Integrative Solution for In-situ Ultrasonic Inspection of Aero-engine Blades Using Endoscopic Cheap Optical Transducers (CHOTs)

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Abstract
In-service non-destructive testing of aero-engine components is challenging for conventional ultrasonic techniques due to their contact nature, the complex geometry of engines and restricted access. Cheap optical transducers (CHOTs) employ principles of laser ultrasonics to remotely generate and detect ultrasound, providing a simple non-contact, couplant-free alternative to the traditional piezoelectric transducers. They are practically weightless nanometre-height patterns attached or printed on the component, and activated by lasers. Cheap, with minimal surface impact CHOTs could be permanently left on the component, used in large numbers or as disposable transducers. Combined with an endoscopic light delivery system to provide access via existing service ports in the engine, they are designed to perform remote ultrasonic inspection in an aero-engine environment. In particular, CHOTs would enable in-situ testing of aero-engine blades, reducing servicing time and costs. This paper presents the developed endoscopic CHOTs instrumentation and experimental results of the remote ultrasonic inspection with surface acoustic waves.

Keywords: Ultrasonic testing (UT), endoscopic inspection, aero engine blade, in-situ testing, cheap optical transducers (CHOTs), laser ultrasonics

1. Introduction

Industrial requirements for current and next generation aircraft are driven by the demand for more time- and cost-efficient operation with simultaneous minimisation of industry environmental impact. Reduction of noise and emission levels as well as fuel consumption, along with provision of more flights, place increased demands on the engine components. In-service structural health monitoring and non-destructive testing (NDT) of these components are essential for safe operation of an aircraft. At the same time the requirements for lower operation costs, including reduction of time and cost of in-service operations without impairing passenger safety, lead to the demand for testing methods and instrumentation able to provide real-time and on-site inspection.

Turbine and compressor blades of an aero-engine are among the most critical components that are prone to the development of fatigue and stress defects and are especially challenging for in-situ testing. Their location within the engine offers very limited access, and is further complicated by a multi-stage assembly of the blades. It is common to perform visual in-situ inspection of the engine parts using a borescope via a specially provided access port. This endoscopic access method is being increasingly adopted to provide similar in-situ inspection by other NDT methods [1-3]. Most conventional NDT techniques, however, require direct surface access (e.g. dye penetrant, eddy-current testing) and so are unable to detect presence of defects in locations where components are joined together and their surface is partially obscured by other parts of the assembly, such as a corner of a blade dovetail inserted into a disc.

Ultrasonic testing with surface acoustic waves (SAWs), traditionally performed with wedge piezoelectric transducers (PZTs), enables inspection of such locations [4]. The difficulty of using PZTs in an aero-engine is their requirement to be in contact with the test
surface and the need to use a couplant to exclude the presence of air between the surfaces of the transducer shoe and the component for the measurement to take place.

A possible solution is offered by the use of the cheap optical transducers (CHOTs) that employ principles of laser ultrasonics [5] to remotely generate and detect ultrasound. These transducers are nanometer-height patterns attached to or printed on the surface and activated remotely; they can be used to independently generate (g-CHOT) or detect (d-CHOT) ultrasound, or in a coupled configuration to perform both functions [6]. CHOTs are activated optically by laser light and do not require instrumentation to contact the surface. They can be manufactured by a number of methods directly on a component at the production stage or applied in-situ, and are very versatile and fully customizable offering increased control over the characteristics of the generated ultrasound [7]. The CHOT pattern geometry can be configured to produce plane or focused, surface or bulk acoustic waves [8] of desired frequency and directivity. Their small size and nearly-zero weight allow these transducers to be left on a component without affecting its operation. The main advantages CHOTs offer, compared to other laser ultrasonic techniques [9-11], is the simplified probe instrumentation able to work in locations with limited access, greater efficiency [12] and method robustness to environmental vibrations.

This paper extends the development of the CHOT technology to NDT applications, with particular focus on enabling in-situ testing of aero-engine components. The ability of the CHOT system to successfully perform non-contact, couplant-free ultrasonic feature detection is demonstrated on aluminium (Al) samples. Here, CHOTs for plane SAWs were used in a pitch-catch configuration with endoscopic delivery of the activation and probing beams, used for generation and detection of acoustic waves respectively. Results from a similar inspection performed with a wedge piezoelectric transducer are also presented for comparison.

