

A Study of Time-of-Flight Diffraction Technique Using Photoelastic Visualisation

Edward Ginzel¹, Farhang Honarvar², and Amin Yaghootian³

1- Materials Research Institute, Waterloo, Ontario, Canada

2- NDE Lab., Faculty of Mechanical Engineering, K. N. Toosi University of Technology, Tehran, Iran

Email eginzel@mri.on.ca

Abstract

Time-of-Flight Diffraction (ToFD) technique has been part of nondestructive testing (NDT) for over 30 years and provides a useful role in flaw detection and flaw sizing. This paper reviews the principles of ToFD and presents a photoelastic technique for visualization of the waves generated during a ToFD measurement. A sample made of optically fused glass with an embedded target is used in the experiments. The results show the waves which are diffracted from the upper and lower tip of the target as well as the lateral and backwall waves. These results also provide a better understanding of the diffraction phenomenon that takes place during a ToFD measurement.

Keywords: Nondestructive Testing, Flaw Detection, Time-of-Flight Diffraction (ToFD), Photoelastic Visualization,

Background

Maurice G. Silk and his colleagues at the National NDT Centre, in Harwell, UK are credited with developing the ToFD technique in the early 1970's. The impetus for their work was the need to know with some accuracy, the vertical extent of flaws detected in the pressure retaining components. Fracture mechanics engineers have long known that the flaw dimensions as well as the metal structural properties and service conditions need to be quantified in order to determine if a component can operate without failing (fracturing). This put a new demand on NDT in that "accurate" flaw sizing was required as an integral part of the equation for determining whether or not a component could be left in service, or required removal or repair. Over the years there have been many international exercises carried out comparing ToFD to the traditional inspection methods such as radiography and pulse echo techniques. Without exception each of the trials confirmed the ability of ToFD to provide results for planar defects with a greater accuracy.

Bill Brown [1] presented a paper on the internet (www.ndt.net) in September of 1997 where he laid out some of the basics involved but also made a loud statement on the "mystique" that had built up around ToFD by that time. He stated about the misunderstandings of ToFD;

"Some of this lack of understanding emanates from the mystique built up by those responsible for its introduction. For many years scientists promoted the technique as a highly specialised 'sizing' tool - so complex that it required their specialist knowledge and sophisticated technology to effectively apply - and unsubstantiated claims were made about what the technique could and could not achieve."

There should be no "mystic" in science. Photoelastic visualisation of ultrasound was first introduced to NDT

1- Researcher

2- Associate Professor

3- PhD Candidate

applications by Hanstead and Wyatt [2-4] and reached a limited popularity in the 1970s. Today it has been modernised with video capture and intensity analysis capabilities to again provide a useful tool for understanding the complexities of wave mechanics. It is used here to examine the details of the ToFD process.

ToFD Principles

ToFD as an inspection technique is considered a “pitch-catch” setup whereby transmitting and receiving probes are used opposite to one another and on the same side of the test surface. The basic ToFD setup is illustrated in Figure 1. When an ultrasonic wave is incident on a crack-like defect, besides specular reflection of the wave from the crack, part of the wave is also diffracted at crack tips. The diffracted energy spreads over a wide angle and can be picked up from almost anywhere along the surface of the specimen.

ToFD is a very powerful ultrasonic technique which could be used for both detection and sizing of defects. Accurate sizing is accomplished by determining the location of the tips of the flaw by measurement of time of arrival of echoes bouncing off the flaw tips. Lateral wave, which travels near the top surface, and backwall reflection signals are used to define the region of interest and the two diffracted signals from the two edges of an embedded crack are expected to appear in between. By knowing the transit time between the longitudinal-diffracted echoes from the top and bottom of the crack, the defect depth and defect size may be obtained as below [5].

