The Feasibility of Optical Interference-based NDE Methods to Inspect Helicopter Rotor Blades

Dirk Findeis, Jasson Gryzagoridis
Dept. of Mechanical Engineering, Univ. of Cape Town,
Private Bag, Rondebosch, 7700, South Africa

ABSTRACT

Currently, the NDE procedure for Alouette helicopter rotor blades consists of a visual inspection followed by a manual acoustic inspection procedure by trained personnel using purpose manufactured tapping hammers. The former inspection is aimed at detecting surface cracks and corrosion whereas the latter is intended to inspect the rotor blade for possible areas of delamination between the alloy skin and the leading edge spar or blade root reinforcing strip. This paper investigates the feasibility of using either the authors locally developed Portable Digital Shearography or Electronic Speckle Pattern Interferometry in conjunction with Mechanical Impedance Analysis in order to determine the possible presence and extent of defects more accurately and reliably. Both optical inspection techniques are discussed, their theory and apparatus presented and the inspection procedure described. The principle of Mechanical Impedance Analysis is also outlined and the inspection method described. The successful results of the study as well as defects detected are presented and discussed. Outlining the potential of using this alternative NDE method as an on-site, in-situ inspection procedure concludes the paper.

Keywords: NDE, defect detection, delamination, helicopter rotor blades, Digital Shearography, Electronic Speckle Pattern Interferometry, Mechanical Impedance Analysis

1 INTRODUCTION

The range of aircraft and helicopters used by the South African Airforce is diverse and includes the Pilatus Astra trainer as well as the Turbo Dakota C47TP. Included in the group is the small and versatile Alouette helicopter, which has been used successfully for a number of years by the defence force. The Alouette fleet is substantial can be found in operation at most of the Airforce bases within South Africa. The helicopter has undergone moderate modifications to meet local conditions but has always been considered easy to maintain. Two types of routine non-destructive testing (NDT) inspections are carried out on the Alouette. The first level of NDT work is of the type, which can be performed locally by aircraft fitters. The second level would be the use of e.g. Radiography or Eddy Current techniques, which have to be performed by trained NDT personnel. The personnel required for this work is provided by the two NDT sections within the Airforce, the first of which is based in Pretoria and the second at Ysterplaat in Cape Town.

One of the many key components of the Alouette, is the set of rotor blades. Each composite blade consists of a spar, which is a one-piece alloy. The shape of the spar determines the profile of the leading edge of the blade. Attached to the root end of the spar is a yoke shaped steel cuff, which is used to attach the blade to the hub via two taper pins. A one-piece light alloy skin is first shaped over the spar, then bonded to the spar and finally riveted to the trailing edge. At the inboard and outboard edges the skin is riveted to two ribs. The hollow blade is finally filled with moltoprene, which bonds to the spar and alloy skin to maintain blade rigidity and airfoil profile.

Regular NDT inspections of the three main rotor blades are performed locally by trained aircraft fitters. There are two types of inspections, which occur at different intervals. The first inspection takes place every 25 hours and consists of a visual check of the yoke shaped steel cuff at the root end of the spar with the blades installed. Should any cracks be suspected, the blades are removed and checked by NDT personnel using dye-penetrant.

The second inspection occurs every hundred hours or six months and requires removal of the set of blades. During this inspection, the blades are visually checked for cracks and then further inspected for debonding between the alloy skin and
spar, as well as the alloy skin and the moltoprene at the inboard root side of the blades. For this purpose, trained aircraft fitters carry out this inspection using purpose made tapping hammers. The entire area under inspection is lightly tapped with the hammer and the fitter notes the sound of the impact to determine whether the bond of the substructure is intact or has separated. This process typically takes three hours to complete. Should any debonding be detected, the blade has to be returned to the manufacturer for further inspection to determine the extent of the delamination and possible repair or replacement. If put back into service, the debond area has to be re-inspected every 25 hours to monitor its growth. The exception to this rule is if a debond is detected within the first 10mm of the edge of the alloy skin along the inboard reinforcing rib. For this type of debond, the blade is still considered fit for service, but has to be re-inspected every 25 hours by the fitter to monitor the growth of the debond.

