blade Root Failure", 20 December 1985.

D. D. Napier & Son Ltd. Material Specification DNS 210, "Aluminium Nickel Iron Bronze (Suitable for Compressor Rotor and Stator Blades)", 12 April 1957.

E. Discussion with Mr D.E. Glenny (Aero Propulsion Division, ARL), 26 November 1985.

F. ANNEX H. A/MATS DIV Ref: M76/85/SRL - BM2/47 of 20/8/86.

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* Examination was by necessity limited to assessing the condition of the disc fir tree root upper land (as the mating part of the blade was not recovered after the blade failure). Inspection of this surface did not indicate any areas of fretting or scoring which could be attributed to poor contact or blade movement. That is not to say that a light gap or clearance at the blade/disc fir tree root upper land did not exist at the initial build or during engine operations.

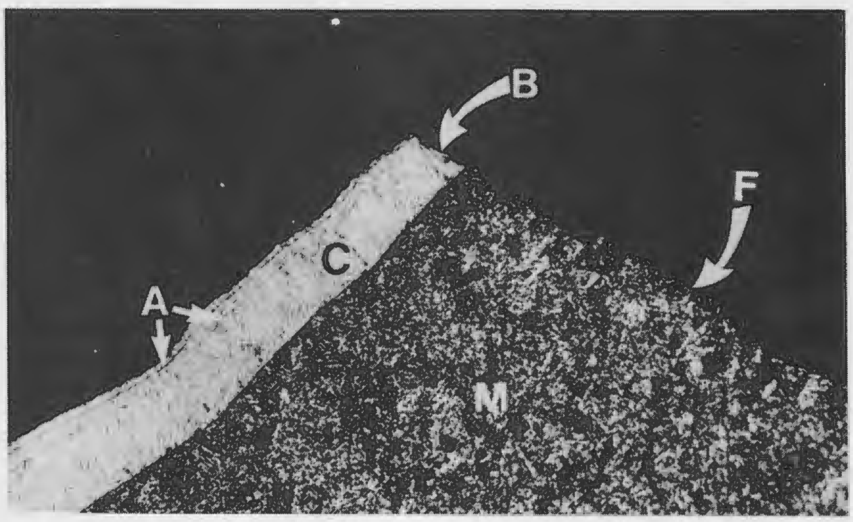


FIG 1. POLISHED AND ETCHED METALLOGRAPHIC SECTION FROM THE FAILED BLADE FROM ENGINE SN GA2033. THE AREA SHOWN IN THIS PHOTOGRAPH IS IMMEDIATELY ADJACENT TO THE PRIMARY CRACK INITIATION SITE (ESTIMATED TO BE WITHIN 0.2 mm). THE PRIMARY CRACK FRACTURE SURFACE IS ARROWED F; THE BLADE MATERIAL IS LABELLED M; THE COPPER PLATE IS LABELLED C; AND THE FRACTURE SURFACE OF THE COPPER PLATE IS ARROWED B. NOTE THAT THE ETCHANT HAS REVEALED THE BOUNDARIES (ARROWS A) BETWEEN THE DIFFERENT LAYERS OF COPPER PLATE (THREE IN ALL). SIGNIFICANTLY THESE BOUNDARIES FINISH ABRUPTLY AT THE BREAK IN THE PLATING (ARROW B). THE THICKNESS OF THE COPPER PLATE IS ABOUT 0.05MM AT THE BREAK.

Magnification: 160
Etchant: Potassium Dichromate

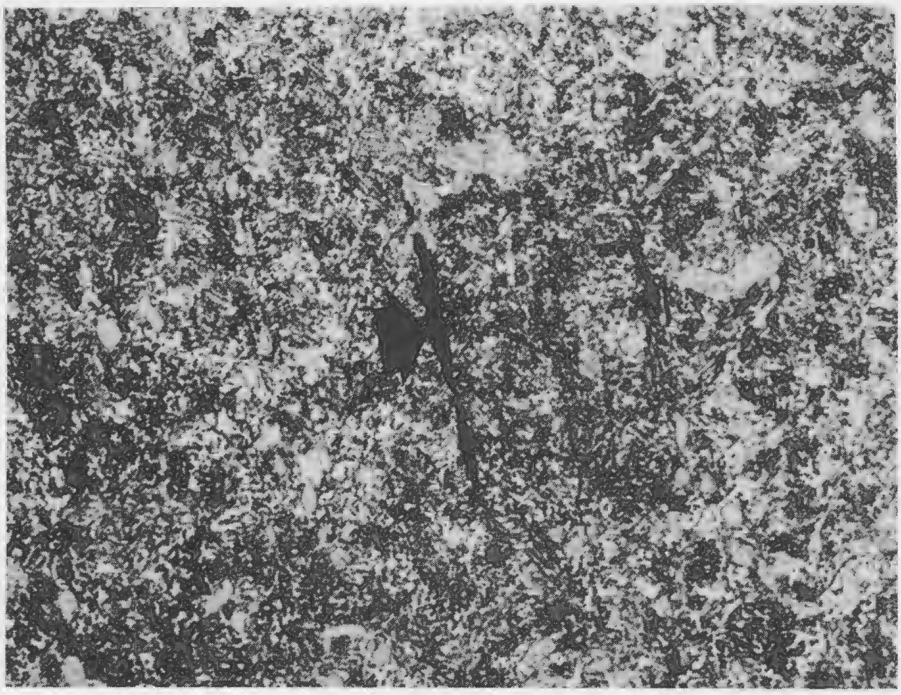
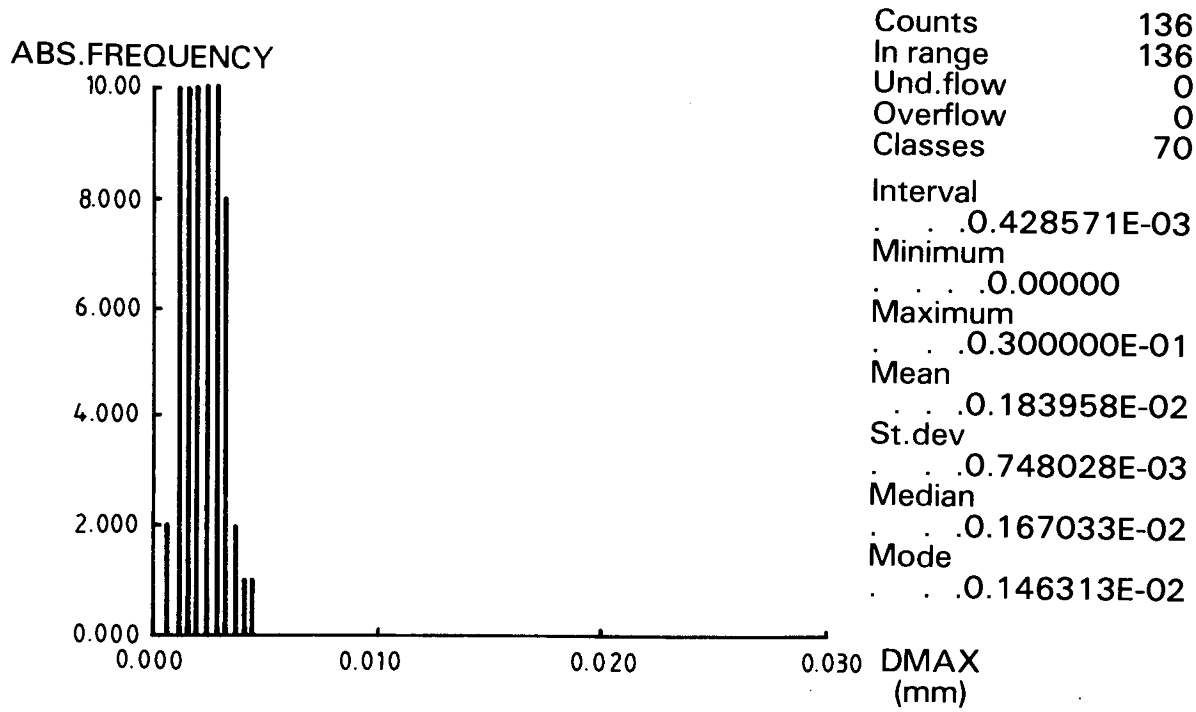


FIG 2. A STRINGER TYPE INCLUSION (ARROWED) OF THE TYPE FOUND IN THE FAILED BLADE AND IN OTHER 7PJ BLADES. THIS TYPE OF INCLUSION WAS NOT FOUND IN BLADES FROM OTHER BATCHES EXAMINED. THE LENGTH OF THIS INCLUSION IS ABOUT 30 MICRONS.

Magnification: 1100
Etchant: Potassium Dichromate



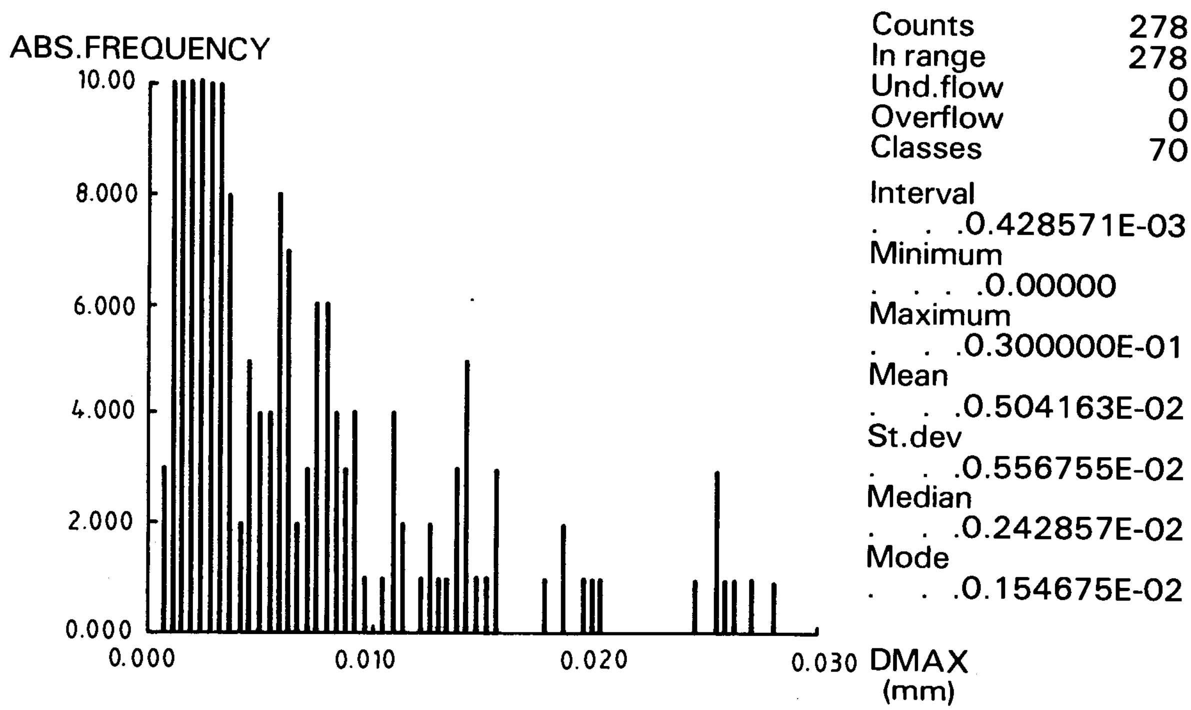


FIG 3 GRAPHICAL REPRESENTATION OF THE INCLUSION SIZE AND DISTRIBUTION ANALYSIS OF THE FAILED BLADE (BOTTOM GRAPH) AND A BLADE FROM BATCH 7AZ. 'DMAX' IS THE MAXIMUM PARTICLE DIMENSION (I.E. IN THE CASE OF THE INCLUSION SHOWN IN FIGURE 2, DMAX WOULD BE THE LENGTH OF THE INCLUSION. 'ABS FREQUENCY' IS THE NUMBER OF TIMES THE PARTICULAR DMAX WAS DETECTED. NOTE THAT THE FAILED BLADE HAS A HIGHER OVERALL PROPORTION OF INCLUSIONS AND, IN PARTICULAR, A GREATER NUMBER OF INCLUSIONS WITH A DMAX OF GREATER THAN ABOUT 5 MICRONS. SEE PARAGRAPHS 5 & 6 OF THE TEXT FOR A MORE DETAILED DISCUSSION.