2. Instrumentation

A basic CHOT measurement system for generation and detection of ultrasound [6] requires a pair of CHOTs on the surface of a sample, a generation and a detection laser to illuminate the corresponding CHOTs, minimal optics to expand and collimate the beams and to collect the returning probing beam (containing ultrasonic information), and a photo-detector. To enable operation of the system in instances where CHOTs are not in direct line of sight, laser light is coupled into optical fibres providing the means for endoscopic operation. The generation and detection of ultrasound are performed by the CHOTs, located on the test object. The instrumentation is required only to deliver and collect the laser light to and from the patterns.

2.1 Generation of ultrasound

The g-CHOT, used for generation of ultrasound, is a pattern consisting of the alternating areas of high and low absorption that provide an absorption contrast to the incident laser light (figure 1(a)). It converts incident radiation energy into acoustic waves using principles of laser ultrasonics. Localised thermal expansions of material resulting from absorption of the pulsed laser radiation via a photo-thermal effect create thermo-elastic stresses inside the material, producing acoustic waves [6-8].

The laser used for generation is a Q-switched 1.064μm Nd:YAG laser with 7ns pulse duration at 1kHz repetition rate, and 650mW average power output. Minimal optics is used to couple the beam into a high-power multimode optical fibre and a collimating lens used at the exit of the fibre to illuminate the g-CHOT. The power output after the fibre was measured to be 480mW, corresponding to ~75% coupling efficiency. The use of a collimated beam allows a flexible stand-off distance during the measurement and ensures operation in the thermo-
elastic regime, while the only alignment required for the generation is to position the laser beam onto the g-CHOT. The acoustic frequency, type and directivity of the generated waves are determined by the CHOT design.

Here, the g-CHOT was produced to generate 4MHz plane SAWs on Al samples. Operation at the required frequency is achieved by appropriate matching of the spatial period of the pattern to the acoustic wavelength: $\sim 720\,\mu\text{m}$, considering the Rayleigh wave velocity in the material (2905 m/s in Al). Chromium (Cr) was chosen as the material of the pattern to provide a sufficient absorption contrast to the underlying Al at 1.064μm, with Cr and Al absorbing $\sim 45\%$ and $\sim 6\%$ of the incident radiation respectively.

![Figure 1. (a) Photograph of a g-CHOT, (b) Photograph of a d-CHOT, (c) Generation and (d) detection of ultrasound with CHOTs (sample cross-section)](image)

### 2.2 Detection of ultrasound

The d-CHOT is a pattern similar to a g-CHOT but designed to reflect the light. It acts as a reflective diffraction grating introducing a controlled phase difference into the incident beam, and separating it into diffraction orders (figure 1(b),1(d)). d-CHOT translates acoustic waves propagating underneath it into intensity modulation of light. When the spatial period of the d-CHOT is matched to the acoustic wavelength, the changes in the height of the pattern, caused by the propagating SAW, alter the instantaneous efficiency of the d-CHOT grating and the distribution of energy between the diffraction orders. The ultrasound detection is achieved by monitoring intensity modulation in one of the orders [6-8].

#### 2.2.1 Probing

The probing laser used for detection in the present experiment is a continuous wave (CW) second harmonic Nd:YAG laser, emitting at 0.532μm ($\lambda_{\text{det}}$) with 60mW power output. Again, the laser beam is coupled into a fibre using standard optics and collimated by the lens upon the exit of the fibre for d-CHOT illumination. Here, a single-mode fibre is used to preserve Gaussian intensity distribution in the illuminating beam. The measured power after the fibre was 40mW, corresponding to $\sim 65\%$ coupling efficiency. As in the case of generation, the alignment consists of positioning of the probing beam onto the d-CHOT. Here, however, the efficiency of detection and the acceptance angle of the collecting optics place some restrictions on the incidence angle of the probing beam.

A d-CHOT with the step height $\sim 66\text{nm}$ was produced and coated with silver for optimum reflection at the wavelength of the probing laser ($\lambda_{\text{det}}$). The step height is chosen to
produce a phase shift of $1/4\lambda$ between the light reflected from the top and the bottom of the grating. This provides maximum detection sensitivity and robustness to vibrations without requiring stabilisation [11]. When used jointly, the spatial period of the pattern is matched to that of the g-CHOT and the generated acoustic wave, which corresponds to $\sim720\mu$m in the experimental results presented.