Although this NDT technique has worked in the past, the inspection technique is currently under review for a number of reasons. The initial cost of inspection is relatively small, the cost of sending the blades to the manufacturer for further inspection and subsequent return is considerable. Even though the trained fitters are experienced and are subjected to routine hearing tests, the inspection is very subjective in that it relies on the interpretation of the tapping sound. There also is no record of the inspection procedure and no accurate mapping with respect to the debond boundary can be obtained. Therefore, where debonds need to be monitored on a 25 hourly basis, it is very difficult to determine whether their size has grown or not. Another disadvantage is that the technique is a manual scanning process, which is time consuming. The age of the fleet also suggests that a more reliable NDT technique be applied to reduce the risk of not detecting a flaw on an ageing blade.

2 OPTICAL INTERFERENCE TECHNIQUES

The application of optical interference techniques has been the subject of interest and much research within the Department of Mechanical Engineering\(^2\).\(^3\). One of the most recent accomplishments at our non-destructive evaluation NDE laboratory at the University of Cape Town was the completion of a research project, which entailed developing a low cost portable Digital Shearography Camera\(^4\), suitable as a technology demonstrator for non-destructive evaluation (NDE) procedures. The authors were approached by the Air Force to investigate the suitability of the Shearography prototype as well as Electronic Speckle Pattern Interferometry (ESPI) as an alternative NDE technique for the inspection of the Alouette rotor blades.

2.1 Shearography

Because ESPI\(^5\) and Digital Shearography\(^6\) can be used to monitor an objects' surface displacement when stressed\(^7\), both optical interference techniques are suited for the detection of material and structural defects. The presence of a defect weakens the structural integrity of an object, which in turn locally influences the object's surface deformation when stressed. The manner in which Shearography measures the rate at which an object deforms under stress is outlined below: The object under inspection is illuminated with a monochromatic light produced by a laser. The light, which reflects off the object surface, is viewed through a set of shearing optics. The function of the shearing optics is to laterally shear the image of the object into two, causing the two sheared images to overlap. Due to the monochromatic nature of the laser light, the overlapped images interfere and produce a unique speckle pattern. This speckle pattern is focused onto the CCD plane of a video camera, captured and digitised by a computer. This set-up is shown schematically in Figure 1.

A speckle pattern of the unstressed object is initially captured and stored in a computer as a reference image. The object is then stressed artificially by either mechanical, pressure or thermal methods, which in turn causes the object to deform. If the relative displacement between two points on the object surface changes due to the applied stress, a corresponding change in the laser beam path length occurs, causing the intensity

![Figure 1: Typical Shearography Set-up](image-url)
distribution of the speckle pattern to change. By recording these subsequent speckle patterns, digitising them and comparing them to the initially stored image, a final image is produced, which consists of alternating black and white 'zebra-like' fringes.

Mathematically the fringes can be represented by Equation 1 as:

\[ \Delta \phi = \frac{4\pi}{\lambda} \left( \frac{\partial d}{\partial x} \right) S \]  

(1)

where:
- \( \Delta \phi \) = correlation phase,
- \( \frac{\partial d}{\partial x} \) = displacement rate,
- \( S \) = magnitude of shear,
- \( \lambda \) = wavelength of the laser light,

Equation 1 above indicates that the correlation fringes along which \( \Delta \phi \) is constant, represent lines of constant displacement rates. The spacing between adjacent fringes is a function of the displacement gradient according to Equation 2,

\[ \frac{\partial d}{\partial x} = \frac{n\lambda}{2S} \]  

(2)

where:    
- \( n \) = no of fringes.

This implies that for a given object surface area, an increase in displacement gradient will produce a corresponding increase in number of fringes.

### 2.2 Electronic speckle pattern interferometry

ESPI on the other hand, directly records the surface displacement of an object in response to the applied force. The set-up can be briefly described as follows: a laser light beam is split into two. One of the beams, the object beam, is used to illuminate the object. The other beam is called a reference beam, which is later combined with the light reflected off the object. Due to the monochromatic properties of the laser light, the object and reference beam, when combined with a partial mirror, produces a unique speckle pattern. The speckle pattern is captured by a video camera and digitised in a computer as with the shearography system. Figure 2 schematically details the layout.

To perform an ESPI inspection process, a speckle image of the unstressed object is first captured and stored in the computer. The object is then stressed causing the object's surface to displace. This causes the beam path length of the light reflected off the object surface to alter without changing the characteristics of the reference beam, which in turn causes the unique speckle pattern to change. When compared with the original stored speckle image, a final image containing the familiar zebra-like fringe patterns is produced. The process is highlighted by Equation 3 below:

\[ d = \frac{n\lambda}{\cos \alpha + \cos \beta} \]  

(3)

where:    
- \( d \) = out of plane displacement of the object due to the applied stress,
- \( \alpha \) = angle between the direction of object displacement and camera viewing angle,
- \( \beta \) = angle between the direction of object displacement and object beam.
From Equation 3 above it becomes evident that the object displacement magnitude is constant along a fringe contour, but changes between consecutive fringes due to the increase or decrease in the magnitude of \( n \).

