Non-Destructive Measurement and Evaluation of Surface Cracks Using Ultrasonic Rayleigh Waves – A Review

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Abstract: Quality control and inspection methods have become a critical challenge in everyday situations of the engineering profession. This is due to the evolution of the materials used today in industry and also increasingly complex and critical nature of many of the products and structures produced with them. Ultrasonic measurement is widely used especially in oil and gas and aerospace industries. This method is used because it is effective and not involving damaging the original parts. In ultrasonic measurement there are few types of waves emitted and where one of it is Rayleigh wave or mostly known as surface wave. Surface waves are generated when longitudinal waves intersects a surface near to the second critical angle. This review paper will describe about the types of waves emitted and produce and also some of the research that has been done related to the surface wave. This research can contribute to green environment because it reduces waste by suggesting the uses of Perspex.

1. Introduction
With the evolution of materials, increasingly complex and critical and critical nature of products, quality control and inspection methods become critically challenging [1]. Many methods were used by the industries to maintain the quality of their products and at the same time taking care the safety of their workers. One of the methods that commonly used is Non-Destructive Test (NDT). This method is commonly used by the industries because it is more efficient, and it could reducing testing time compared to destructive testing like compression and tensile test.

NDT is one of the techniques that uses many types of sophisticated and advance engineering tools to complete the work. It is a technique of testing used by the industry to evaluate the material, component, structure or system properties for characteristic differences or defects or discontinuities in welding without causing damage to the original part [2]. Many inspections usually in oil and gas sector uses NDT. There are few testing methods for NDT and one of the techniques that commonly used is Ultrasonic Testing (UT). UT is one of the most commonly used methods for NDT in different.
applications whereas, ultrasonic signal characteristics, such as ultrasonic wave reflection and dispersion, are used for evaluation of material properties and flaw detection [3]. UT consist of ultrasonic transducer, pulser/receiver and a display unit shown in Figure 1. Ultrasound has considered to be a suitable technique for characterizing surface crack, in particular through the use of Rayleigh wave and acoustic emission [4].

![Figure 1. (a) Ultrasonic Flaw Detector (receiver and display unit); (b) UT probes (transducer) [5]](image)

Ultrasonic transducer or probe emit a wave that is called ultrasonic wave. This ultrasonic wave consists of two types of waves that is acoustic waves and elastic waves. This research focusing more on elastic surface wave or Rayleigh wave. There are various types of surface waves transmitted from across the surface of the solid and one of it is Rayleigh wave. A Rayleigh wave rolls along the ground just like a wave rolls across a lake or an ocean, because it rolls, it moves the ground up and down, and side-to-side in the same direction that the wave is moving [6]. The nature of the wave is non-dispersive; that is, the velocity is frequency independent as long as it travels on flat surfaces [1].

Rayleigh surface wave is suitable for the detection of abnormalities usually surface cracks on parts or materials. Ultrasonic probe has to be attached to the wedge before running the process. Wedges allow to detect internal flaws in test materials by utilizing a specific angle and transducer designed for specific applications [7]. Conventional wedges have already been designed into specific angle depends on the specific task.

2. Ultrasonic Testing

2.1 Types of wave
2.1.1 Longitudinal Waves
Longitudinal waves are frequently used in ultrasonic testing because of the characteristics of the wave itself. Longitudinal wave is also one of the elastic waves. The oscillation of longitudinal wave occurs in longitudinal direction or the direction of wave propagation. Longitudinal waves develop compression and rarefaction while travelling in the medium. The pressure is high when the particles are together and the region is known as compression, in the situation where the pressure is low and when the particle are separated, and the region is known as rarefaction [8]. The concept of this wave movement can be shown with a coil of spring as shown in Figure 2.
Figure 2. A longitudinal wave and its transverse representation [9].

The distance between the centres of two consecutive regions of compression or rarefaction is defined by the wavelength, $\lambda$. It is known as constructive interference when the compression and rarefaction regions of two waves overlap with each other and destructive interference when the compression and rarefaction region does not coincide[8]. There are three types of longitudinal waves that is sound wave, ultrasound wave and seismic p-wave.

Sound wave is an example of longitudinal wave. Sound wave is generated by the vibrating motion of particles through a conductive medium. In sound wave, the wave amplitude is the difference between the wave-induced maximum pressure and the undisturbed air pressure[8]. The propagation of the speed of sound will depends on the type, the medium composition, and the temperature of the medium which the sound wave propagates.