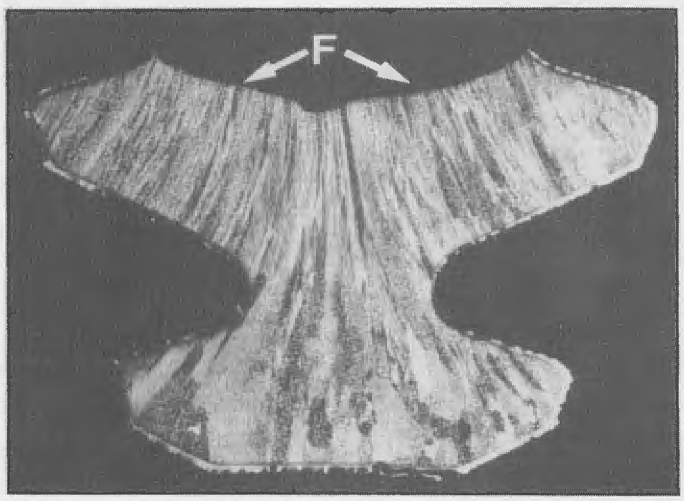


FIG 4. PHOTOGRAPH OF THE ETCHED MACROSTRUCTURE OF THE FIR-TREE OF THE FAILED BLADE. THE FRACTURE SURFACE IS ARROWED F. NOTE THE DISTINCTLY BANDED STRUCTURE, AND COMPARE THIS WITH FIGURE 5.

Magnification: 16
Etchant: Potassium Dichromate

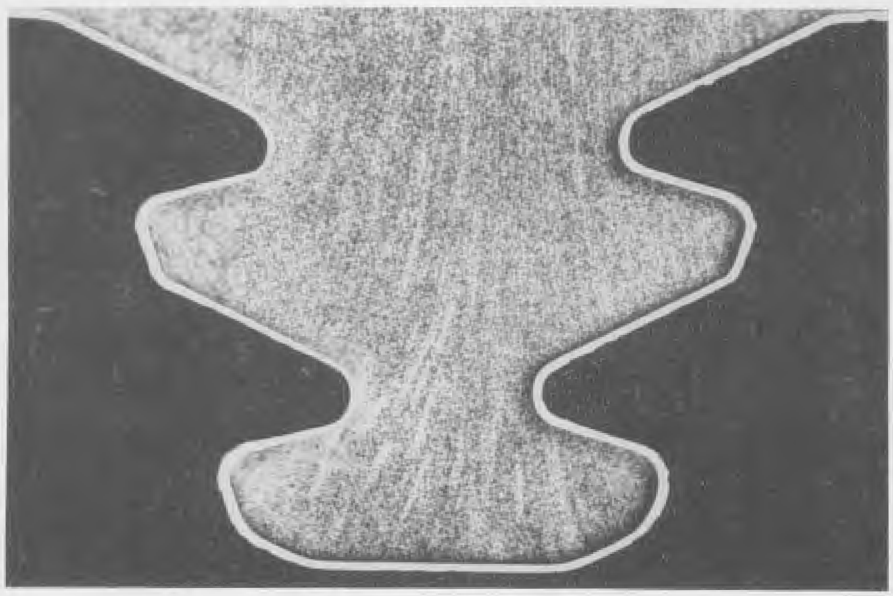


FIG 5. MACROSTRUCTURE OF A BLADE FROM BATCH 7AZ. THIS STRUCTURE IS TYPICAL FOR ALL BLADES EXAMINED WITH THE ONLY *EXCEPTION BEING THE* FAILED BLADE (SEE FIGURE 4).
Magnification: 16
Etchant: Potassium Dichromate

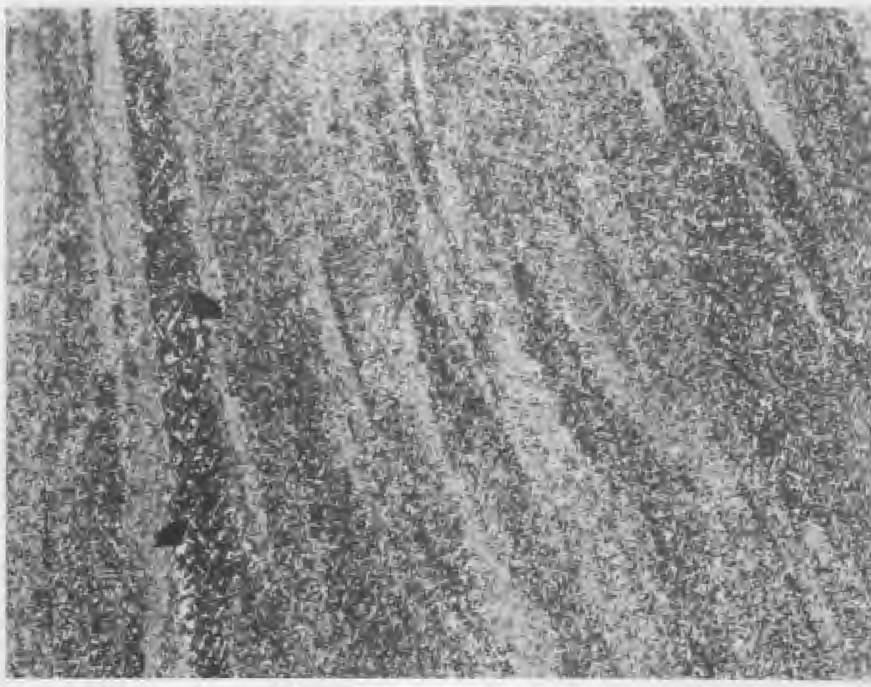


FIG 6. MICROSTRUCTURE OF THE FAILED BLADE. A HIGHLY BANDED STRUCTURE IS EVIDENT. THE LIGHT GREY, MOTTLED PHASE, WHICH IS IN THE MAJORITY, IS PREDOMINANTLY AN ALPHA MATRIX CONTAINING KAPPA PRECIPITATE. THE DARKER BANDS CONTAIN BOTH DARK AND LIGHT ETCHING PHASES (ARROWED – SEE ALSO FIGURES 7 & 8).
Magnification: 100
Etchant: Potassium Dichromate

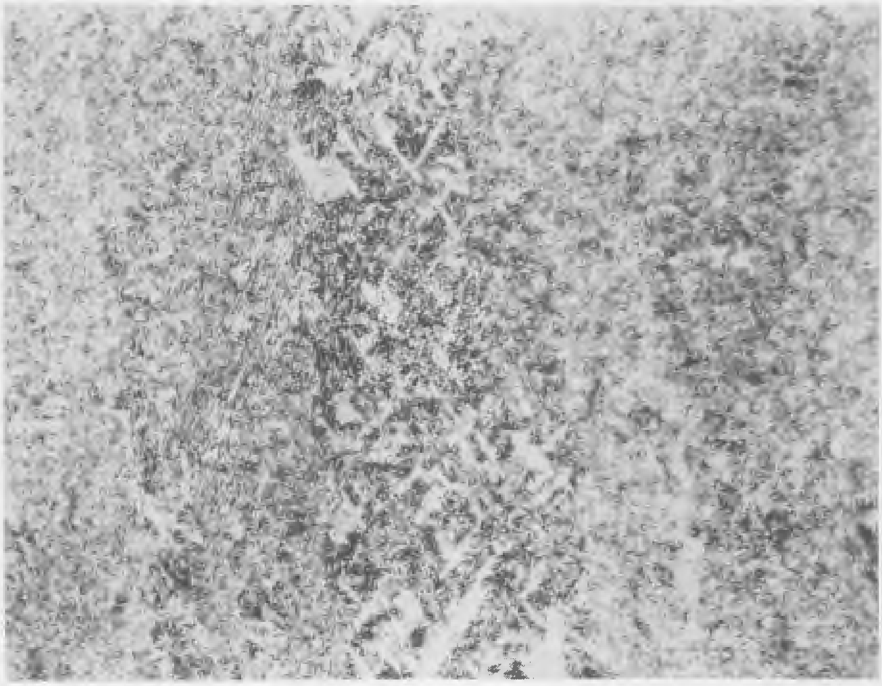


FIG 7. HIGHER MAGNIFICATION MICROGRAPH OF THE AREA ARROWED IN FIGURE 6 (SEE ALSO FIGURE 8). THE MICROSTRUCTURE WITHIN THE DARK STRIPES IS A MIXTURE OF DARK AND LIGHT ETCHING PHASES WHICH IS CLEARLY DISTINGUISHABLE IN STRUCTURE FROM THE ALPHA PLUS KAPPA STRUCTURE OF THE MAJORITY OF THE BLADE.
Magnification: 500
Etchant: Potassium Dichromate

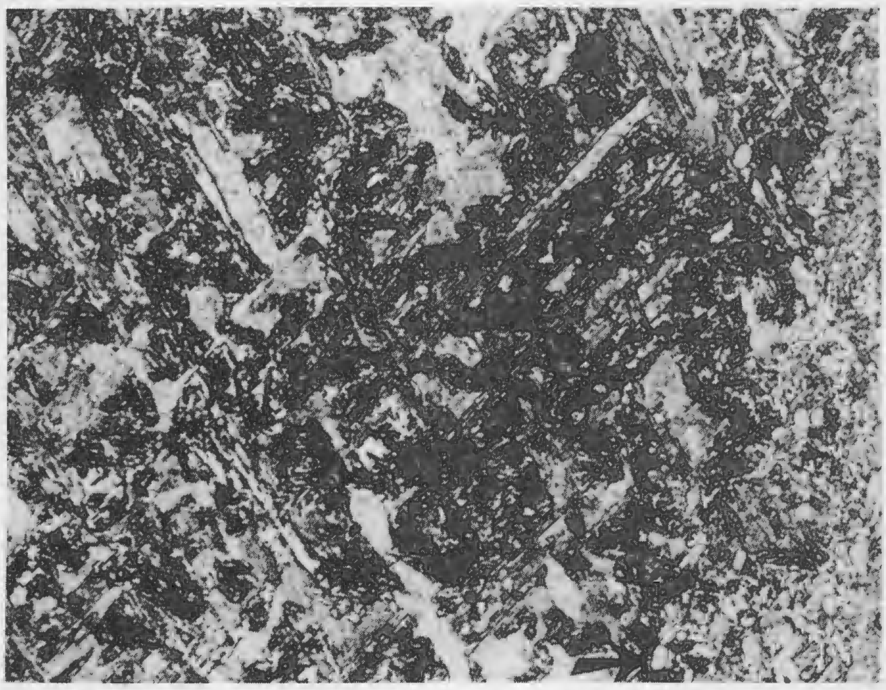


FIG 8. AT THE MAXIMUM MAGNIFICATION AVAILABLE ON THE OPTICAL MICROSCOPE THE STRUCTURE OF THE DARK STRIPES SEEN IN FIGURES 6 & 7 WAS FOUND TO CONSIST OF A MIXTURE OF ALPHA (LIGHT GREY) AND WHAT APPEARS TO BE PARTIALLY DECOMPOSED BETA (DARK GREY TO BLACK – SEE TEXT). NOTE THE SIZE OF THE ROUNDED PARTICLES OF KAPPA (ARROWED) AND COMPARE WITH FIGURE 9.