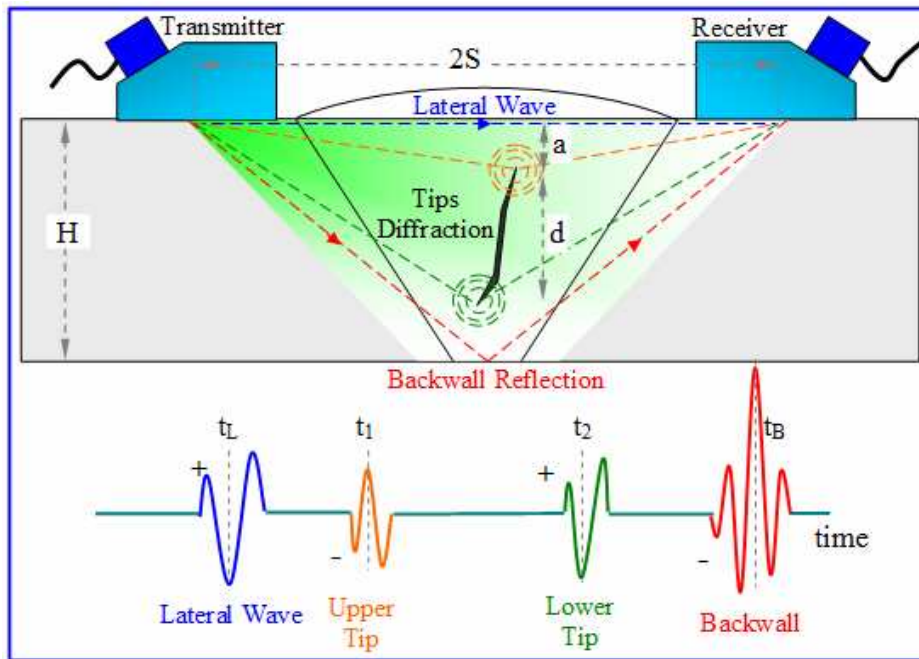


Figure 1: The basic ToFD configuration

$$a = \frac{\sqrt{c_L^2 t_1^2 - S^2}}{2} \quad (1)$$

$$d = \frac{1}{2} \left(\sqrt{c_L^2 t_2^2 - S^2} \right) - a \quad (2)$$

where a is the defect depth, d is the defect size, c_L is the longitudinal wave velocity inside the material, $2S$ is the distance between the probes indices, t_1 and t_2 are , respectively, the travel times of waves diffracted from the top and bottom of the crack (Figure 1).

The normal ToFD display incorporates an axis of motion and A-scans are captured and presented as greyscale images as in Figure 2. This greyscale image is called either a B-scan or D-scan, depending on the direction of scanning. Original ultrasonic terminology used B-scan to indicate a cross-section view and was

independent of scan direction. Some ToFD users like to use B-scan to indicate the results when the scan motion is parallel to the beam direction and D-scan for presentations where the scan motion is perpendicular to the beam direction.

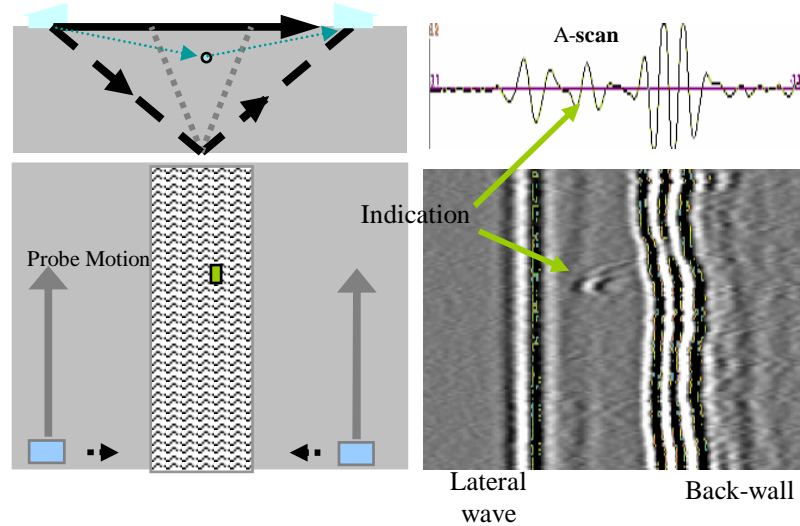


Figure 2: The ToFD B-scan presentation.

When an incident longitudinal wave front meets the defect, the wave is diffracted as both longitudinal wave (L-wave) and shear wave (S-wave). Since the shear wave velocity is lower (almost half of longitudinal wave velocity), the longitudinal-diffracted wave reaches the receiver first [6]. Therefore, in the greyscale image, the lateral and backwall echoes serve as borders and echoes originating from defects lie between these two lines.

Visualisation Principles

Photoelastic visualisation involves synchronising a high intensity pulsed light with the ultrasonic pulses of a piezo-element. The images are obtained by cross-polarising the light and then observing the increased intensity of light due to the effect of pressure changes rotating the light out of the null condition. The basics are illustrated in Figure 3.

