A near infrared technique for non-destructive evaluation

P Pallav, G Diamond, D Hutchins and T H Gan

The use of near infrared signals for NDE measurements is described. It will be shown that such signals can be used to image the internal structure of many types of non-metallic materials, including polymers, ceramics, and packaging materials. This completely non-contact technique is likely to have many applications in the inspection of materials and structures.

1. Introduction

There are many NDE inspection situations where it is not always possible to use traditional methods. For instance, there are situations in which materials are both non-conducting electrically, and non-ferromagnetic, which restricts the testing options. If the use of ultrasound is difficult (for example because of additives, inclusions or air pockets increasing scattering, or because of viscoelastic behaviour), then the options available are restricted further. Other examples where new technologies would be of benefit are where remote access is required, or where the material to be tested is in motion. There are also situations where other established techniques, such as X-ray inspection, are not possible, either because of restricted access, or because of concerns over the use of ionising radiation.

It has been found that near infrared (NIR) signals in the 700 – 900 nm (0.7 – 0.9 μm) wavelength range can be used to image many types of material. Preliminary work in this area was reported recently at the annual QNDE conference\(^{(1)}\). This is an interesting technique, in that it uses conventional optical components to test non-metallic samples. This is in contrast to a technique known as THz imaging\(^{(2)}\). This technique shows much promise to NDE, but has some limitations – it is currently complicated and expensive to use, and experiences significant absorption in both liquid water and water vapour. Thus, a technique without these drawbacks would be potentially very useful.

There has already been work reported on the use of infrared (IR) signals in the medical imaging field. Traditional IR, at longer wavelengths than NIR, has been widely used for thermal imaging\(^{(3)}\). These methods have been used for the thermography of many materials, including composites\(^{(4)}\), and many other types of structures\(^{(5)}\). NIR signals are defined usually as having wavelengths in the 0.7 – 2.5 μm range (although astronomers often extend this range to 5 μm), and traditional thermography is rarely performed in this wavelength range. However, transmission of NIR signals has been used for medical imaging\(^{(6)}\) and for monitoring blood oxygenation status, especially in the brains of newborn infants\(^{(7)}\). This approach was based on the measurement of the frequency dependent phase shift and demodulation of intensity modulated near infrared light, which was transmitted through an infant skull. The technique has also been proposed as a method for the detection of dental caries\(^{(8)}\), chemical imaging of biological tissue\(^{(9)}\), burns injuries\(^{(10)}\), dermatological disorders etc. NIR signals have also been used as a laboratory tool for food inspection\(^{(11, 12)}\), but has not been used routinely as an imaging technique.

The present work has thus been designed to investigate whether a simple but effective NIR technique could be developed, which could be used as a general NDE tool for non-metallic materials. As will be seen, this is indeed possible and there are many applications in both traditional NDE and in other areas, such as security scanning.

In the current experiments, NIR signals at a wavelength of 850 nm have been used. At these wavelengths, transmission through a non-conducting specimen is almost totally a function of absorption and scattering. For a fixed molecule and fixed surrounding conditions, attenuation of light through a test sample can be treated as combined contribution of scattering and absorption, where both are a function of wavelength. This can be written in the form of equation (1):

\[
\alpha(\lambda) = \sigma_s(\lambda) + \sigma_a(\lambda) \quad \text{(1)}
\]

where \(\alpha(\lambda)\) is the overall attenuation of a signal with an optical wavelength \(\lambda\), passing through the test material, \(\sigma_s(\lambda)\) is attenuation due to scattering, and \(\sigma_a(\lambda)\) is attenuation due to absorption. Rayleigh and Mie scattering both tend to increase as \(\lambda\) decreases, \(i.e\) as the wavelength moves towards the ultraviolet (UV). At longer wavelengths, towards the IR region, scattering tends to become weaker while other mechanisms increase in importance, such as the effect of absorption due to inter-atomic vibrations. By operating close to the visible region, the absorption due to chemical bonds is minimised, so that transmission through objects becomes more feasible for NDE purposes.

2. The near infrared technique

Although NIR signals in the 700 – 900 nm wavelength range are able to penetrate into many non-metallic materials, the through-transmitted signal is still highly attenuated due to scattering and absorption within the sample. An appropriate signal recovery technique is crucial for successful imaging of the test material. In these experiments an autocorrelation technique, namely lock-in detection, has been implemented via hard-wired analogue electronics. This increases detection sensitivity.

The lock-in detection technique has been implemented in these experiments for NIR signals at a wavelength \(\lambda = 850\) nm.