Magnification: 1000
Etchant: Potassium Dichromate

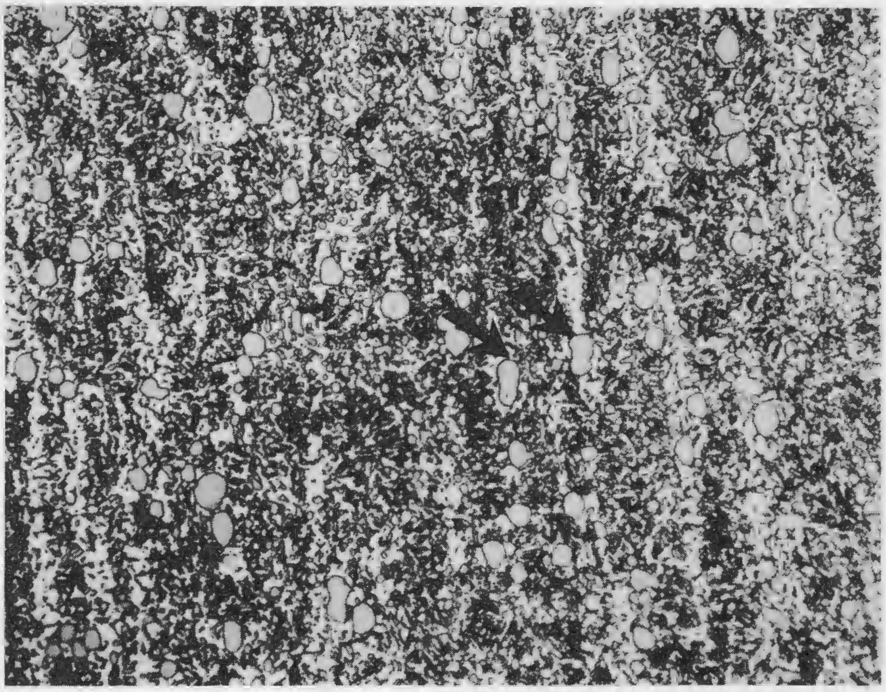


FIG 9. PHOTOGRAPH OF THE MICROSTRUCTURE OF THE BLADE FROM BATCH 7AZ SHOWN IN FIGURE 5. THE STRUCTURE CONSISTS ENTIRELY OF AN ALPHA MATRIX CONTAINING ROUNDED PARTICLES AND LAMELLAE OF KAPPA. NO EVIDENCE OF INCLUSIONS OF THE TYPE SHOWN IN FIGURE 2 WERE FOUND IN THIS BLADE OR ANY OTHER BLADES EXAMINED FROM BATCHES OTHER THAN 7PJ. NOTE THE SIZE OF THE ROUNDED KAPPA PARTICLES (ARROWED) IN COMPARISON TO THAT OF THE FAILED BLADE. (FIGURE 8) – ALSO NOTE, HOWEVER, THAT THE MAGNIFICATIONS ARE DIFFERENT.

Magnification: 800
Etchant: Potassium Dichromate

ANNEX I

GAZELLE ENGINE COMPRESSION BLADE FAILURES - PLATING INVESTIGATION FINAL REPORT

As outlined in the preliminary report (Annex B) it was considered that the plating on the 7th stage compressor blades was very poor. Severe nodulling of the copper coating had occurred, and adhesion of the copper coating to the blades was also poor. Whether the severe nodulling was sufficient to cause stress concentration points in critical areas of the blade fir tree roots was not investigated.

Following experimental work at MRL, based on the Hawker de Havilland Specification HPS 1. 03.07, Mr B. Wilson, of Corrosion Control Group, visited Hawker de Havilland to discuss the problems associated with the plating procedures. These revolved around the following topics:

1. Periodic reverse copper plating.
2. Cleaning prior to plating.
3. Stripping of copper deposits.
4. Cause of nodules in the copper plate.

During the course of the discussion at Hawker de Havilland, it was evident that:-

1. **Periodic reverse plating specification** - Hawker de Havilland had not followed their own periodic reverse plating specification. It was hard to fathom exactly what had been done on refurbishment of the blades and perhaps not surprising that odd results had occurred. Their original periodic reverse plating had been used last some 5 years previously when their periodic reverse plating rectifier supplied asymmetrical cycle with respect to both current and time and in that case copper would be deposited.
2. **Cleaning procedures** - Hawker de Havilland agreed that the procedure in the specification was inadequate and suggested the use of a cyanide dip. This method was tested during the course of the visit and was a great improvement on the previous method.
3. **Stripping of coatings** - Hawker de Havilland had not followed their own specification for stripping of the copper coating from the blades, as the method used would not remove as much basis metal as the method in the specification. A method used by Rolls Royce has been suggested for future use. It is similar to the method investigated at MRL which stripped copper without attack on the basis metal.
4. **Reasons for the poor plating** - The reasons for the lack of adhesion of the plating and nodules on the blades could only be guessed at. Hawker de Havilland had used a bath and equipment too large for such a small job - this would increase the possibility of inaccurate current control. Too high a current could produce nodules on the surface.

Hawker de Havilland have proposed a modified specification to copper plate future Gazelle blades, incorporating improved plating and cleaning techniques (see Appendix 1). More accurate control of the plating will be imposed and a much lower maximum current density will be employed to decrease the possibilities of nodular deposits.

Additional MRL Work

Using the above modified Hawker de Havilland plating Specification, work at MRL has shown that:

ANNEX I (cont.)

1. The solution used for copper removal from the nickel/aluminium bronze blades works well and no attack occurs on the basis metal.
2. The cleaning of the blades was improved using a cyanide dip rather than the 10% hydrochloric acid solution used previously.
3. An adequate plating rate was achieved using the periodic reverse cycle suggested (35 sec plating; 7 sec deplating).

In the course of the above work, a number of bath parameters were varied in an endeavour to simulate the severe nodulling obtained on the 7th stage compressor blades. The significant results were:

(a) A fine grained, smooth copper deposit was obtained under all conditions, including the most adverse plating condition, (i.e. high current density, no periodic reverse plating) using a freshly prepared copper plating bath.

(b) An "aged" and worked plating bath with correct concentrations of bath components except a high carbonate level (above 130 g/l) produced nodulled deposits under all conditions, i.e. at low or high current densities and with or without periodic reverse plating.
NOTE . The increase in carbonate level will occur over a period of time by the slow oxidation of cyanide to carbonate. Cyanide must be added to the plating bath on a regular basis to maintain its concentration level, and this is the source of the increasing carbonate concentration.

(c) Fine-grained and smooth copper deposits were produced when the carbonate levels were reduced to below 100 g/l. Low current density (2.5 A/dm^2) and periodic reverse plating produced the best result.

Conclusions

1. The modifications suggested by Hawker de Havilland to the copper plating Specification No. HPS 1.03.07 are adequate to ensure smooth deposits on the compressor blades.

2. Analysis for carbonate levels in the plating bath is considered necessary to prevent the possibility of nodulling of the copper deposits. A maximum level of 100 g/l of Na_2CO_3 is suggested.

Recommendations

1. The proposed Hawker de Havilland plating Specification be adopted for plating of Gazelle compressor blades.

2. The carbonate level of the plating bath should be kept below 100 g/l.

3. The copper stripping solution based on ammonium persulphate $(NH_4)_2S_2O_8$ be used not only to strip copper off blades for reworking but also, as suggested in our preliminary report, for removal of small amounts of copper plating evenly. This would help during fitting of blades to the rotor assemblies.

Appendix to Annex I

Copper Plating of Compressor Blade Roots - Plating Procedure Proposed by Hawker de Havilland

PART A : Removal of Previously Applied Copper Coating.

1. Vapour degrease.
2. Alkaline clean.
3. Rinse in cold running water, 1-3 minutes.
4. Strip the copper coating in a solution of 10 g/l $(NH_4)_2S_2O_8$ in water until the copper is removed.
5. Rinse.
6. Replate as soon as possible.

PART B : Copper Plating.

1. Vapour degrease.
2. Mask with wax.
3. Cathodic alkaline clean.
4. Rinse in cold running water, 1-3 minutes.
5. Waterbreak check (if water breaks on component within 30 seconds, repeat steps 3 & 4).
6. Immerse in sodium cyanide dip solution (31-39 g/l NaCN; 8-15 g/l NaOH).
7. Rinse in cold running water, 1-3 minutes.
8. If smut is apparent, scour with a pumice slurry and bristle brush, rinse thoroughly.
9. Repeat steps 5 to 8.
10. Copper strike for 30 seconds at 4 volt. Make electrical contact before immersing blades in plating solution. (Hawker de Havilland solution 3 in Spec. HPS 1.03.07).
11. Readjust voltage and current to 2.5 A/dm^2 (max.) and commence copper plating, using the following periodic reverse plating cycle - Cathodic 35 seconds
    - Anodic 7 seconds
12. Rinse in cold running water, 1-3 minutes.
13. Hot rinse.
14. Dry and demask.

ANNEX J
STRESS ANALYSIS OF GAZELLE STAGE 7 COMPRESSOR BLADE FIR TREE ROOT

1. INTRODUCTION

1.1 Propulsion Mechanics Group comment was sought on the fir tree root stresses of Gazelle 7th stage compressor rotor blades. This request was made to assist the investigation into an in-service failure of a blade by fatigue across the neck of the blade top fir tree serration. Copper plating is employed to eliminate clearance in the fir tree root fixing. Particular comment was sought on the effect of clearances between the top fir tree shoulder of the blade (ie. platform shoulder) and the disc and the impact on fatigue life. A theoretical analysis was carried out (Reference 21 to main report); the results are summarized here and discussions presented on the possible fatigue effects.