### 2.2.2 Signal detection

A coherent fibre bundle is used to collect the probing light diffracted by the d-CHOT from the sample and deliver it to the photo-detector. The use of imaging fibre preserving spatial distribution allows the diffraction orders to be collected and transferred from the sample to the user-side of the fibre where the detection takes place. In the experiments presented here, a leached fibre bundle consisting of 18k individual fibres of diameter $\sim11\mu$m from Schott is used. A lens on each side of the bundle is used to collect and extract the diffraction orders, and an iris diaphragm is placed in front of the photo-detector to isolate one of them. Intensity modulation produced by the propagating SAW is monitored in the 0-th diffraction order.

Since the ultrasonic information is contained in the modulation of intensity and measurement can proceed even with a single diffraction order, it is not required for all of the diffracted light to be collected. This provides some flexibility in alignment with the main requirements for this channel consisting of 1) the ability of the system to physically collect the light returning from the d-CHOT and 2) alignment of the order of interest with the iris.

Two cameras are installed into the system. One to provide visual means of alignment of the beams on the CHOTs on the sample and one to facilitate the alignment and isolation of the selected diffraction order with the iris.

### 3. Endoscopic CHOT detection experiment

The potential of the endoscopic CHOT system for NDT applications is demonstrated by performing remote ultrasonic detection of the controlled features introduced to a number of samples. Rectangular-profile slots representing surface defects were produced by milling on three Al samples, where the width and the length of the slots are fixed, and the depth is varied between the samples from $1/2\lambda_{\text{acoustic}}$ to $2\lambda_{\text{acoustic}}$ (table 1). Another (defect free) sample is used for calibration measurement. These samples were tested both with CHOTs and a piezoelectric wedge transducer of the same frequency for result comparison.

<table>
<thead>
<tr>
<th>Sample #</th>
<th>Slot depth</th>
<th>Slot width</th>
<th>Slot length</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>1</td>
<td>$2 \lambda_{\text{sw}}$</td>
<td>1.46mm</td>
<td>1/3 $\lambda_{\text{sw}}$</td>
</tr>
<tr>
<td>2</td>
<td>$1 \lambda_{\text{sw}}$</td>
<td>0.75mm</td>
<td>1/3 $\lambda_{\text{sw}}$</td>
</tr>
<tr>
<td>3</td>
<td>$1/2 \lambda_{\text{sw}}$</td>
<td>0.39mm</td>
<td>1/3 $\lambda_{\text{sw}}$</td>
</tr>
</tbody>
</table>

Manufactured sample and slot dimensions and geometry were chosen to account for the following factors: sample thickness – to exclude the possibility of Lamb wave generation (10mm is sufficient at 4MHz), length of the sample and the CHOTs location - to allow a clear time resolution of the echoes, slot location on the sample (considering the target application of the system) - to represent a distance characteristic for the appearance of cracks at $\sim10$mm from the bottom surface of a blade dovetail, and the slots dimensions – to represent the macroscopic appearance common to the dovetail fractures. The dimensions and quality of the slots were verified by white light interferometry.
CHOTs for generation and detection of plane 4MHz SAWs were produced on the samples (figure 2). To aid their respective alignment, both patterns were produced at the same time by evaporation of 66nm of Cr through a mask onto the sample (creating a g-CHOT and a base for the d-CHOT) and coating one of the patterns with 100nm of Ag to create a d-CHOT.

Used jointly, a g-CHOT and a d-CHOT are equivalent to the use of two transducers in a pitch-catch configuration placed next to each other. Therefore, an additional echo of the ultrasound detected by the d-CHOT in the first pass is present in the A-scan even in the absence of any sample features. A typical signal demonstrating d-CHOT registering first pass of ultrasound generated by the g-CHOT is shown in figure 3.

Experimental setup showing the sample being tested, exit of the fibre channels and the detection system is presented in figure 4. The pulser containing the generation and probing lasers with the corresponding coupling optics is not shown.