Although ToFD is a two-probe technique, the process of visualisation images only the transmitted pulse. Since the receiving process produces no pulse of its own, the photoelastic images need only the transmitter mounted on the specimen.

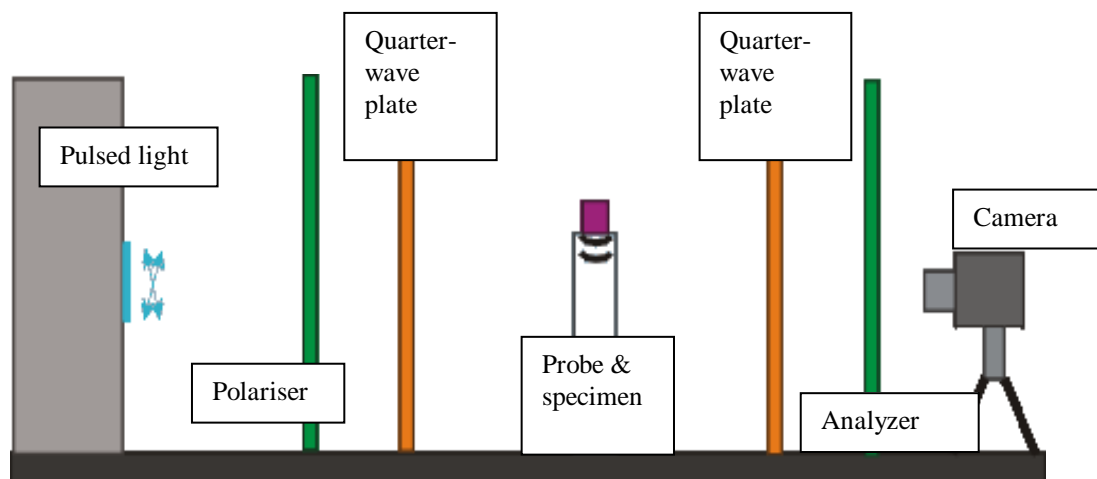


Figure 3: Photoelastic visualisation basics

Equipment Used

Photoelastic System

Figure 4 illustrates the probe setup (right) for the ToFD imaging using the portable photo-elastic system (left).

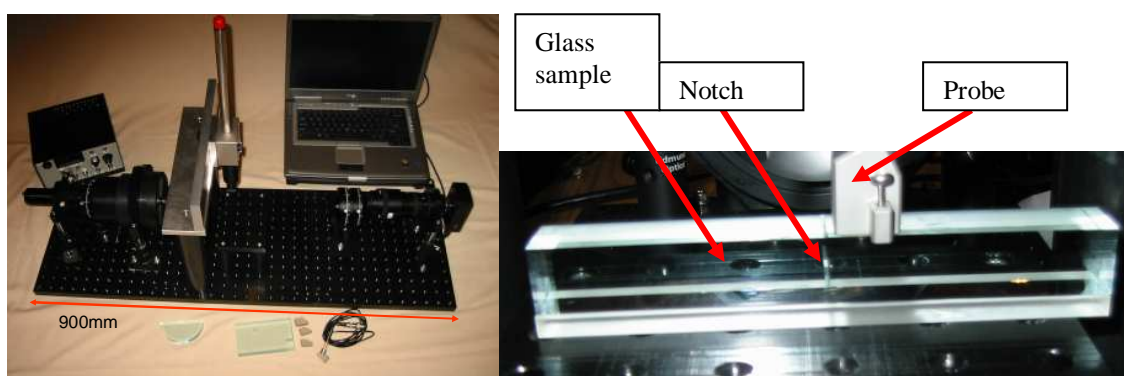


Figure 4: Portable Photo-elastic system

The portable system used produces a delayed light triggering which can be synchronised to an internal clock or via the TTL out to or from an external supply (such as an ultrasonic phased-array instrument). A tuneable pulser is provided for single element demonstrations and provides up to 300Vpp to the probe.