2. ANALYSIS

2.1 The PAFEC finite element package was used to analyse stress and strains in the blade and disc fir tree roots. Details of the finite element technique are given in Reference 21 to the main report. A 2D model of the blade and disc was used to independently assess the effects of centrifugal and bending loads with varying conditions of clearance between the disc and blade platform shoulder. The finite element mesh (shown at Figure 1) was of sufficient density to adequately define stress concentrations. Combined loadings were assessed by:

- appropriate superposition of the separately computed centrifugal and bending load cases (assuming minimal movement between contacting fir tree surfaces), and
- a finite element model subjected to combined centrifugal and bending loads which allowed for the effects of relative movement.

2.2 The load cases of interest are:

- CF. at maximum rpm (19900); a coefficient of friction 0.36 was assumed (copper-steel, static, lubricated). Normal operating rpm is 16600 - 19600.
- steady bending load. A tangential blade bending moment of 350 N.mm was assumed.
- blade vibration at first flap mode of approximately 1800 H_z. Amplitude and duration unknown. An arbitrary blade tip amplitude of 2.0 mm peak-to-peak was assumed.

2.3 Centrifugal (direct) loads. Top shoulder gap due to radial growth is 9.3 micron and nominal fir tree root stress (direct stress and bending stress due to fir tree restraint) is 84 MPa. These values are similar to those determined by Rolls Royce (Reference A), in a review of fir tree stress. The model predicts a peak concentrated stress of 343 MPa; the stress concentration factor (s.c.f.) of 4.1 is similar to the theoretical value of 4.6 according to Heywood (Reference B). Friction load assumed uniform on all blade upper fir tree surfaces increases the stresses by 8%.

2.4 Bending Loads. The restraint suggested by Rolls Royce (Reference 22 to the main report) was taken for a nominal reference stress ie. when a gap exists between the top shoulders of the blade and the disc the blade is considered to be cantilevered from below the neck of the top fir tree. Nominal bending stress is 127 MPa for 1.0 mm blade tip displacement. The finite element model of this restraint permitted slight relative movement between disc and blade. Other possible restraint conditions of full and partial interference were also analysed using the finite element model i.e. contact alternately or continuously during blade vibration so that part of the bending load is transferred to the disc via the blade top shoulder. Table 1 shows the stress developed per millimetre blade tip displacement for the three restraint conditions described. The blade top fir tree radius peak stress for the reference condition (case A) is 1.7 to 5 times higher than for conditions whereby contact (case B) or interference (case C) at the shoulder occurs.

ANNEX J (cont.)

TABLE 1

Bending Stress at blade Top Fir Tree Radius
Blade tip amplitude 2 mm peak to peak

Restraint Condition at top shoulders	Tension Side			Compression Side		
	gap m	nom MPa	max MPa	gap m	nom MPa	max MPa
A. Clearance at both shoulders	5.28	127	263	-5.28	-127	-263
B. Zero clearance at compression shoulder	2.50	64	154	0	-30	-33
C. Interference at both shoulders	N/A	17	50	N/A	-17	-50

2.5 Steady loads. C.F. and steady bending loads. Superposition of case A bending loads and C.F. loads gives a maximum stress consistent with minimal sideways movement of the blade within the disc slot:

	nom MPa	peak MPa	gap m
Concave side	107	391	10.3
Convex side	61	295	8.4

2.6 Vibratory Loads. The relative effect of combined centrifugal and alternating loads with and without blade platform shoulder contact is shown by superposition of stresses. Peak values are shown at Table 2. The difference in nominal stresses is relatively greater for maximum stress and smaller for stress range.

TABLE 2

Combined Peak Stress at Blade Top Fir Tree Radius
19900 rpm and 2 mm Blade Tip Amplitude Peak to Peak

	Initial restraint condition at top shoulders	min MPa	max MPa
A.	Clearance at both shoulders	92	594
B.	Zero clearance at compression shoulder	310	486
C1.	Interference at both shoulders, reducing to zero at max rpm	-33	143
C2.	Interference at both shoulders and maintained to full extent of bending	-300	200

The combined load model showed that if friction is permitted then a large sideways movement can occur thereby reducing the bending moment for a given blade tip displacement. At the same time the movement changes the position of peak stress towards the point of contact between disc and blade fir tree projections as shown on Figure 2B. Figure 3 plots the progressive closure and opening of clearance as blade bending moment is increased.

ANNEX J (cont.)

3. DISCUSSION

3.1 The allowable stress criteria for steady state and vibratory loads are determined from the manufacturer's experience. The Rolls Royce (Napier and Sons) criterion for C.F. stress (Reference A) uses a value of 0.1 yield strength half that of the mean specification figure for HIDURAX 1/12A aluminium nickel iron bronze alloy (Reference 16 to main report) and a factor of .375. It is probable that this criterion is based on both photoelasticity analysis and service experience in a vibration prone environment. From the Rolls Royce Report on experimental investigation of fir tree neck failures and effect of gap (Reference 22 to main report) it is apparent that the blade design is optimised ie. nearly equal stresses at aerofoil root and fir tree neck. Thus an improvement in the fatigue life in one area (by reducing stresses, or concentrations) will not improve the fatigue life of the total blade. The report suggests that fir tree neck fatigue life is improved (relative to the aerofoil root, for a blade vibrated in a static fixture) if the initial blade platform shoulder gap is 76 micron (.003") or less. The fatigue lives were not reported probably because the testing was not designed for that purpose and the number of blades tested at each clearance was very small. Further testing designed to eliminate the possibility of preferential stress raisers in the aerofoil root radius would be required before the results could be considered conclusive.

3.2 The finite element analysis of restraint conditions quantified what is apparent by inspection ie. that fir tree root neck stresses will be reduced if the blade platform is supported at one or both shoulders. However the clearance developed at maximum rpm is such that a relatively large blade tip displacement eg over $\pm$ 1.7 mm is required before the 9.3 micron gap is closed and stress limitation is achieved unless the blade is able to slide sideways. In this case contact occurs at smaller tip displacement eg 0.2 mm and, for the arbitrary $\pm$ 1 mm tip displacement, stress limitation is achieved for an initial gap of up to 25 microns. Friction will limit the ability of the blade fir tree to move within the disc slot and actual movement may depend on the nature of excitation; the true result is expected to lie between the two extremes. Testing is required to determine the likely condition.

3.3 An assessment of fatigue life is dependent on the fatigue data available, ideally fatigue data drawn from blade and disc slot testing. Relative judgements may be made if the general shape of the material S/N curve is known. In the absence of fatigue data for this specific alloy, heat treatment, geometry and loading some typical values and approximate correlations for copper-based alloys are assumed. Fatigue strength at 10^7 cycles is assumed to be 290 MPa based on an empirical correlation with UTS, fatigue strength for a typical notch sensitivity and stress concentration factor is assumed to be 140 MPa (Reference B). Using a Goodman Diagram (Figure 4) the effects on fatigue life of the different restraint conditions are compared. It is likely that the fatigue life for steady load cycles (0-MAX RPM-0) is greater than 10^7 cycles (Point 0). To quantitatively assess the effect of gap or no gap for a 2 mm peak to peak blade tip amplitude an S/log N ratio of 120 MPa at 10^7 cycles is assumed; the material typically does not show a fatigue limit. Fatigue life is approximately doubled if initial gap is zero (Point B) compared to an initial gap of over 25 microns (Point P). Figure 4 shows the beneficial effect of optimum initial interference (Point C1), this result is expected because interference reduces both the steady load stress range and clearance. Point C2 requires a very large initial interference.

3.4 The duration and amplitude of blade vibration is unknown. While a life of 10^7 cycles is entirely adequate for 0-MAX RPM-0 cycles it represents a failure in extremely short time for vibration of sufficient amplitudes at 1800 Hz. It is apparent that the service load spectrum for the blade does not usually contain high levels of vibration because fatigue failures are rare. For low vibration amplitudes at maximum rpm there is no beneficial effect of reduced blade-disc clearances.

3.5 Additional stress concentrations in the fir tree neck area eg. machining marks, corrosion, material defects or plating defects will develop higher local stresses and will be the initiation sites for fatigue cracks. The fatigue life will be shortened by additional stress raisers but not as severely as theoretical stress concentration factors would indicate.

ANNEX J (cont.)

3.6 In summary the analysis predicts a beneficial result from minimising blade-disc fir tree clearances in particular the blade platform shoulder gap. However the effectiveness of the build clearances in increasing fatigue life is limited by the following factors:

a. rpm: the clearance developed due to C.F.

b. blade vibration : the actual service spectrum (amplitudes, frequency and duration). Amplitude must be sufficient to close the gap to limit stresses, the resulting stress level and duration forms a proportion of fatigue life.

c. blade-disc movement within the fir tree slot: the response to excitation including the effect of friction.

d. S/N characteristics.

Without experimental testing to characterise these factors the fatigue life improvement must be considered a theoretical possibility and not a design procedure. Nevertheless the build procedures which control blade/disc clearance or interference offer an additional protection against fatigue damage due to vibration, particularly at low rpm.

4. CONCLUSION

4.1 Stress analysis of the Gazelle stage 7 rotor blade fir tree predicts that an increase in fatigue life of the fir tree neck area is possible if initial clearance between blade platform shoulder and disc is minimised. The increase in fatigue life is more apparent for large amplitude vibration at low rpm.

4.2 The build procedure of copper plating to achieve zero clearance and preferably interference at the blade platform shoulder is supported. Use of anti-galling compounds is supported. Attention should be given to eliminating stress concentrations in the fir tree neck areas.

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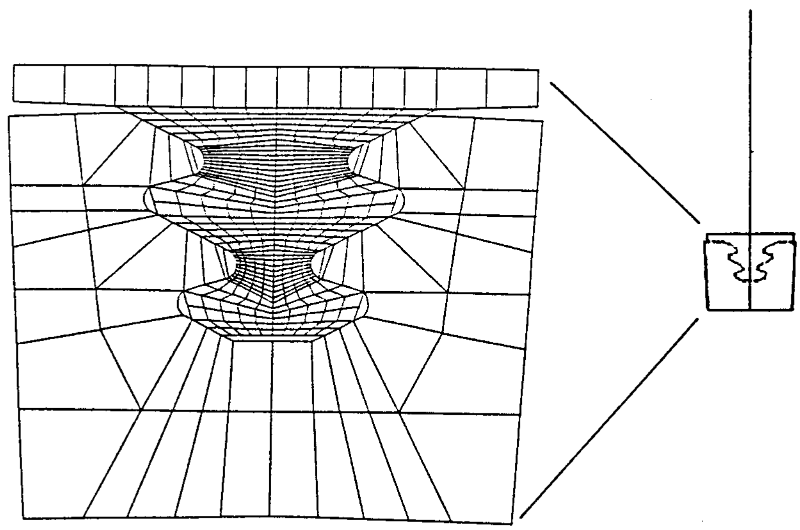
B. Heywood, R.B. Designing by Photoelasticity, Chapman & Hall Ltd, London 1952.

