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Ultrasonic Testing for Mechanical Engineering Domain: Present and Future Perspective

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A B S T R A C T

Ultrasonic testing uses high frequency sound waves of a range between 0.5 to 15 MHz to conduct testing. The basic principle and applications of ultrasonic testing techniques are enormous use under the domain of mechanical engineering applications. Importance of ultrasonic testing of rails, train wheels, carbon fiber reinforced plastic, aeronautical defects in composite structures, testing of welds, and some other applications are increasing day by day. Literature survey reveals that it is a challenging task for practitioners and researchers to increase the efficiency of non-destructive testing techniques for identifying and localization defects in different mechanical engineering components/parts. Basic fundamentals applications of ultrasonic testing of metal, non-metal, ceramics, polymers, concrete, etc. are briefly explained. Present and future perspective of ultrasonic testing for mechanical engineering domain are discussed along with the sub new development in the area of ultrasonic testing.

Keywords: Ultrasonic test, Non-Destructive Testing (NDT), Carbon Fiber Reinforced Plastic (CFRP), Glass Fiber Reinforced Plastic (GFRP), Composites.

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1. Introduction

Ultrasonic testing uses high frequency waves above the human hearing range for the purpose of inspection. High Frequency Waves (HFWs) are passed through the material under an inspection. These HFWs travel at different speeds in different materials; but the speed of waves will remain constant throughout a given material. In this way, when these waves are passed through a given material, we can interpret its geometric properties and inspect the material for flaws and other defects. A probe sends a high frequency sound wave into the material being tested. There are two output signals, one from the initial sound wave of the probe and the second due to the back-wall

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echo (see Figure 1). A defect causes a third indication and thus reduces the amplitude of the back-wall echo.

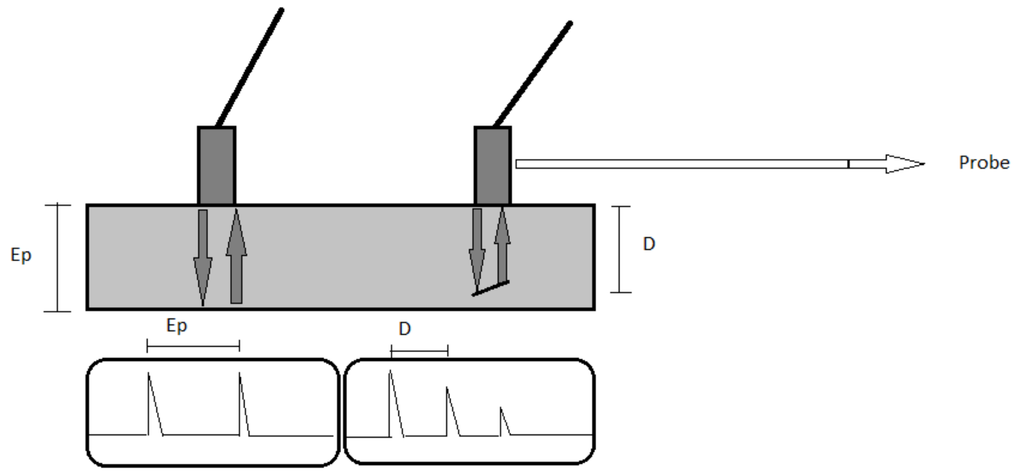

Figure 1. Basic principle of ultrasonic testing.

Conventional materials such as composites, rails, welds, etc. can be easily inspected by pulse eco ultrasonic non-destructive [27]. In pulse echo system, the high frequency sound waves (ultrasonic wave) is passed through the material and the wave gets reflected from the opposite surface and is received by the crystal transducer [27]. The defect is picked up by amplitude of echo and its position. The wave can suffer multiple reflections but the one caused by defect can be easily picked up.

In manufacturing of electrical appliances, automobiles, and several other structures, the bodies are mainly assembled by spot welding. These welds were conventionally inspected by destructive methods of inspection. So, the technique for inspection of welds was developed. These welds are inspected by the use of ultrasonic waves (lamb waves). These waves are passed through the weld and the nugget or point of spot weld causes the distortion or reduction in the signal strength [24]; therefore, quality of the weld can be judged by NDT.

Ultrasonic testing plays an important role in maintenance of aircrafts and other composite structures such as Carbon Fiber Reinforced Plastic (CFRP), Glass Fiber Reinforced Plastic (GFRP), etc. The main property of these structures is their strength to weight ratio that is maximum; but if the working is considered they suffer a lot of damage from high as well as low impacts. So, as to ensure their efficient working in such environments they should be maintained carefully and on a regular interval. Ultrasonic testing plays an efficient role in detection and localization of defects in such structures. Some other NDT techniques such as thermography, x-ray radiography, magnetic particle inspection, etc. can also be used for detecting fault in composite structure.