Target Materials

In the 1970s fused silica glass was the preferred material used for most experiments. More recently it was found that Soda-lime glass has acoustic velocities somewhat closer to the metals encountered in NDT. Acoustic velocities of these materials are tabulated below:

Table 1: Acoustic velocities of materials

Material	Compression Velocity	Transverse Velocity (Sv shear)
Fused Silica glass	5970 m/s	3770 m/s
Soda Lime glass	5800 m/s	3450 m/s

Holes and notches are relatively easy to fabricate in the glass, however, exotic imaging of diffraction effects has been accomplished for “embedded” targets. It is possible to fabricate small notches in the glass using a

technique called optical fusion which provides a near perfect transmission of sound at the fused surface. The block is cut and polished with a notch on one side then optically fused so only the target presents the reflecting and diffracting geometry. An example of the square notch in the glass is illustrated in Figure 5. This is a photo of the photoelastic effect with a pulse having passed the notch. Note that although the pulse reflects at the notch, there is no reflection at the vertical seam where the optical bond is made.

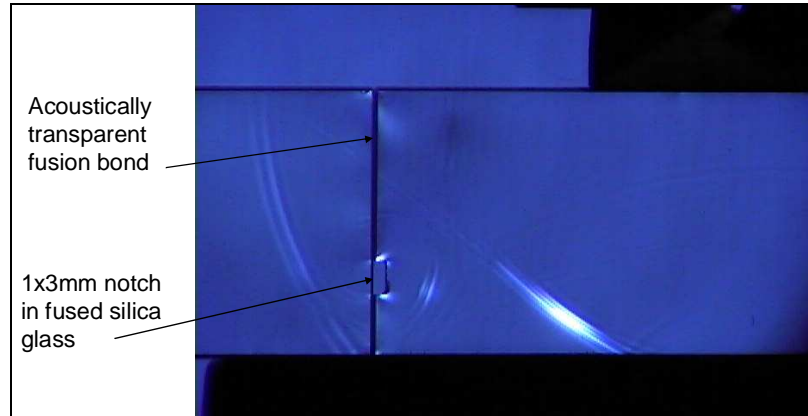
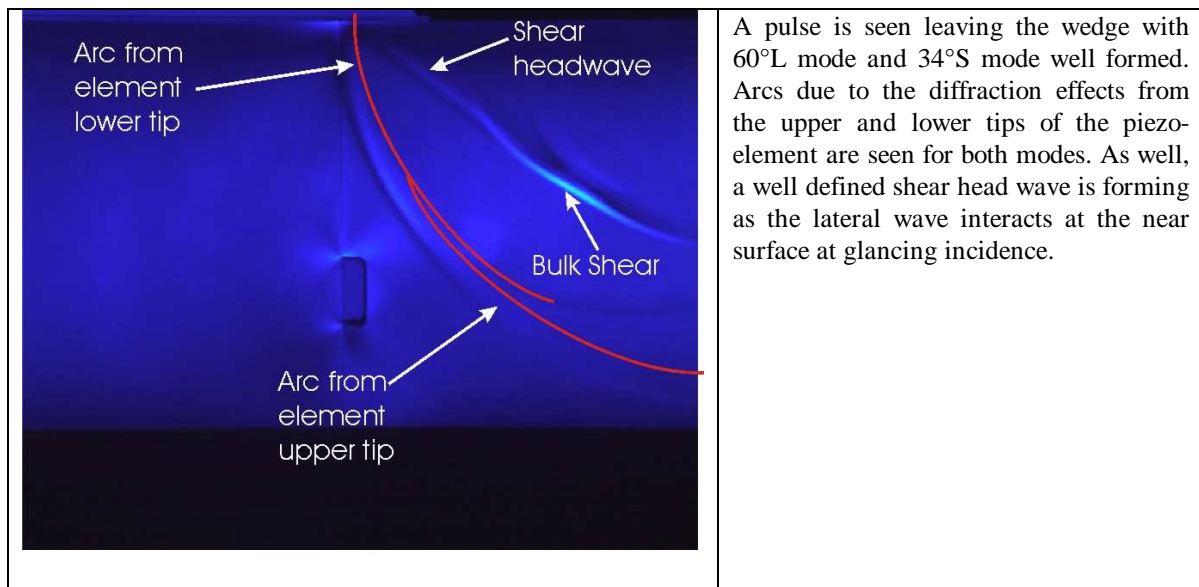


Figure 5: Optically Fused glass with embedded target

ToFD Visualisation Images

The following is a sequence of images showing the ToFD diffraction process in several stages of progression. Note that in the first frame 2 red arcs have been used to highlight the element edge diffractions that form the compression mode pulse and frames 3, 4 and 5 have faint black circles added to aid in locating the tip diffraction patterns off the notch. Frames 1 through 7 are considered in Figure 6.