Gazelle stage 7 rotor
2D Cyclosymmetric finite element model



Finite element mesh

FIG. 1 2D FINITE ELEMENT MODEL

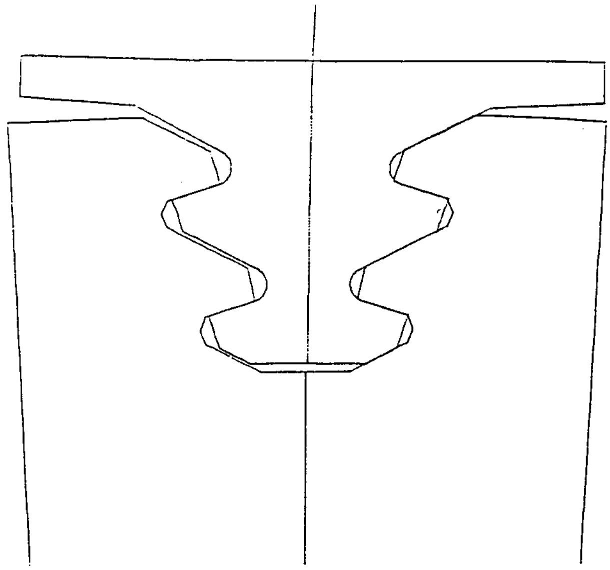


FIG. 2A DISPLACEMENT PLOT
COMBINED LOADS

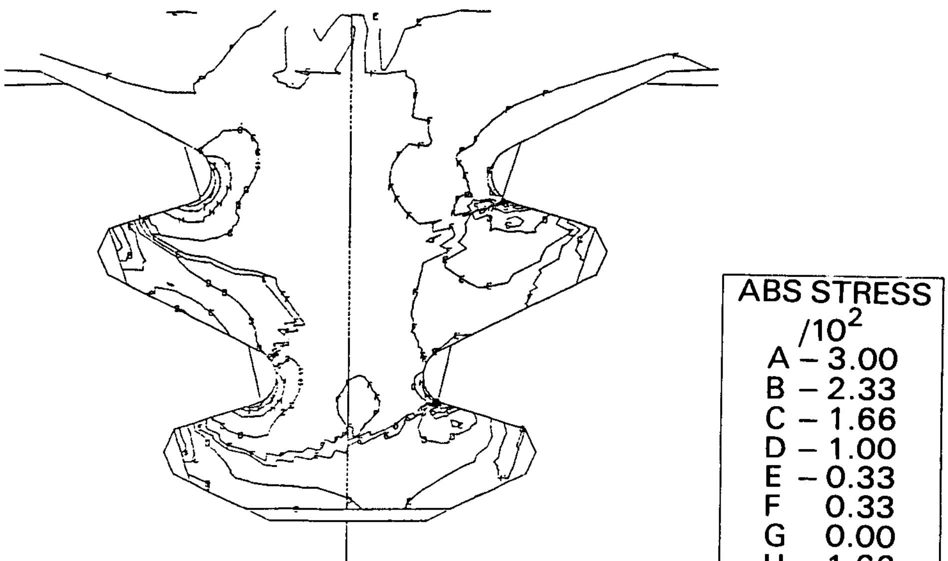


FIG. 2B STRESS CONTOUR PLOT
COMBINED LOADS

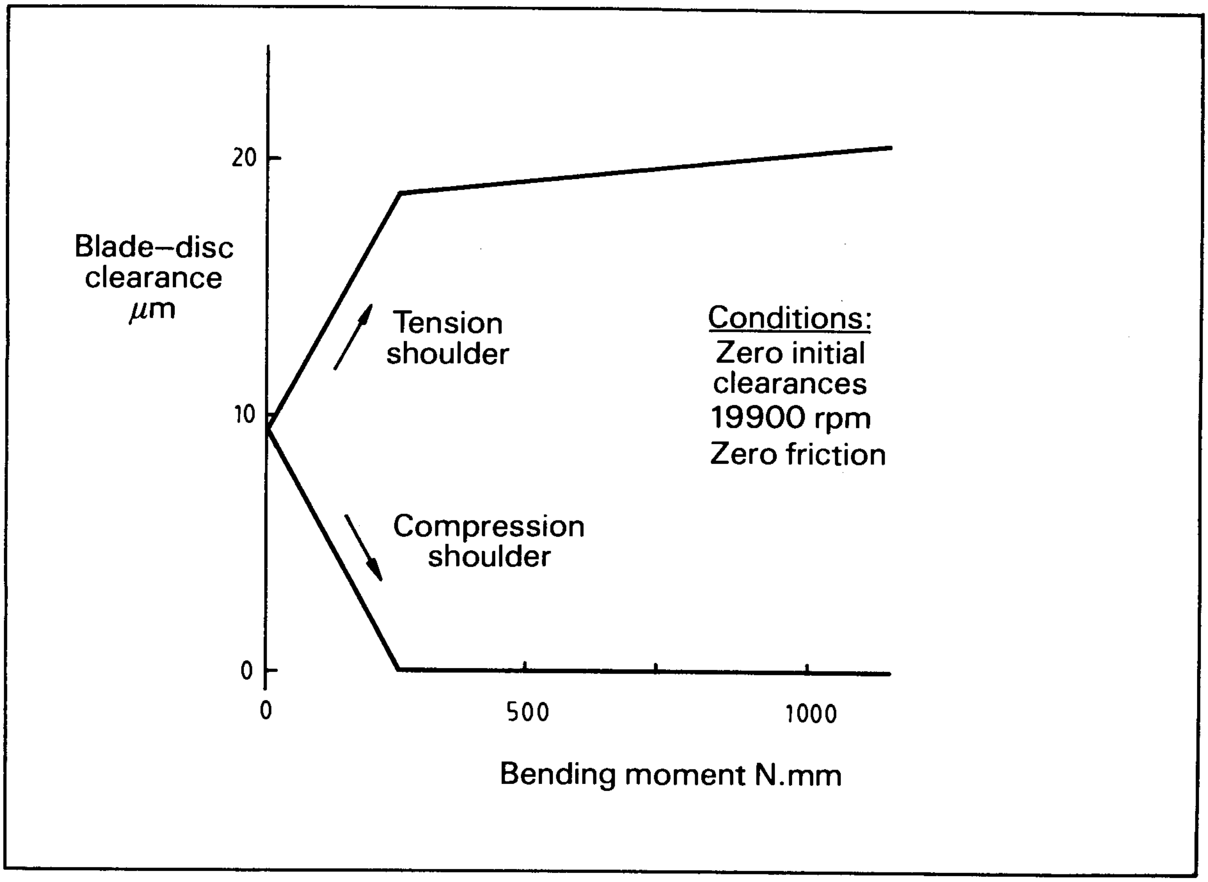


FIG. 3 BLADE-DISC CLEARANCE VS. BENDING MOMENT

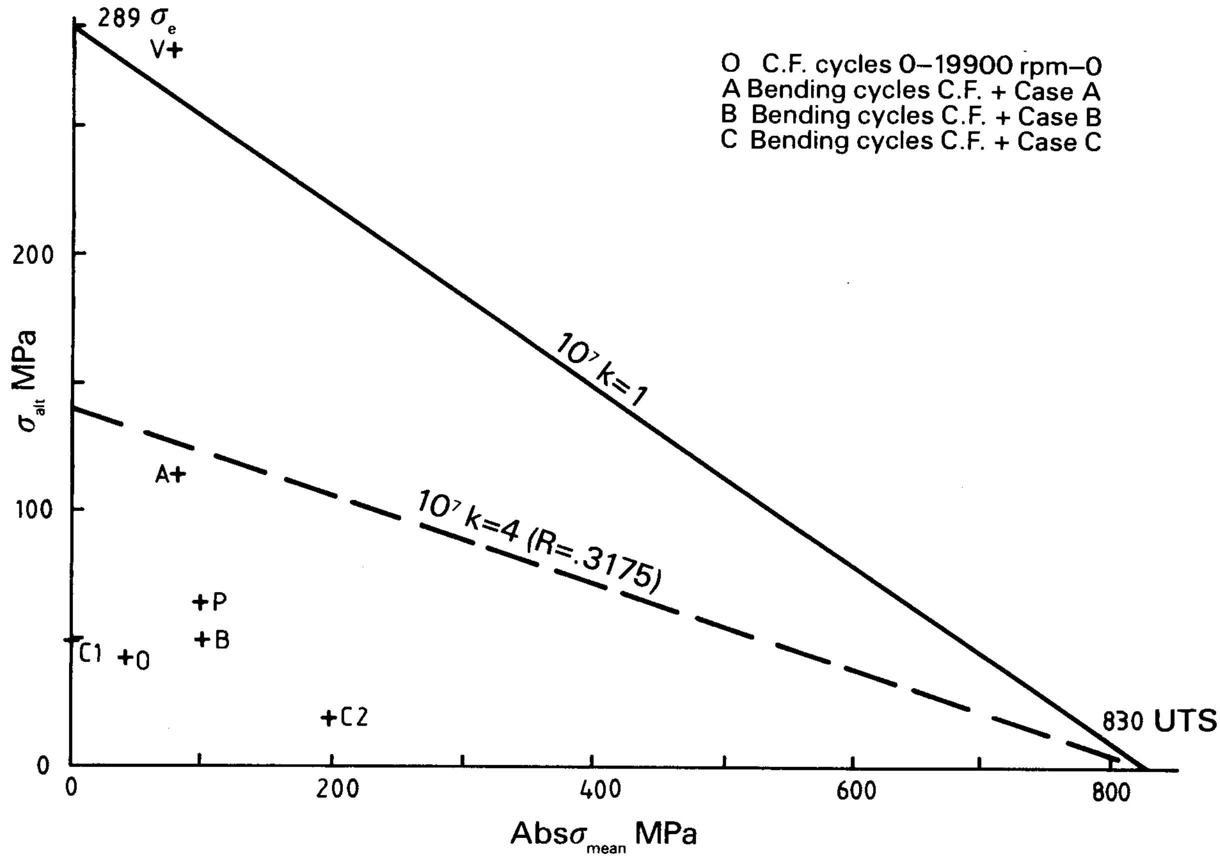


FIG. 4 GOODMAN DIAGRAM

ANNEX K

PRELIMINARY INVESTIGATION OF THE USE OF HOLOGRAPHIC INTERFEROMETRY TO DETECT ILL-FITTING COMPRESSOR BLADES

1. INTRODUCTION

The technique of holographic interferometry (HI) can be used to observe small displacements (order of microns) of an object's surface between two slightly different stress states. In this work preliminary observations are reported on the use of HI in detecting the small displacements of compressor blades when correctly fitted blades are subjected to a small force. The work is reported in greater detail in Reference A.

2. HOLOGRAPHIC INTERFEROMETRY

The basic principles of HI can be found in References B-D. The key procedure of HI is the recording of holograms of the object's surface. Holograms enable the reproduction of the optical field of an object so that a three dimensional image can be viewed. The recording of a hologram requires illumination of the object with the monochromatic, coherent light from a laser and for conventional holograms laser light is also required to view the hologram. Holograms are typically recorded on very high spatial resolution photographic plates.

In the work reported here, two holograms have been recorded on the one photographic plate. In the time between the two separate exposures used to record the two holograms, a small perturbing force applied to the blades was removed. Therefore two slightly different object surface states were recorded. This technique is termed double exposure HI. When a hologram recorded in this way is used to view the image of the object, then as long as the displacements are small, the object's surface will usually appear to be modulated by light and dark regions. This modulation is caused by the interference between the two slightly different optical fields of the object, and the modulation is usually called interference fringes. Further discussion on the reason for the formation of the fringes and the location of the fringes can be found in Reference D.