The lock-in algorithm is illustrated in the simulation shown in Figure 1. Typically, the NIR source is driven with a 3 kHz sinusoidal modulation signal, as illustrated in Figure 1(a). This is transmitted across a test sample, after which it is highly attenuated, Figure 1(b), and embedded in noise generally much higher than the received signal, Figure 1(c). It can easily be seen that the received signal cannot be distinguished visually from noise in this received noisy signal. This noisy signal is now multiplied with the 3 kHz modulation signal used as reference, and then rectified (Figure 1(d)). The result is a large reduction in noise, and an increase in the signal-to-noise ratio. Note that in these experiments, it was assumed that there was no phase shift in the modulation signal, due to the short distance of travel and the speed of light. The rectified output was then filtered to get rid of ripples and averaged over a period of time to obtain a mean DC level. The final DC level
obtained using this technique then becomes a function of the signal amplitude transmitted across the test sample. This simple approach can then be used for imaging.

The whole process illustrated in Figure 1 was implemented using hard-wired analogue electronics. This meant that the sensitivity was optimised, as the algorithm did not have to deal with quantisation noise inherently introduced by digital electronics, and was thus able to pick up even minute changes in received signal level.

The variation in NIR signal amplitude received across the test sample can be described by the Beer-Lambert law, and is given by equation (2):

\[ I = I_0 e^{-kd} \]  

Here, \( I \) is the intensity of NIR wave received across the test sample, \( I_0 \) is the intensity of incident NIR wave, \( k \) is the extinction coefficient, \( c \) is the concentration of the absorbing species in the material and \( d \) is the distance the light travels through the material. Differences in attenuation of the incident signal after passing through regions with and without defects can be used to locate and image defects and inclusions within the test sample (14), and if required, can be used to obtain a value of \( k \), although this was not normally done in the present experiments.

The experimental arrangement used for NIR inspection of test materials is shown in Figure 2. The experiments used an 850 nm light emitting diode (LED) as source, commonly used in television remote controls. The LED had a 3 mm aperture and 40° angle of projection. For better resolution and contrast, a 5 mW laser source with a 5 mm spot size was used as source for some experiments. A standard infrared photodiode was used as receiver, with a visible aperture of 5 mm. An optical filter was placed on top of the photodiode aperture to further filter out visible light; this improved the sensitivity of the receiver. The transmitter and receiver were aligned in a through-transmission mode, across the test sample, and were mounted on an X-Y scanning stage for imaging purpose. The transmitted 850 nm NIR light was modulated using a 3 kHz square wave signal generated using a signal generator. The lock-in technique described above was implemented for signal detection and recovery.

The lock-in algorithm was implemented using a custom-built hardware based lock-in amplifier unit. The received signal was multiplied with the transmitted reference signal and averaged over a period of time to get a DC voltage level, using the lock-in amplifier. The resultant DC output was sent to a custom-built signal evaluation and scanning system assembled using the PXI unit from National Instruments Ltd, in conjunction with custom-built LabVIEW based signal scanning software.

Sample images were created by scanning the transmitter-receiver pair across the test sample using an X-Y stage controlled by the LabVIEW system. A typical scan used a 1 mm step size. Data was recorded at each position within a particular scan, to form the image of the test sample.

3. NDE of non-metallic materials

It has been found that NIR signals can be transmitted through many types of ceramics. For example, signals are transmitted through engineering ceramics, such as alumina. Figures 3(a) and (b) show photographs of a fragment of an alumina sample, commonly used inside bullet proof vests, on one side of which copper tape was pasted. Scanning was performed under darkroom conditions, so that no stray light source was present to provide reflection from the surface. The resulting NIR image is shown in Figure 3(c). The copper tape was detected well, demonstrating through-transmission. It was observed in further laboratory tests that NIR signals at \( \lambda = 850 \text{ nm} \) were capable of penetrating through a range of ceramic materials.
materials (such as china clay used for dinner plates etc), although more tests are needed to determine the types of ceramics for which NIR imaging is feasible.

There is also interest in detecting objects within expanded foam material. Figure 4(a) shows a photograph of expanded polystyrene foam, in which a metal rod had been placed. A scan of the object, shown in Figure 4(b), demonstrates clearly that the metal rod had been detected. Note, however, that the image of the metal object was much extended beyond the known diameter. This was thought to be due to the effects of scattering from the structure within the foam material. This scattering is a phenomenon which requires further research, and can possibly be reduced substantially by careful design of additional optical components. This is the subject of current research.