Ultrasonic testing has been quite efficient in identification of Barely Visible Impact Damages (BVIDs). BVIDs are caused by low velocity impacts such as hammer dropping on the work floor, lightning impact, and hailstones. These impact causes delamination or dis-bonding in the composite structure. Section 2 explains the literature survey based on ultrasonic testing. Section 3 deals with results and discussion of testing of rails, testing of train wheels, testing of CFRP, testing of plastic pipes, and testing of spot welds. Lastly, Section 4 concludes our observations and suggests the future scope of ultrasonic testing.

2. Literature Review

Prior to World War II, sonar technique was used for sending the sound waves through water and observing its returning echoes for characterizing the submerged object triggers the development of ultrasound investigators for exploring this idea in the medical diagnosis. In between 1929 and 1935, Solkov experimentally proven that ultrasonic waves can be used for detecting metal objects [25]. In 1935, Mulhauser obtained a patent for using ultrasonic waves and two transducers to detect flaws in solids [19]. During 1940 and 1945, the combined effort of Firestone and Simons came with pulsed ultrasonic testing techniques. From 1960s the onwards application of NDT became popular in the domain of manufacturing and automation like welding, casting, forging, machining, etc. More information about use of NDT during monitoring systems of welding can be found in [23, 24].

The authors of [21] presented a paper on inspection of rails by ultrasonic testing. In this paper, they investigated and discussed about the ultrasonic testing of rails. The type of waves, type of rails, types of the used gauges, and the used equipment techniques were discussed. The results and conclusions of this testing were discussed. This paper clearly showed the efficiency and importance of ultrasonic testing in identification and localization of defects in rails. The work [21] presented a paper on ultrasonic testing of rail wheels without disassembly. The train wheels undergo a lot of stress and high thermal stress; thus, they should be inspected very carefully and inspection should be carried out at regular intervals. But inspection requires complete dismounting of wheels which is time consuming. Differential-type integrated hall sensor matrixes were used, which were embedded in the rails. So, as the train enters the shed, the wheels are tested for defects by D-IHaSM. D-IHaSM works with a good speed and high spatial resolution. Inspection cannot be carried out at much higher train speed.

The authors of [3, 4] presented a paper on non-destructive testing of composites structures in aircrafts. The presented paper consists of a comparison of various NDT techniques. The inspected materials were GFRP, hybrid composite, sheets made of al alloy, and CFRP. The inspection was carried out by ultrasonic testing, PZT sensing, vibration based inspection, and thermography. UT provided a detailed defect evaluation whereas using thermography BVIDs were not detected. Kamsu-Foguem [8] presented a paper on the importance of NDT and structural health monitoring of aircrafts, and provided an approach of equivalent alternative. As maintenance is important at every level, so a person inspecting the composite may or may not be allowed to access the equipment. This study provides alternatives in case of the equipment is inaccessible. Garnier et al. [11, 15] presented a paper on detection of aeronautical defects using NDT. The materials under observation were carbon/epoxy composites, sandwiched honeycomb core, and Kevlar skins. The defects were BVIDs that caused delaminating or disbanding. The used NDT techniques were UT, infrared thermography, and speckle shearing interferometry. The results concluded the UT is more accurate and it detected the defects more easily as compared to thermography and sherography. In UT, the wide range of probes should be used.

Sun and Zhou [15] presented a paper on laser ultrasonic testing the induced delamination defect due to drilling. One of the major defects encountered by aircrafts is the delamination caused by drilling. Moreover, assembling as a final step drilling operation is carried at several spots and at times; defects are induced. Their paper discusses about the laser ultrasonic testing of such parts. Bates et al. [6] presented a paper on thermal non-destructive testing of aircraft components. Thermal NDT is 30 times faster than ultrasonic c-scanning. Results of this study were verified by ultrasonic testing. Takada and Hirose [16] presented a paper on ultrasonic testing of spot welds. They investigated and discussed about how the diameter of welded spot (nugget) distorts or causes reduction of signal strength of the high frequency wave passed through it. They used the lamb waves (type of ultrasonic waves). The larger nugget diameter or distortion of signal is the quality of the spot weld. Tabatabaeipour et al. [26] presented a paper on UT of friction stir welds. Friction stir weld is a new technique in which the metal gets fused due to the heat generated by the friction. In the study, the specimen under observation was welding of al alloy. The defects were BVIDs (100-700 µm*)* and were not detected by UT. So, a new approach of oblique incident ultrasonic testing is used. A pulse echo with 3.5 MHz transducer was used to detect the defects.