3 EXPERIMENTAL PROCEDURE

Two Alouette helicopter rotor blades were delivered to the NDT laboratory. The Air Force as well as the blade manufacturers had rejected this particular set of blades. Routine NDT inspections had picked up advanced debonding on the root end of the spar in one of the blades, which was confirmed by NDT personnel. Because the blades are manufactured in sets of 3 and blades cannot be replaced individually, the entire set was rejected. The second blade supplied, which was fit for service, was provided for comparison purposes. Each blade measured approximately 5 m long by 450 millimetres wide and weighed in the order 70 kilograms. The leading edge protection strip was still present on both blades.

The intention of the investigation was to use both Shearography and ESPI techniques. The shearography prototype is fully portable, the ESPI system however is still laboratory based. For this purpose, a solid steel table mounted on air cushions and shock absorbing rubber foot pads is used. A continuous wave helium-neon laser provides the monochromatic light. All optics used for ESPI work are mounted on magnetic bases which provide for solid positioning on the steel table.

Due to the length of the blades, they had to be placed diagonally across the table with the leading edge facing downwards and the trailing edge facing upwards. Even in this configuration the outboard side of the blade protruded beyond the door of the laboratory. In order to keep the blade in its vertical position, the steel cuff at the root end of the blade was clamped in a vice. Approximately two-thirds down the length of the blade, the leading edge was supported by a vee-shaped magnetic base. Figure 3 illustrates the layout and dimensions.

The ESPI setup was then configured around the blade and set up in such a way that the camera and expanding object beam were both directed onto the root section of the blade, where the light alloy skin edge joins the spar and inboard reinforcing rib. The angle \( \alpha \) was approximately 5 degrees and the angle \( \beta \) was in the order of 8 degrees. The cosine of these two angles could therefore each be assumed to be unity. The software used to control the image acquisition from the video camera is MS DOS based and captures the video images in a 512 x 512-pixel format. When performing an inspection procedure, the operator has the option to generate the fringe patterns, which are displayed on a separate monitor, either continuously in real-time or on-demand. The on-demand feature allows closer analysis of the generated fringe pattern before they are updated.

Once the ESPI set-up had been completed, the Portable Shearography NDT unit was configured. The system consists of a fully adjustable Shearography Head Unit, which is mounted on a sturdy tripod. Inside the Head Unit is housed an infra-red diode laser, a CCD camera, as well as the mirrors and beamsplitters required for the shearing configuration. The camera zoom and focussing controls are mounted on the top of the head unit and the shearing magnitude and orientation controls are mounted on the side, next to the laser and camera power cable and video connections.
A Microsoft NT driven PII PC with custom written software is used to control the digitiser card, real-time image acquisition and fringe generation routines. A window style interface allows the operator to control all the digitiser options whilst simultaneously watching the video or real-time fringe generation sequence on the SVGA monitor. The user also has the option of pausing the inspection process at any time for closer scrutiny or storage purposes. Two power supplies, one for the camera and one to control the power output of the laser diode, complete the package, which is depicted in Figure 4.

The tripod was placed directly behind and slightly above the ESPI set-up. The front of the Shearography Head Unit is just visible in Figure 3 on the left-hand side. The camera and laser were then configured to view and illuminate the same area of the alloy skin edge and blade root spar. It was also determined that both systems and associated lasers could be operated independently without interfering with the other system. This was due to the fact that the visible helium-neon laser was blocked out by the narrow band infra-red filter incorporated in the Shearography Head Unit. The infra-red laser did not interfere with the ESPI set-up due to the absence of a corresponding reference beam and general incoherence with respect to the helium-neon laser.

Due to the size of the blade on the table and the thickness of the spar at the root, mechanical loading of the blade to cause deflection was not considered. Vacuum or pressure stressing could have been an option, but was not considered due to the lack of a suitable vacuum dome with the correct shape to match the blade airfoil profile. Thermal heating was finally chosen as a suitable form of object stressing. The first method of application was with a conventional hairdryer, which was found not to be suitable. The heat could not be applied evenly, and the extent and duration of heating could not be repeated successfully. A infra-red heating lamp and switch, mounted on a small stand was found to be far better suited, as the heating process was more uniform and controllable.