To indicate transmission across other types of similar material, a scan was performed on blue structural closed-pore rigid foam. The sample shown in the photograph of Figure 5(a) was scanned over the area shown, with the beam from the source incident upon this surface. On the far side, saw cuts were made into the surface, which then had the appearance shown in Figure 5(b). Finally, the resulting NIR scan is shown in Figure 5(c), where the presence of the saw cuts in through-transmission is clearly evident.

4. Applications in dentistry
Detection of cavities inside a tooth could also be an area of application. The bulk of a tooth is mainly formed of crystalline calcium phosphate (tooth enamel), dentin protein and other organic materials. It was expected that NIR within the 700 nm to 900 nm window will have a high transmission through tooth volume and thus would be able to image any defect present within the tooth sample. Figure 6(a) shows a tooth with cavity present on one side. Dental pulp within the tooth sample was completely dried up. This tooth sample was scanned using NIR at $\lambda = 850$ nm with transmitter facing the side from where the cavity was not visible. Again, the scan was performed in dark room conditions to avoid light from other sources. The result of the scan is shown in Figure 6(b). The dental cavity could easily be identified as the contours present in the dental image of Figure 6(b). It was seen that there was high amount of NIR transmission across the tooth sample so that a sharp image for the purpose of defect detection could be formed. Thus, NIR could be researched as a possible safer replacement for X-rays for dental scanning purposes.

5. Scanning of packaged materials
With the growing threat of terrorism around the world, the security of personnel and goods has become a major concern. In transportation hubs such as airports and other such sites, baggage screening is performed as a matter of routine. NIR within the 700 nm to 900 nm wavelength range could act as a complementary technique to X-ray and metal detection baggage screening used at such locations.

Figures 7 to 9 illustrate examples of NIR screening of packages of different materials for security purposes. Figure 7(a) shows
an example of a cardboard box, which, as shown in Figure 7(b), contained a metal paper clip, a metal battery, a plastic pen cap and a wooden stick with a cotton bud. Objects of different materials were placed within the cardboard box to demonstrate the capability of NIR to detect a range of materials. It can be seen in the NIR image that resulted from scanning the closed box, Figure 7(c), that all the objects inside the box have been clearly imaged, with some of the lettering imprinted in black on the top and bottom of the cardboard box also being detected. Black lettering was detected due to the high level of NIR absorption by the ink used on the outer surface of the box.

Figure 8. (a) Photograph of a diskette box, both closed and showing the contents as a metal key and a piece of Blu-Tac material. (b) NIR image taken in transmission through the closed box, showing the two objects

Another example of package screening is shown in Figure 8. Here a metal key and Blu-Tac™ material were placed within a plastic box. Figure 8(b) shows a through-transmission NIR image of the box where both the key and the Blu-Tac™ material has clearly been detected.

Figure 9 shows another example of package screening where beetles kept inside a closed highly absorbing Styrofoam box have been clearly detected. The range of packaging materials used here demonstrates the versatility of the current technique to image objects within a range of containers.

Since NIR signals in the wavelength range used can be transmitted through many polymer materials, they can be used to inspect objects for metallic inclusions which are not visible from the outer surfaces of the object. For example, NIR signals tend to be completely attenuated by magnetic and metallic materials. As...
an example, a scan was performed to try and detect the electronic ‘chip’ and wire hidden within the structure of a typical ID card (and which are also commonly found in credit cards etc). One side of such a card is shown in Figure 10(a), and this was scanned using NIR signals at $\lambda = 850$ nm, with the result being shown in Figure 10(b). The electronic chip and wire concealed inside the thin ID card was easily picked up in through-transmission NIR imaging. Also of interest is that the magnetic strip and bar code were detected, as well as the printing on both sides of the card, the black ink being opaque to the NIR.

6. Conclusions
It has been demonstrated that modulated NIR signals, together with lock-in detection, can be used to image a wide range of materials. There are clear benefits in the case of food materials, where transmission through certain foodstuffs (such as bread dough) is possible where ultrasound cannot be used effectively. It also has the advantage that it is often not unduly disturbed by air layers, so that it can be used for many types of packaging. This would not be possible for air-coupled ultrasound, where the presence of an air layer would lead to significant loss of signal. The work did, however, give an example of where NIR and ultrasound could be used in a parallel way for improving the image obtainable, using a nut in chocolate as an example.

The NIR technique has been demonstrated in many different types of sample and object, with applications ranging from dentistry and medical imaging to use for security screening. It is hoped that the work presented here, which is a first look at the technology, will lead to much interest in this technique in the future.

7. References