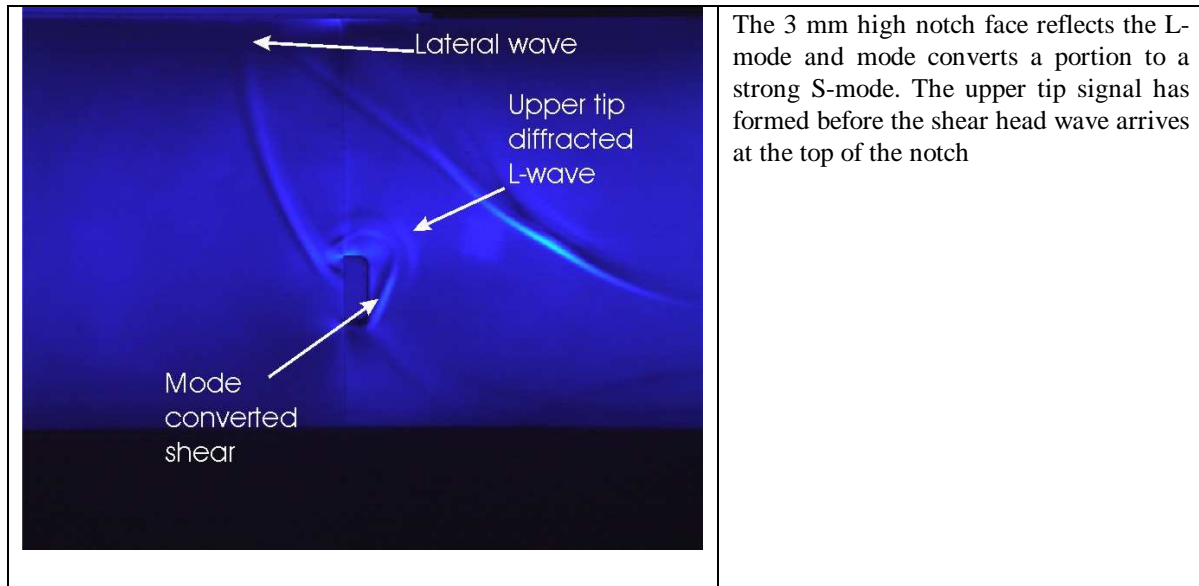
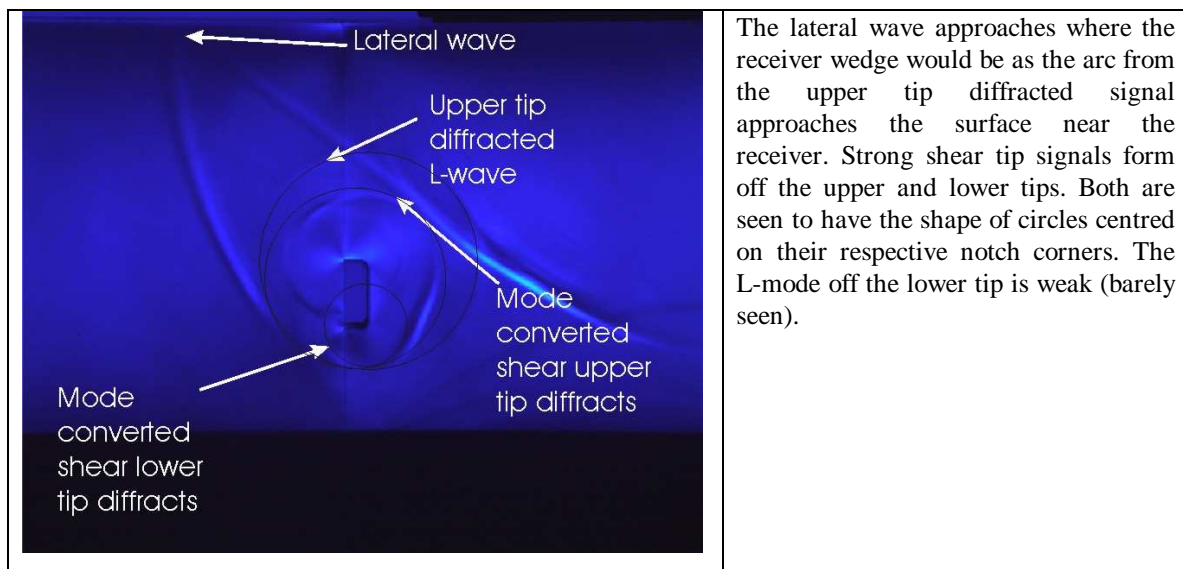