Chassignole et al. [10] presented a paper on UT of austenitic steel welds. They are primarily used in coolant piping system of nuclear industry. These welds are rough grained, heterogeneous, and anisotropic. This causes beam skewing. The shear waves are more distorted than the longitudinal ones. Ultrasonic scattering should be taken into account for such cases. Carvalho et al. [9] presented a paper on reliability of NDT of pipe welds on oil industry. The encountered defects were LP (lack of penetration), LF (lack of fusion), and undercut. The results showed the dominance of automatic UT as compared to manual UT and radiography. For undercut defects the UT is not quite efficient. Zhu et al. [17] presented a paper on UT of plastic pipes of polyethylene (high density) and polyvinyl chloride. These pipes are used to distribute or provide water from distance. The ultrasonic frequency was 10 MHz in the experiment and the focal distance was 75 mm; cracks and voids were investigated by UT.

Iyer et al. [22] presented a paper on UT of concrete pipe. These were the underground buried pipes which carried water and pipes of sewage. Two approaches were made by testing equipment with both transducers on same side and transducers opposite to each other. The equipment with transducers opposite to each other was quite successful. Armitage and Wright [4] presented a paper on multifunctional approach for testing of CFRP composites. The encountered defects were micro-cracking, delamination, and disbanding. The optimum inspection was achieved in all circumstances under non-linear technique. They developed a new approach which is programmable and reconfigurable. It consists of all the non-linear UT regimes as well as pulse inversion technique. The authors of [2] presented a paper on NDT of thermoplastic reinforced composites. The test pieces under observation were glass fiber and polypropylene. The foreign objects were induced by compression molding. The NDT was carried out to observe fiber orientation and fiber defects like waviness. The NDT techniques were x-ray radiography and ultrasonic testing. They highlighted the advantages and limitations of UT and radiography.

The work [1] presented a paper on UT of impact damaged fabric composites. Materials under observation were CFRP and NCF (non-crimp fabric). Dynamic impact testing was done and the work piece was then inspected by UT; pulse echo technique of UT was applied; advanced NDE procedure was applied. The results concluded that UT NDE is a very efficient technique. The authors of [20] presented a paper on the study of steel structure subjected to the high temperatures (fire). The behavior was examined by UT. As the temp increases, the mechanical properties of the structure degrade, so is it feasible to reuse such steel under fire. The structure was heated to 1000 ^{0}C and then cooled. The cooled structure undergoes 0.67% of wave speed. After observation under microscope it was found the texture changed into martensite and bainite. The element's ductility and elasticity were reduced to a great extent. Side trimming shear machine can be equipped with UT then we can get more output from steel plant [5]. Cernadas et al. [13] presented a paper on NDT of plates on visualization of lamb waves. The technique combines ultrasonic with optics. The lamb waves are generated while TV holography is used to detect them. This technique provides instantaneous displacement produced by lamb waves. Thin walled mechanical parts are inspected and it provides a good visualization.

3. Results and Discussion

3.1 Testing of Rails

Ultrasonic testing plays an important role in the testing of railway tracks, which conventionally were tested by destructive testing techniques. A sample track under observation was destructively tested and the behavior of underlying categories was predicted. Nowadays, the non-destructive ultrasonic testing is playing an important role in maintenance and testing of tracks, which has reduced quite a large wastage which was caused due to destructive testing.

Various equipment used in non-destructive ultrasonic testing of rail tracks consists of

- Single rail tester.
- Double rail tester.
- Multi probe rail tester.

The equipment is briefly discussed below.

- Single rail tester: It is capable of testing only one rail at a time. In this equipment, 5 probes are provided. The provided probes are:
  - 70° and 70° backward.
  - 37° and 37° backward.
  - 0° normal probe.

70° probes are used to detect defects in rail heads. 37° probes are used for detecting defects originating from bolt holes. 0° probe is used for detecting defects situated in head or foot (horizontal defects).

- Double rail tester: It is capable of testing both rails at a time. In this equipment only three probes are provided. The provided probes are:
  - 70° and 70° backward.
  - 0° normal.

0° normal probe is used for detection of horizontal defects. 70° and 70° backward probes are used for detection transverse defects in head.

- Multi probe rail tester: In this tester only two probes are provided. The provided probes are:
  - Vertical probe.
  - Angle probe.

The probe material for detection of ultrasonic waves is barium titanate.