The interference fringes can be related to the small optical phase differences caused by the displacement of points on the object's surface. For a small displacement d of a general point Q shown in Figure 1, the resultant phase difference can be written as

$$\cos\ \theta = K.d$$

where K is a vector defined by the optical arrangement used to illuminate and view the object. If the object was illuminated from a direction k_1, and is later viewed through the hologram from a direction k_2 then the vector $K = k_2 - k_1$ and is termed the sensitivity vector. The vectors k_1 and k_2 are the propagation vectors of the incident and scattered light and both have magnitudes of $2\ \pi / \lambda$, where λ is the wavelength of the laser light used. The phase difference θ will vary over the object depending on changes in d and K.

3. EXPERIMENTAL

The holograms recorded in this work were obtained using a 15mW He/Ne laser operating at 632.8nm. The compressor disc and optical components were mounted on a 4ft by 8ft vibration isolated table. Double exposure holograms were recorded for two different blade orientations and sensitivity vectors. In one orientation the blades were viewed end-on, and in the other the blades were viewed from the side. The optical arrangements for the end-on configuration are shown in Figure 2. Diagrams of the arrangement of the photographic plate, compressor disc, illumination beam and sensitivity vector are shown in Figures 3-4 for the end-on case and the side view respectively.

The perturbation force which caused the displacement of the compressor blade was produced by an ordinary wooden clothes peg, clamped around a pair of blades. The procedure followed was to record the first hologram with the clothes peg in position, then remove the peg and record the second hologram. Four different pairs of blades were investigated. One pair had had material removed to ensure that they both were ill-fitting the other pairs were selected at random.

ANNEX K (Cont.)

4. RESULTS

Photographs of the reconstructed double exposure holograms are shown in Figures 5-12. Figures 5-6 show the end-on and side views respectively of the ill-fitting pair of blades. It should be noted that these figures are photographs of virtual images and show interference fringes for the sensitivity vector defined by the camera's axis. When the virtual images are viewed live, the pattern of interference fringes changes as the viewing direction and hence sensitivity vector, is altered. The direction of the sensitivity vector for the end-on views determined that the fringes observed on the platform are predominantly due to displacements in the radial direction, assuming there is no sideways movement of the platform. In the side on view, the observed fringes are also predominately due to displacements in the radial direction, assuming there is no out-of-plane movement of the blade.

5. DISCUSSION

It can be seen from a comparison between the views for the ill-fitting blade pairs (Figures 5-6) and the other blade pairs (Figures 7-12), that there are more fringes in the ill-fitting case. This indicates, as expected, that there is significant movement of the fir-tree in the ill-fitting case.

A comparison of the end-on views of the left blade in the pairs of nominally good blades (selected at random), (Figures 7, 9 and 11) shows that their response to the applied load is similar. However, for the right blades, whilst Figures 7 and 11 are similar, in Figure 9 the fringe pattern resembles the fringes in the ill-fitting case (Figure 5), although not as many fringes are observed. Further indication that this blade is undergoing greater than normal displacement can also be seen in a comparison of the side on views (Figures 8, 10 and 12).

At this stage there has been no attempt to quantify the magnitudes and directions of the displacements, or the load applied. However, further work is proceeding in this direction. It is anticipated that the loading mechanism will be changed to allow a variable load to be applied to one blade at a time. Also the optical arrangement is being altered to incorporate a front surface mirror to enable both end-on and side-on views to be recorded simultaneously.

The technique of HI applied in this work, in which a continuous wave laser was used and with exposure times of 10 seconds, requires the use of vibration isolated tables. This is necessary as any vibrations of the object or optical components during exposure will result in unwanted fringes and holograms of poor quality or no hologram at all. This restriction can be removed if, instead of a continuous laser, a pulsed laser is used. Pulsed lasers can be designed to deliver two accurately separated pulses of light, with pulse times of 30 nanoseconds and with energies of several joules. If clear access can be gained for illumination with the laser light, then it is possible that an in-situ testing technique could be developed. However, it would require a significant allocation of manpower and resources to determine the feasibility of this technique.

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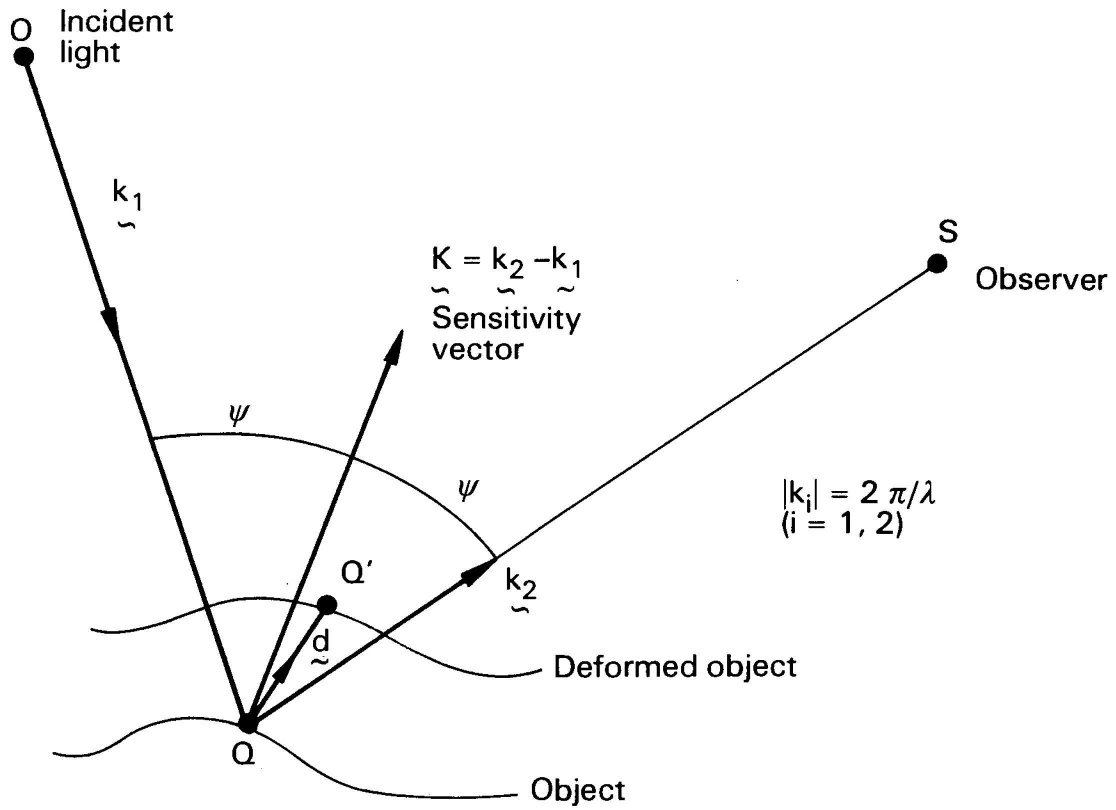

FIG. 1 OPTICAL ARRANGEMENT DEFINING SENSITIVITY VECTOR

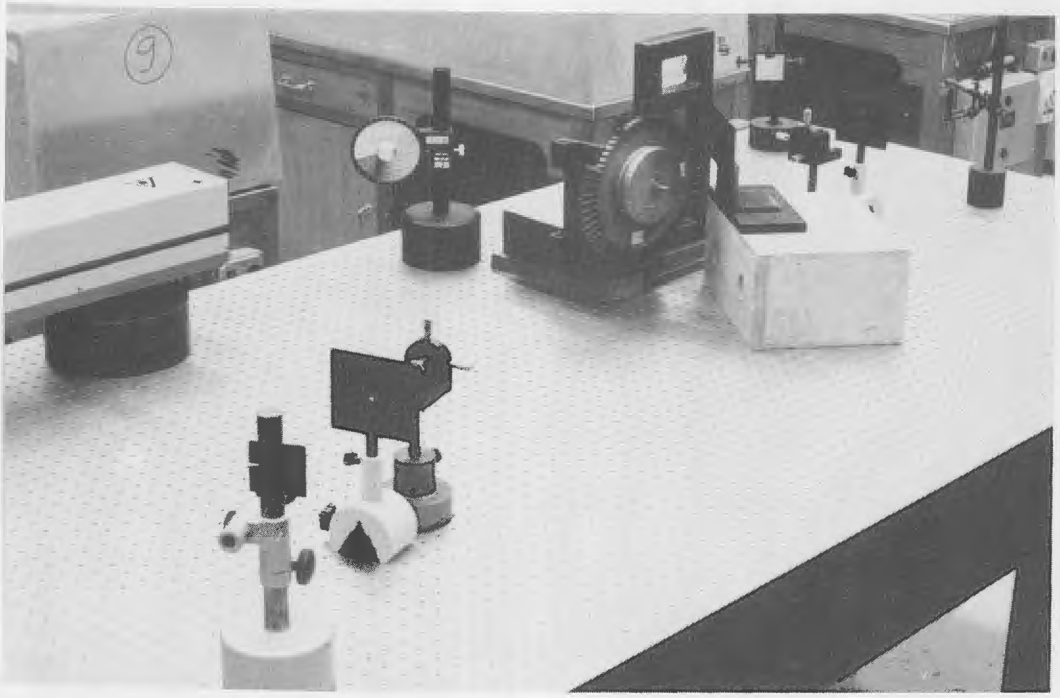

FIG. 2 OPTICAL ARRANGEMENT FOR END-ON CONFIGURATION.