Figure 6: Frame sequences of the ToFD process



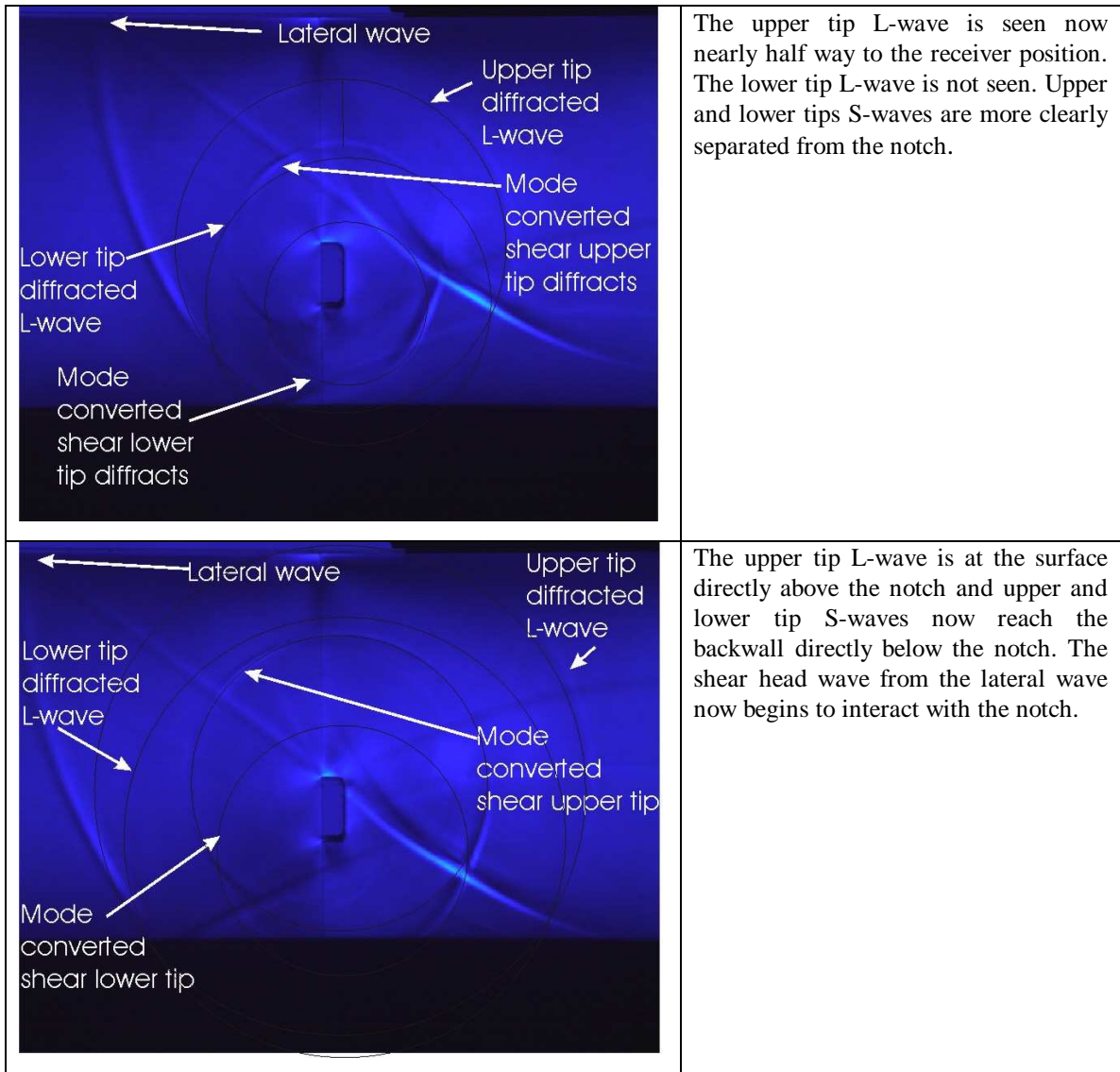
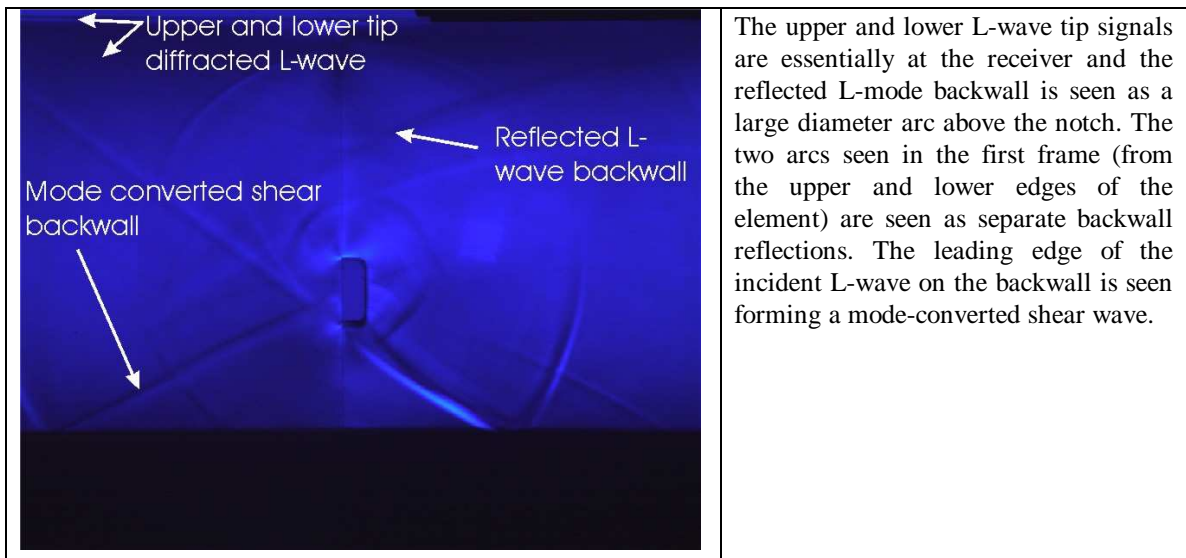