4 INSPECTION RESULTS

Both ESPI and Shearography set-ups quickly revealed that the entire ‘critical area’, which requires the routine 100 hour maintenance inspection, could be inspected in one session. The mat green paint finish of the blades was a poor reflector, which was improved dramatically by brushing the surface with a little talcum powder.

4.1 Reject main rotor blade results

The first blade to be inspected was the defective blade. Figure 5 depicts the fringe pattern obtained from a real-time inspection sequence of the rejected blade. For this test the infra-red lamp was directed directly onto the area of the blade under inspection. Heat from a 150w lamp was applied for approximately 5 seconds, which caused uniform heating of the area being scrutinised. This was briefly confirmed by an initial uniform fringe pattern, which almost immediately changed to the pattern depicted in Figure 5. The triangular / elliptical fringes in the upper half of the image reveal the area where the alloy skin is bonded to the moltoprene. The abrupt change to a low fringe density below outlines the location of the aluminium spar. The thermal diffusivity of aluminium is far greater than for moltoprene, hence the greater transfer of heat from the alloy skin into the spar and subsequent minimal deformation. The irregular fringe formation to the left of the centre of the image reveals the location of the debond. Here the alloy skin has debonded, hence the heat applied via the infra-red lamp is retained with the
The second inspection was conducted with the infra-red heat applied to the left of the area being inspected. This form of blade heating required a longer heating period, typically in the order of 10 seconds. Figure 6 reflects the results of the inspection sequence. The uniformly spaced, near vertical fringes indicate the bending which the blade is exposed to when heated away from the area being inspected. The kink in the vertical fringes, running horizontally along the blade indicates the edge of the spar. The second kink in the fringe pattern along the bottom of the image is caused by the leading edge protection strip. Even though this fringe pattern is fundamentally different from the one depicted in Figure 5, the area of debonding is visible in Figure 6. The zigzag fringes to the right of the centre of the image reveal the location of the defect. The localised deflection due to the reduction in heat transfer capabilities of the debond area, is superimposed onto the global bending of the blade to produce the unique localised fringe pattern.

The blade was then inspected using the Portable Shearography NDT Camera. Because shearography relies on the shearing of the object image into two, this can be accomplished by either shearing the image horizontally or vertically. This causes the system to be sensitive to the rate of displacement only in the direction of shear. The blade was inspected using first the horizontal shearing configuration and then the vertical shearing configuration. For both configurations, the debond area was detectable and the result of the vertical shearing configuration is shown in Figure 7 below. For this inspection, direct heating for 5 seconds with the infra-red lamp was applied. Here again, the difference in displacement rates between the alloy skin and moltoprene bonded section, and the alloy skin and spar bonded sections of the blade can be detected. The area containing the irregular dark fringe dot and semicircular fringe on either side, which is visible to the left of the centre of the image, highlights the location of the debond. When comparing the location of the defect in Figure 7 with those picked up in Figures 5 & 6, one can see that the locations compare favourably.
4.2 Inspection results of the ‘good’ blade

Once the defective blade had been tested, it was decided to inspect the good blade as well, in order to acquire a reference set of fringes for a defect free blade. The blade was fastened onto the table as for the first blade, and the ESPI testing procedure was applied first. The root end of the blade was heated directly for approximately 5 seconds. The result of the inspection can be seen in Figure 8 below. The first observation to be made is that the fringe concentration is not as dense as in Figure 5. This is because the process was only halted after a certain amount of cooling had taken place. The second, more peculiar observation is the fringe irregularity, which can be seen centrally in the image in Figure 8 below, on top of the inboard reinforcing rib. The area of interest is highlighted with a white circle. Here the fringe pattern indicates a localised change in the displacement gradient, where the bonding of the alloy skin to the spar and reinforcing rib should have prevented this type of distortion. This particular blade had been tested and was certified to be free of defects.

The blade was then inspected using the Portable Shearography Camera. The shearing optics were set up for horizontal shearing and the blade area being inspected was heated directly with the infra-red lamp. The fringe pattern obtained from this investigation is documented in Figure 9 and also clearly reveals a defect between the alloy skin and the junction of the spar and inboard reinforcing rib. The irregular shaped fringe in Figure 9 is highlighted with a white circle and indicates an asymmetrical displacement gradient in an area of supposedly high thermal diffusivity.