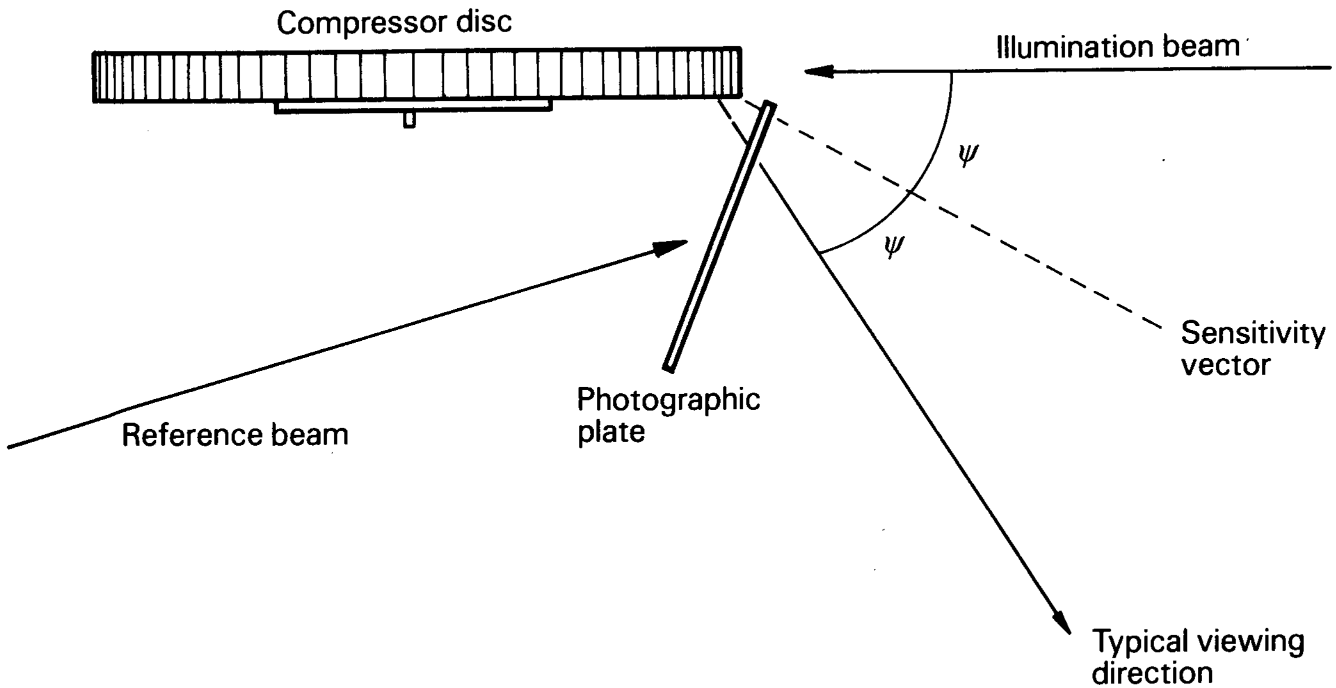

FIGURE 3 TYPICAL SENSITIVITY VECTOR DIRECTION FOR END-ON ORIENTATION

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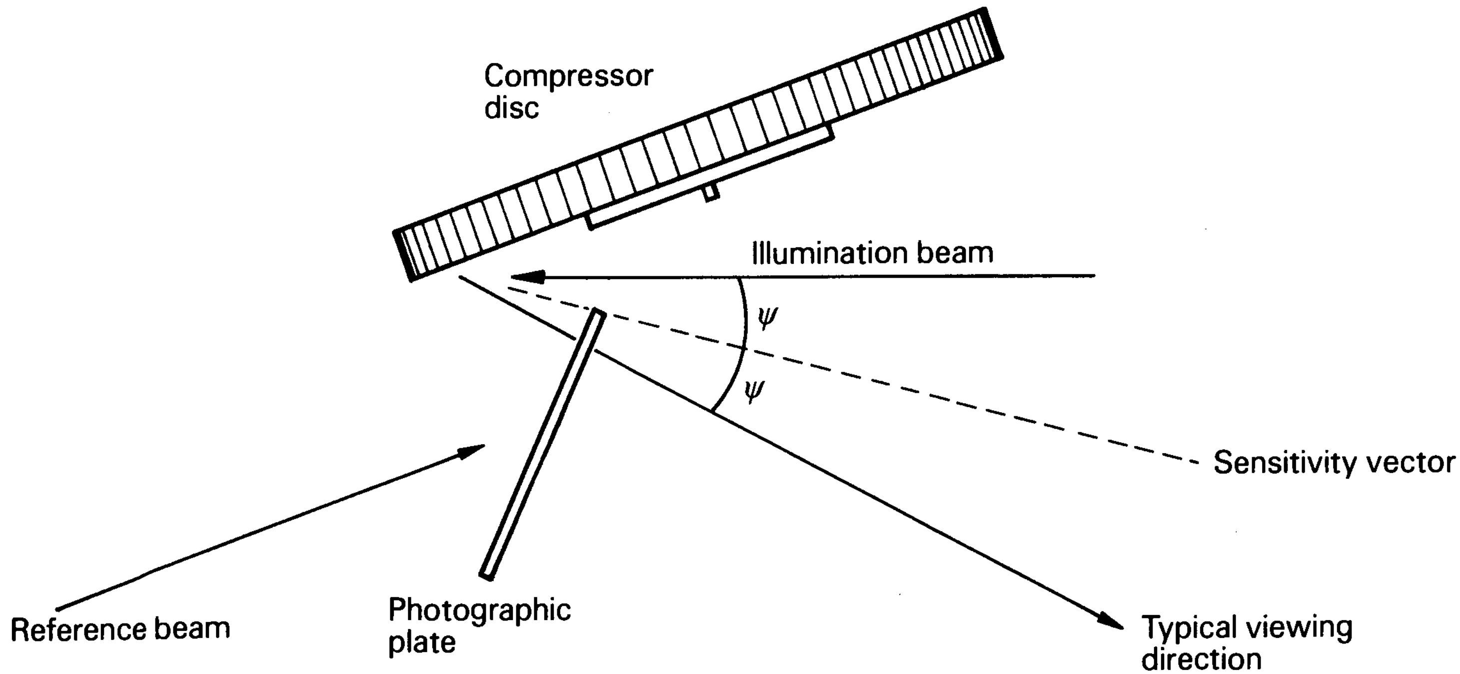

FIGURE 4 TYPICAL SENSITIVITY DIRECTION FOR SIDE-ON ORIENTATION

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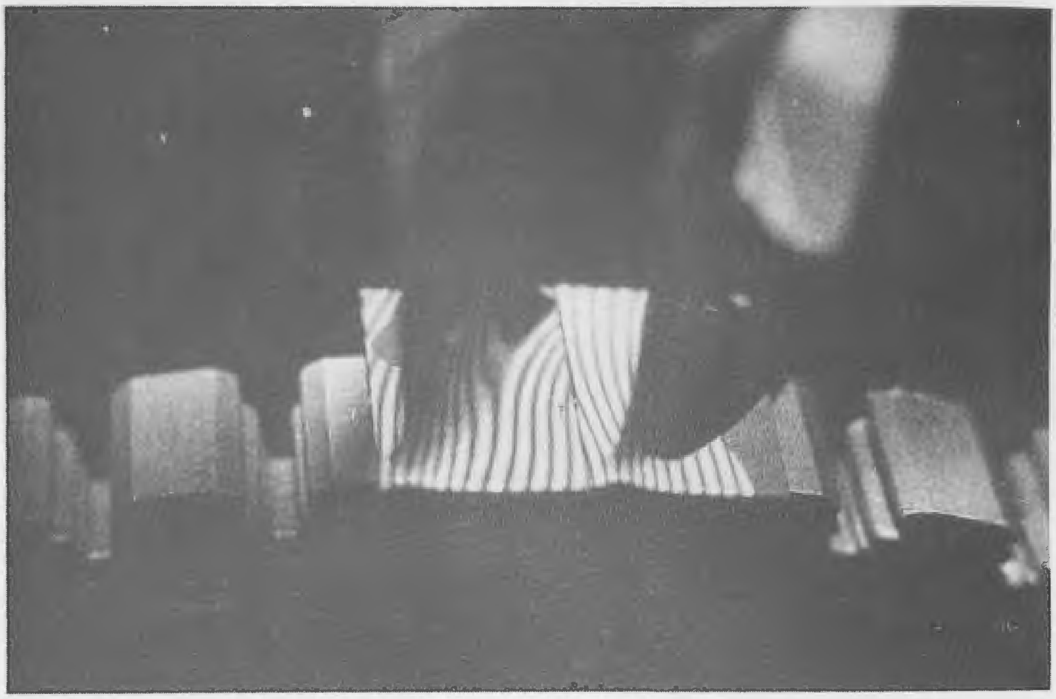

FIG. 5 END-ON VIEW ILL-FITTING BLADE

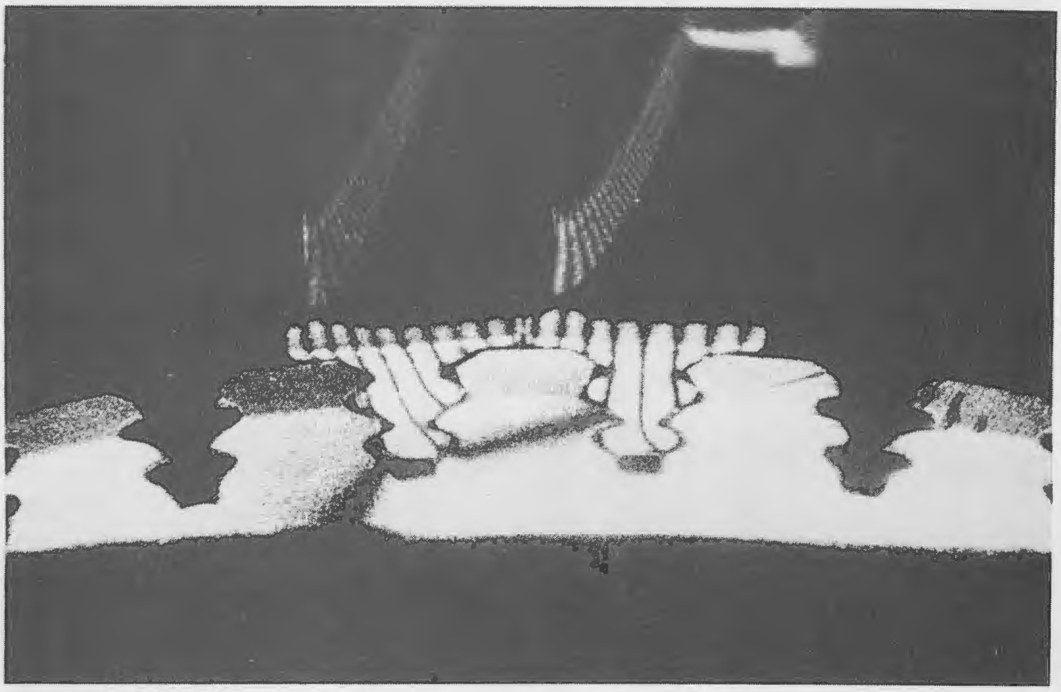

FIG. 6 SIDE-ON VIEW ILL-FITTING BLADE

FIG. 7 END-ON VIEW (BLADE PAIRS 19/20)

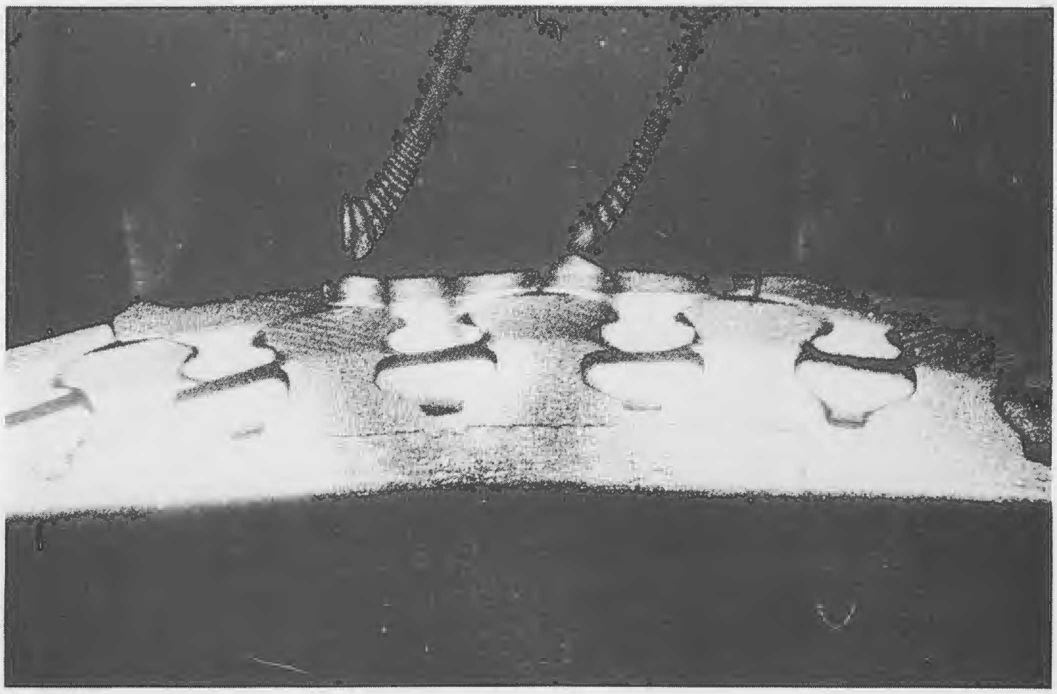

FIG. 8 SIDE-ON VIEW (BLADE PAIRS 19/20)