Figure 6: Frame sequences of the ToFD process (continued)



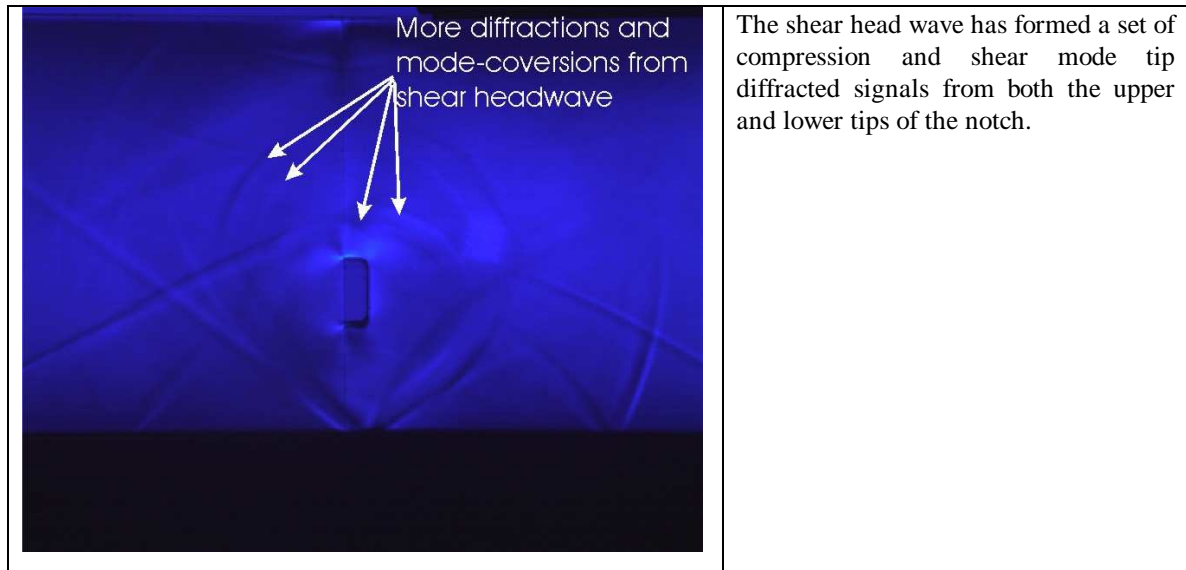


Figure 6: Frame sequences of the ToFD process (continued)