2.1.2 Transverse/Shear Waves

Motion in which all points on a wave oscillate along paths at right angles to the direction of the wave’s surface. Transverse wave can be represented by a sine or cosine curve because of the amplitude of any point on the curve as shown in Figure 3. Transverse wave can be complex which the curves are composed of two or more sine or cosine curves.

Figure 3. Transverse wave [10].

Shear is the shape change of a substance layer, without the change in volume produce by a pair of equal forces acting on the opposite direction along the two faces of layer. Shear wave occurs in an elastic medium when it is subjected to a periodic of shear. Shear wave are transverse wave meaning that the particle oscillation is perpendicular to the direction of wave propagation, and the main force comes from shear stress. Shear wave propagates effectively on a solid material and are not effectively propagate in liquids or gasses. Shear wave are considerately weak wave therefore it still needs some of the energy from longitudinal waves.

2.1.3 Surface Waves

Surface waves can be divided into two, that is Love wave or L-wave and Rayleigh wave or R-wave. L-wave move only along the surface of the earth and travel slower than the S wave [11]. The movement of the wave is similar as the S wave that is there is no vertical displacement; in a horizontal plane, it
moves the ground from side to side but at right angles to the direction of propagation. L wave is harmful since the wave’s path travels horizontally. An illustration of L wave is shown in Figure 4.

![Diagram illustrating the forms of ground motion near the ground surface for L waves](image)

**Figure 4.** Diagram illustrating the forms of ground motion near the ground surface for L waves [11].

The other type of surface wave is Rayleigh wave or R wave. Rayleigh waves travel at the surface of solid material penetrating the depth of one wavelength [12]. This surface wave is the combination of longitudinal and transverse motion which results in an elliptical motion as shown in figure 5. Rayleigh waves is useful because of its sensitivity to surface defects and also the waves follow the surface around the curves. Because of the characteristic of the waves, Rayleigh waves can be used to inspect areas that other waves have difficulty on reaching.

![Diagram illustrating the forms of ground motion near the ground surface for Rayleigh waves](image)

**Figure 5.** Diagram illustrating the forms of ground motion near the ground surface for Rayleigh waves [11].

### 2.2 Ultrasonic Inspection Method

Inspection by using ultrasonic method come in two ways that is straight beam test and angle beam inspection. Both of this method have their own characteristics and purposes.

#### 2.2.1 Straight Beam Test

Like all other techniques, straight beam testing utilizes the fundamental principle of sound energy travelling through a medium. The sound energy will continue to propagate until it disperses or reflects off a boundary with another material. A brief ultrasound pulse is emitted from a transducer into the test material; the signal travels through the thickness of the test piece and echoes from either the back wall of the piece or a discontinuity within the piece. Only a few microseconds after being emitted, the transducer captures the echoing signal. This process is call pulse-echo [13]. Straight-beam testing is commonly used to test the roll stock that will be used for the construction of the pipe body in pipe manufacturing. This technique is also effective in detecting cracks that occur parallel to the surface of the material being tested and discontinuities within the material body, such as voids or porosity areas,
and inclusions within the material [13]. Figure 6 shows that how the wave will be reflected when there is no present of flaw and when there is a present of flaw.

![Image](image_url)

**Figure 6.** (a) No flaw present, (b) Flaw present [14].

### 2.2.2 Angle Beam Test

Although straight beam techniques can be highly effective in identifying laminar flaws, they are not effective in testing many common welds, where discontinuities are usually not parallel to the parts surface. The combination of weld geometry, defect orientation and the presence of a weld crown or bead requires inspection using a beam generated at an angle from the side of the weld. In ultrasonic flaw detection, angle beam testing is by far the most commonly used technique [15].

Angle beam test consist of an ultrasonic probe and a wedge with a specific angle. The ultrasonic probe has to be attached to the wedge for the angle beam test to work. Wedges is an important part for this technique because of the specific angle that the ultrasonic transducer attach to can produce a specific wave. There are many types of wedges that are widely used in the industries. The commonly used angle of beam probes are 45\(^\circ\), 60\(^\circ\) and 70\(^\circ\). This technique use the principle of refraction and mode conversion at boundary to produce refracted longitudinal wave and shear wave in the test piece. The desired refracted angle is calculated by using Snell’s law equation.

\[
\frac{n_1 \sin \theta_1}{\tan \theta_2} = \frac{n_2 \sin \theta_2}{\tan \theta_1}
\]

Where; \(n_1\) is incident index, \(n_2\) is refracted index, \(\theta_1\) is incident angle and \(\theta_2\) is refracted angle. By using this formula, critical angle of the wave can be calculated. Critical angle is an angle of incidence between two different materials at an interface beyond which the new mode appears in the refracted beam and the existing one disappears [16].