5 MECHANICAL IMPEDANCE ANALYSIS

The results obtained from the second blade inspected did not fit the picture presented by the Airforce. In order to support or contradict the findings from the ESPI and Shearography investigations, it was decided to use the laboratory’s Mechanical Impedance Analysis (MIA) equipment to try and verify the presence of debonds in both rotor blades.

MIA employs mechanical vibration, which is applied to the object surface via a probe, to analyse the local stiffness of a structure. The probe consists of two piezo-electric crystals. One of the crystals converts electrical signals into vibrations. By resting the probe on the object surface, the vibrations are transferred to the structure under investigation. The other crystal picks up the objects response to the applied vibration by measuring the phase and amplitude of the returned signal and converts it back to an electrical signal which is then compared with the source signal. Any change in the structural rigidity due to the presence of a flaw will affect the objects’ response to the mechanical vibration, which can be detected if compared with the signal produced by an unflawed section. The use of frequencies in the 1 – 8 kHz range eliminates the need for a probe coupling fluid which simplifies the inspection process.

In order for the technique to be successful, the equipment is first calibrated by monitoring the returned signal from a defect-free sample as well as flawed sample of the object to be tested. The optimum frequency, offset and gain parameters at
which the variation in phase and amplitude between the good and flawed sample is at a maximum, is recorded and used as the testing parameters.

The MIA equipment used was an Inspection Instruments MIA 2500 with integrated cathode ray tube and hand held probe. The reject blade was used to pre-calibrate the tester. The probe was first placed on a good section of the leading edge of the blade and the frequency range scanned. Using the tapping technique, the debond was located, and the frequency scanned again, with the probe placed centrally over the flawed section. The results revealed that for amplitude and gain settings of 50, the amplitude dropped off significantly over a debond area at a frequency of 3800 Hz.

Using the drop in amplitude as a guide, the root section of each blade was scanned for the presence of areas of debonding. The results of the inspection are shown in Figures 10 & 11 below.

![MIA results of the flawed rotor blade](image1)

![MIA results of the good rotor blade](image2)

The inspection of the flawed blade detected a debond area between the alloy skin, spar and root reinforcing rib. The location of the debond is outlined with a black marker, as indicated in Figure 10. When comparing this result with the results in Figures 5, 6 and 7 using ESPI and the Portable Shearography Camera, one can deduce that they match favourably. Of interest is the result shown in Figure 11, which supports the theory of a debond in the ‘defect free’ blade as initially detected using ESPI and the Portable Shearography Camera. The black outline in Figure 11 marks the debond location, which ties up with the results obtained in Figures 8 and 9.

6 CONCLUSIONS

From the results in can be concluded that both Electronic Speckle Pattern Interferometry and Portable Shearography are viable alternatives for the inspection of Alouette helicopter rotor blades. Both optical interference techniques are able to inspect the entire critical section of the blade at once, thereby reducing the risk of missing a spot. The inspection procedure is quick and provides superior, real-time results.

By replacing the acoustic interpretation of the tapping impact sound with digital processing and image rendering techniques, operator subjectivity is dramatically reduced. In addition, these techniques provide the ability to record the inspection results for later scrutiny, future reference or comparison purposes.

The fact that a flaw was detected in a reportedly defect free rotor blade, indicates that the sensitivity of the optical interference techniques are greater than what is currently in practice.

Thermal heating has proven to be an effective means of stressing the object for inspection purposes. Even though different heating layouts generate different fringe configurations, the infra-red lamp method works well and is able to reveal the presence of a debond. More work however is required to determine limitations of various heating arrangements.

The quality of the fringes generated using the ESPI method is generally better than those obtained using the Portable Shearography Camera. Image enhancement during the shearography inspection process is currently kept to a minimum, in
order to maintain high image refresh rates. Replacing the computer processor with a faster version will allow additional image enhancements to be added to the software.

The fact that the Shearography camera is fully portable suggests the option of inspecting the rotor blades on-site. The portable camera is lightweight, can be easily elevated and operates at any angle. By designing a turnkey solution, aircraft fitters could be trained to inspect the helicopter rotor blades in-situ. Should a debond be detected, NDT personnel could then be approached to map the extent of the defect using MIA. The potential also exists to use either ESPI or the Portable Shearography camera to monitor the growth of a debond area, should the need arise.

REFERENCES