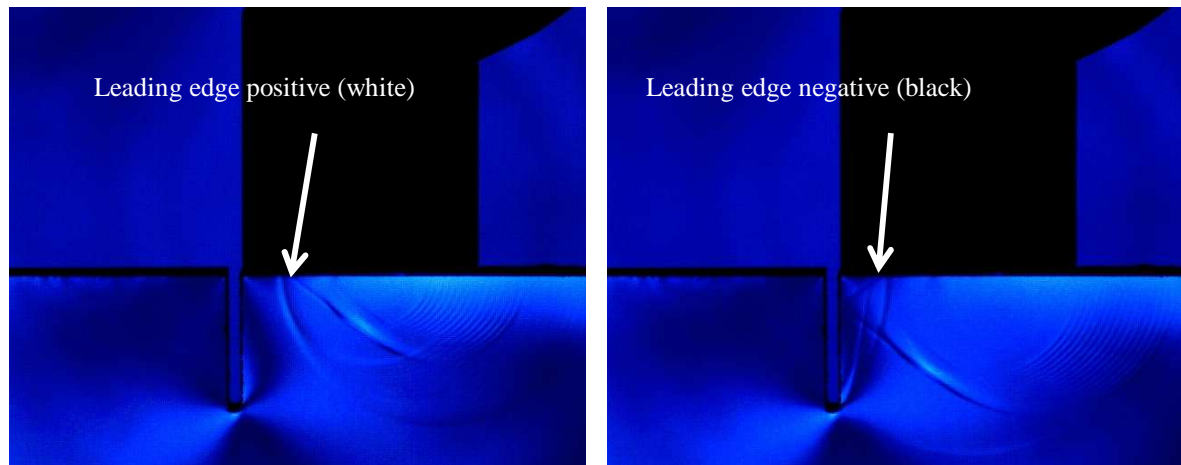


Figure 7: Phase reversal seen by visualisation

Phase information is available by observing the intensity of the pulse image. The blue background provides a nominal zero level with positive pressure indicated by whiter levels of intensity and negative pressure seen as darker levels. The predicted phased change of the incident compression mode off a lower acoustic impedance is seen in Figure 7. Intensity variation to a general darker background at the slot tip and region to the upper left of the slot region is a result of residual stress in the sample.

It has been demonstrated [7] that the photoelastic image intensity is directly proportional to the sound pressure in the sample. This provides an opportunity to obtain an indication of the directivity of the pressure distribution for reflection and diffraction. Figure 8 is a cropped image of the notch area where the incident L-wave pulse has formed the reflected mode-converted shear (similar to frame 2 of Figure 6 above). The null region of diffracted transverse pressure to the upper right and strong forward scattered transverse to the lower left are in accord with the directivity patterns predicted by modelling. Figure 8 uses the original image (left) to generate a spectrum paletted intensity image (right). Residual stress at the top of the notch results in a bright patch. The incoming shear headwave can be seen in the upper right corner.

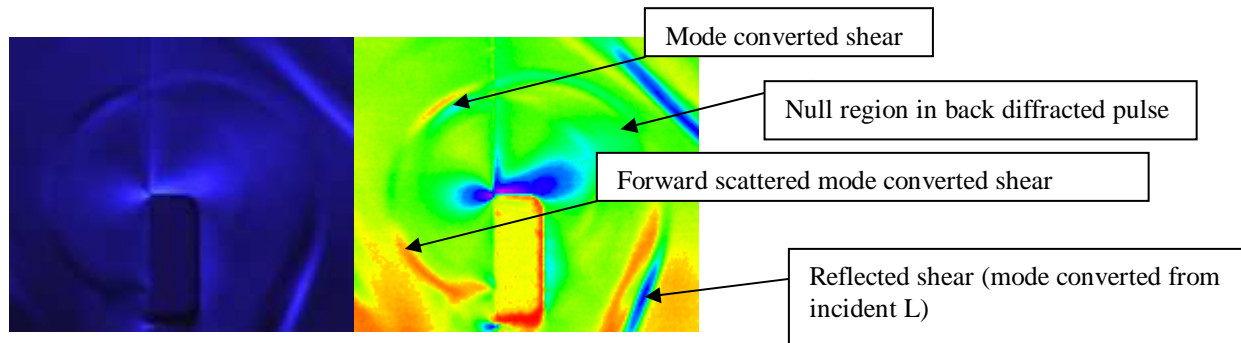


Figure 8: Directivity patterns of diffraction

Conclusion

Features of diffraction, directivity and phase change in ToFD measurements have been demonstrated using photoelastic visualization. Although similar features can be demonstrated using finite element modelling, the process is slow compared to the ease with which the setup can be made using a photoelastic visualisation system.

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