There are two critical angles produce that is, first critical angle and second critical angle. First critical angle is the minimum angle of incidence of longitudinal waves at which the longitudinal wave does not enter the second medium. Second critical angle is the minimum angle of incidence of the longitudinal waves at which the shear wave does not penetrate the second medium.

### 3. Type of Flaw

#### 3.1 Types Defects

There are no perfect manufacturing process. Many manufacturing process will leave defects and failures. In welding techniques, there are also defects that will occur during the process. There are few types of defects that usually happen in the process. This defects can occur on the surface or on the subsurface of the materials.

##### 3.2.1 Porosity [17]

Porosity occurs from the gas bubbles trapped in the metal filler during the solidification process. Porosity can often be avoided if the work pieces are completely clean before any welding process and the welding current are kept below excessive level.
3.2.2 **Cracks** [17]
Crack may develop during the weld metal solidifies and shrink. The weld will become weaker because the weld metal is no longer continuous shown in figure 13.

3.2.3 **Lack of Fusion (LOF)** [17]
The defects occurs when the welding bead fails to adhere, fuse with the base metal, leaving a weak joint shown in figure 14. This can happen because of contaminated surface.

3.2.4 **Irregular shapes** [17]
Each type of irregular shape has their own cause, but they are all result in stress sensitive joints that are subject to failure earlier.

4. Related Research
Lewis and Dally [18] studied reflection and transmission coefficients of Rayleigh wave interactions with wedges. They show that these coefficients vary very rapidly with changes in the wedge angle. This study is important in understanding the effect that an inclined slot or crack may have on a Rayleigh wave. Reinhardt and Dally [19] did some of the first photoelastic studies of Rayleigh wave interaction with surface flaws, in this case machined slots. Although the system used did not have a very good resolution, it was possible to observe the transmitted and reflected signals that were later used by other researchers.

Henzi and Dally [20] performed studies of Rayleigh wave interactions with a quarter plane. Although their objective was to determine the intensity of the various waves generated upon such an interaction, their knowledge, in addition to the studies performed by Burger, et al. [21], have aided in the basic understanding of the interaction of a Rayleigh wave and the side of a slot. An interesting piece of work is that performed by Dally and Lewis [22] on Rayleigh wave interactions with steps. This work allows one to observe the various waves generated when steps are increased incrementally until they are deeper than the penetration of the Rayleigh wave. At that time, it was observed that there was a Rayleigh wave that leads the one that runs along the surface when the step change in elevation is shallower than the penetration of the incident Rayleigh wave. Not only this, the leading wave was described as being broader than the one that follows the surface.

Silk [23], proposed several methods aimed at finding depth rather than length for a real crack. The most interesting of these first measures the times of light between two transducers for the surface wave propagating around the crack, and for the mode converted S-wave originating at the tip. Next, the roles of transmitting and receiving probes are reversed, and the measurements repeated. With these four readings, the time delay involving surface waves can be eliminated altogether, leaving the algebraic equivalent of the bulk S-wave timing method of Lloyd [24]. Silk used this method to find the depth rather than $L$ for conveniently deep (22—30 mm) fatigue cracks to ±0.5 mm.

5. Conclusion
Base on the previous research, it shows that the uses and benefits of surface wave to identify the flaws on materials. Many of the research uses the conventional type of wedges that is out there in the market. For this research, a new design of wedges will be fabricated by using the material call Perspex. Perspex is the better choice because, for most applications of angle beam probes the generated shear wave in steel should be around 3250 m/s. The velocity of longitudinal waves produce by the wedges should be lower than the shear waves. Only plastics and fluids that fulfil this requirement. Therefore, Perspex is the suitable material for the fabrication of the new wedges. The new wedges also will be design with specific angle so that the surface wave can be produce that comply with the second critical angle by referring to the objectives of this research. A few measurement, analysis and calculation have to be done to achieve this specific angle. By using the surface wave produce by the new wedges a set of data will be collected and analyse such as the length of the crack, the depth of the crack and the high of crack.
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Acknowledgments
The authors would like to thank Universiti Tun Hussein Onn Malaysia (UTHM) for its financial support and also to family and friends that always give moral support and motivations.