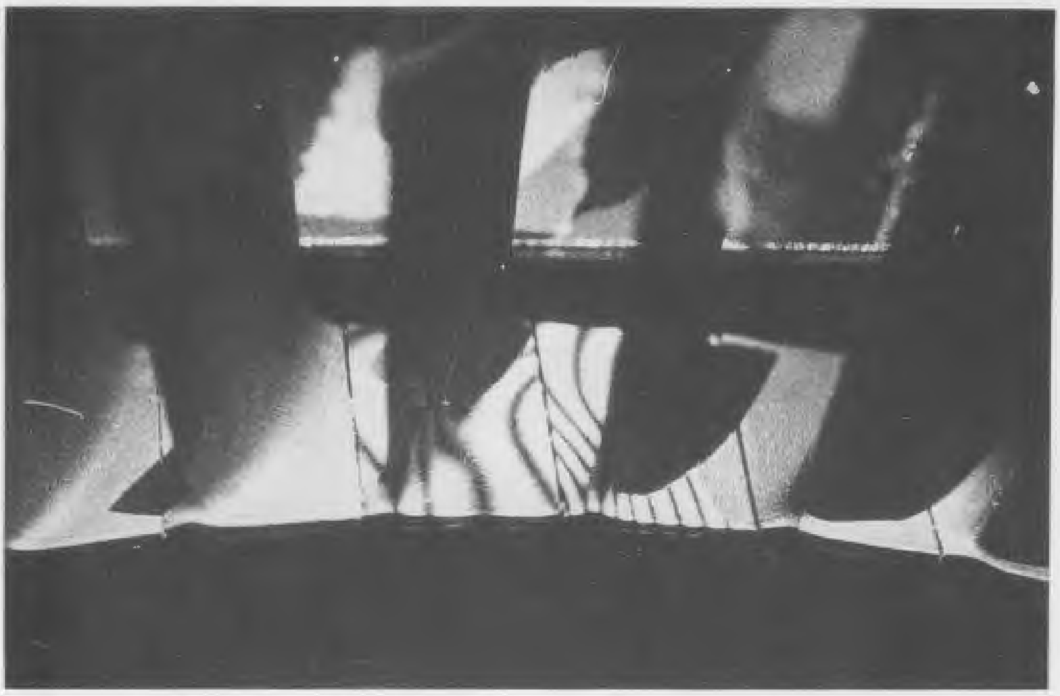

FIG. 9 END-ON VIEW (BLADE PAIRS 35/36)

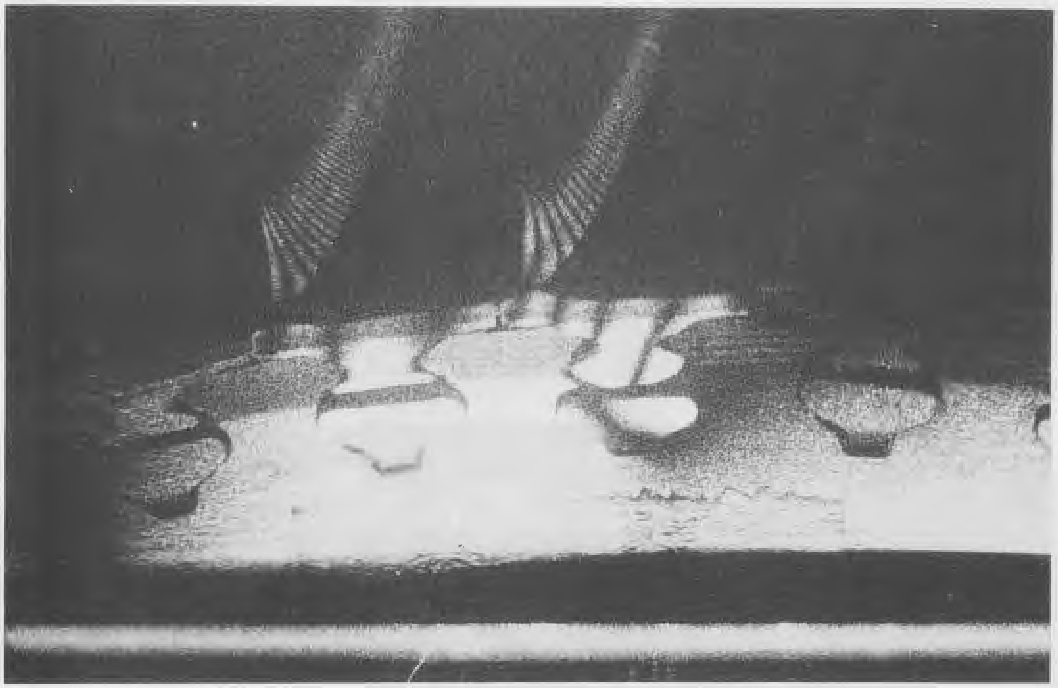

FIG. 10 SIDE-ON VIEW (BLADE PAIRS 35/36)

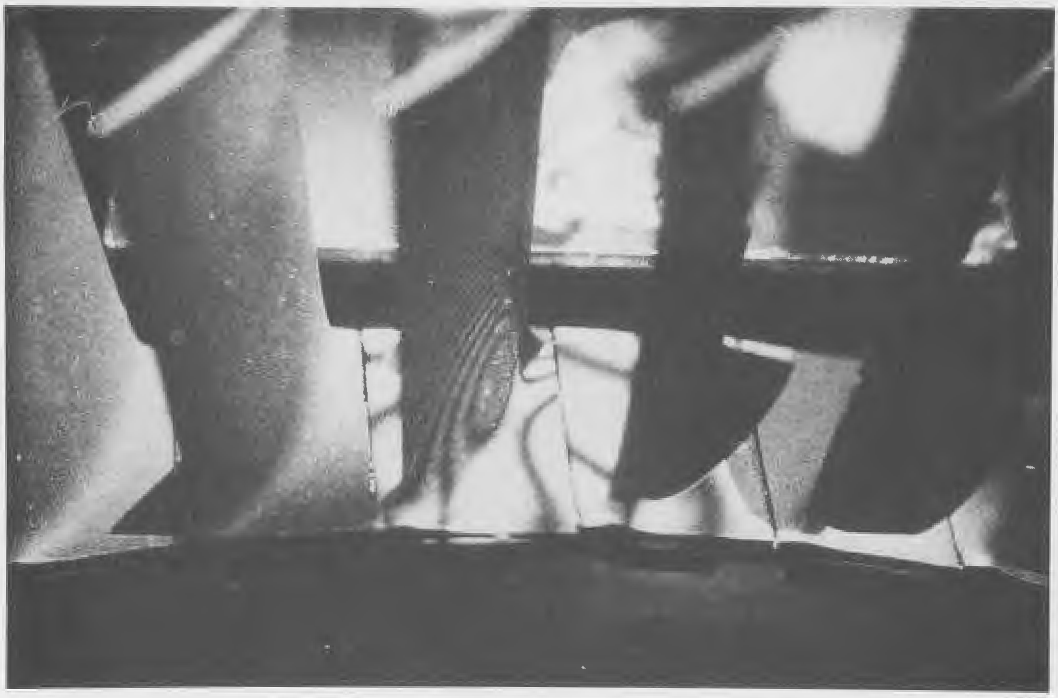

FIG. 11 END-ON VIEW (BLADE PAIRS 45/46)

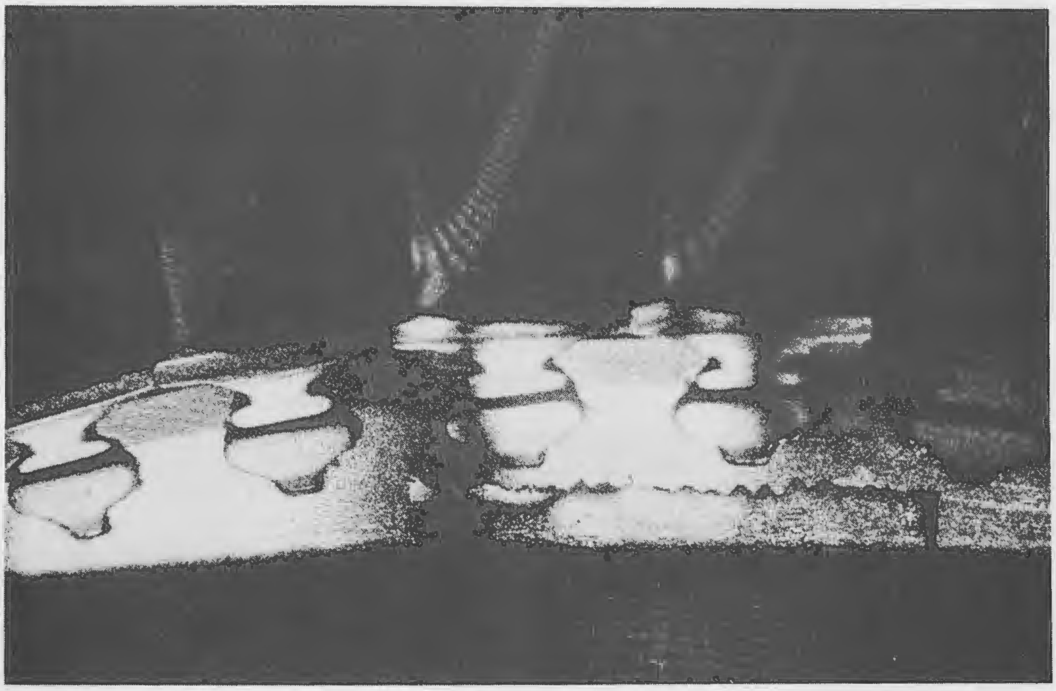

FIG. 12 SIDE-ON VIEW (BLADE PAIRS 45/46)

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16. ABSTRACT
Following a failure of a seventh stage compressor blade in a Rolls Royce Gazelle engine of a RAN Wessex helicopter, ARL was requested to investigate the cause and mode of failure. This report details the investigation and presents a number of conclusions and recommendations which deal with the cause of the failure. It also discusses new assembly methods which could alleviate future rebuild problems.

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