The use of coupled CHOTs also provides unique means of self-calibration. Unavoidable differences in the surface quality between samples and the efficiency differences between manufactured CHOTs from sample to sample can be eliminated from the measurement results by normalising the data to the peak-to-peak amplitude of the first pass of ultrasound detected by the d-CHOT. This value objectively characterises the coupled CHOTs-sample system, including both, the generation and detection efficiency. Such normalisation allows direct comparison of the first-pass relative data between different samples.
Normalised experimental results for endoscopic ultrasonic testing of four Al samples are shown in figure 5(a) where the detected echoes are marked according to the propagation paths in the sample (figure 5(b)). A 5MHz band-pass filter (~2MHz bandwidth) and an amplifier were used during signal acquisition, and the output was averaged over 1000 measurements. The time of flight of the echo produced by the top edge of the calibration sample (marked ‘d’ in the plot) is used as a position marker for comparison with the traces where the slot echoes are present.

The first three traces (figure 5(a)) clearly show the additional echoes (marked ‘c’) caused by the presence of the slots on the surface of a sample, in contrast to the bottom trace from the clear sample. The magnitude of the slot echoes is increasing with the increasing depth of the slot (figure 6), confirming the expected behaviour [4].

Figure 5. (a) A-scans from CHOT inspection of Al samples with slots of various depths. (b) Propagation paths corresponding to the detected echoes.

![Figure 5](image1.png)

Figure 6. Slot depth to peak-to-peak echo magnitude relation
Comparable tests of the same samples with the slots of the similar parameters were performed with a 4MHz wedge piezoelectric transducer (figure 7), where the similar echoes from the slot features and the top edge of the sample were identified (marked with ‘c’ and ‘d’ in the plot respectively). Industrial-type gel couplant was used for this test and the results were averaged over 64 measurements. The difference in the quality of the transducer-sample coupling between the samples is seen to be affecting the amplitude of the echoes.

Comparing inspection results to that of a conventional PZT, the CHOT system has shown the ability to detect surface defects, producing easy-to-interpret A-scans of a similar nature to those obtained with the traditional methods, with the benefit of self-calibration, flexible access and absence of coupling medium.

![Figure 7](image)

(a) A-scans obtained with a piezoelectric transducer. (b) Propagation paths corresponding to the echoes

4. Further work on endoscopic access

The endoscopic systems used for in-situ engine inspections should comply with the standard access port sizes and inter-component paths in the engine, which restrict the maximum diameter of the instrumentation measuring tip to 8-10mm.

Currently used fibre-coupled CHOTs system exceeds this size relying on the standard off-the-shelf optics and fibres (figure 8). The ongoing work is, therefore, to miniaturise the size of the instrumentation by using custom-made optics and reducing the number of the separate optical fibre channels. The combination of the probing and the collecting channels can be achieved by using a single fibre bundle to perform both functions – sending and receiving detection light.

Development of the automated active optics to acquire and track the diffraction orders on the iris is in progress. Such automated alignment system will enable sequential tests of multiple components, which is the subject of the future investigation, eliminating the need for instrumentation adjustments between the tests.
5. Conclusions

The use of the cheap optical transducers (CHOTs) is suggested as a solution to the current industrial NDT challenges; in particular, the in-situ testing of hard-to-reach aero-engine components. Excited optically, with minimal impact on the component, and fully customizable for the application, CHOTs provide a simple alternative to conventional piezoelectric transducers, offering a number of benefits associated with wireless, remote generation and detection of ultrasound.

One of the major advantages of the unique CHOTs detection system is the ability to spatially separate the collection of the ultrasonic information from the sample and the space-consuming hardware and electronics performing the actual signal detection. This dramatically reduces the size of the instrumentation accessing the component and provides the reach to the locations challenging for conventional techniques. Non-contact operation and the use of light as the means of sensing have good potential to allow inspection of multiple or even moving components where the testing instrumentation could be kept stationary.

The work presented here investigated the NDT potential of a fibre-coupled CHOTs system. The instrumentation was described and the experimental results were shown compared to a similar inspection performed by a traditional piezoelectric transducer. Detection of the rectangular-profile slots on the surface of Al samples with an endoscopic CHOT system demonstrated the similarity of results with the traditional methods, at the same time providing the means for self-calibration, vibration robustness and ability to deliver ultrasonic testing to components with limited access. Further work is aimed to reduce the size of the optical heads to fit the 9mm access ports and demonstrate extended system capabilities.

Acknowledgements

The authors wish to thank the Engineering and Physical Sciences Research Council, Rolls-Royce plc, and Schott for their support.
References