3.2 Testing of Train Wheel

Testing of train wheels uses Differential-Type Integrated Hall Sensor Matrixes (D-IHaSMs). The sensor is embedded in rail and provides high spatial resolution. The wheels do not need to be dismounted for inspection. The D-IHaSM sensor is mounted on the rails; as the train arrives, the train wheels are scanned by the sensor and the results are generated. However, the work still needs to be done on testing at higher speeds.

3.3 Testing of CFRP and Comparison of Various NDT Techniques

NDT of BVIDs was carried out carbon/epoxy composites and sandwiched composite specimen. BVIDs are barely visible impact defects caused by low velocity impacts. Identification and localization of such defects are difficult. The main three encountered defects were:

Specimen A: Delamination.

Specimen B: Lightning impact (41 mm and 75 mm defect).

Specimen C: Defected by falling tool or hailstones.

Table 1 shows the comparison of NDT techniques for detecting the defects. The specimen B was tested by UT, infrared thermography, and sherography. The defect was most efficiently detected by UT.

Table 1. Comparison of various NDT [11].

NDT	Length (mm)	Width (mm)
General visual inspection	41	75
Ultrasonic testing		
Frontface	43.5	79
Backface	38.5	63.5
Infrared thermography	36	60
Shearography	37.5	59.5

3.4 Testing of Plastic Pipe

In general, 35% to 65% waste of the supplied water volume is occurred due to the pipe breaks; therefore, a proactive technique is necessary. The tested plastic pipes are high density polyethylene and polyvinyl chloride. These pipes are used to provide water distribution system. The ultrasonic frequency used for testing is 10 MHz with a focal distance of 75 mm. The defects are cracks, grooves, and slots [19]. The defects artificially made grooves and slots, and the ultrasonic c-scans are obtained for the test specimen.

The Figure 2 clearly shows the type of defects that have been inspected. These defects have been examined using UT. The results have been obtained as ultrasonic c-scans. The ultrasonic sketch is shown in Figure 3(a) and the defects are clearly visible in the Figure 3(b).

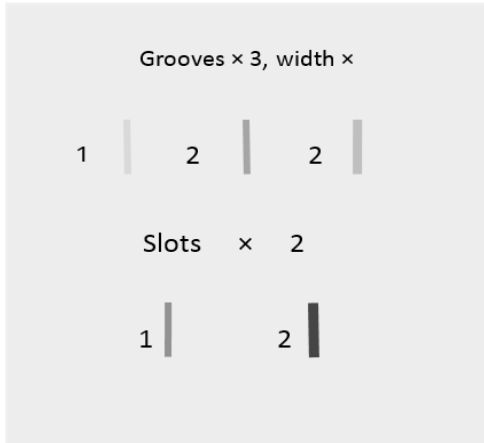

Figure 2. Size of grooves and slots machined [19].

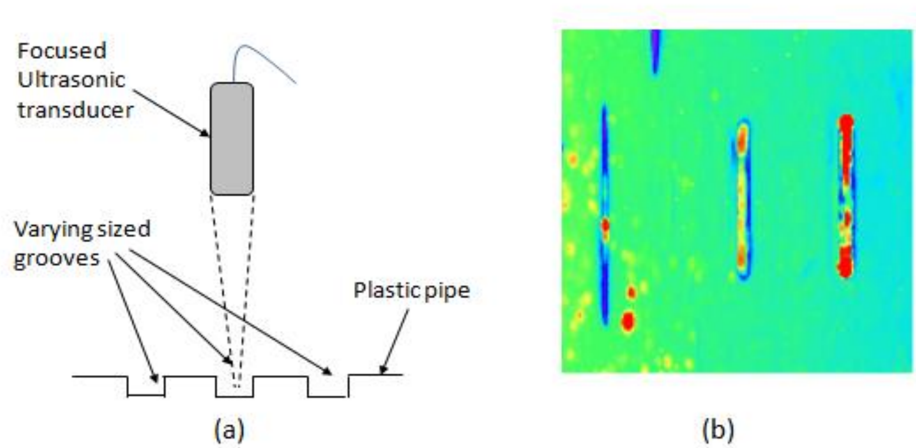

Figure 3(a). Ultrasonic testing sketch (b) detection result [19].

Ahmed et al. [1] demonstrated how to identify the amount of damage induced after impact for the woven jute/glass fabric-reinforced isothalic polyester composites by using ultrasonic testing. El Geurjouma et al. [14] demonstrated how to identify damage in glass fiber due to mechanical loading by using acoustic emission. Czigany [12] developed some correlation between acoustic pattern and fracture toughness for flax–polypropylene (PP) composites. Beilken and Hinken [7] identified the defect occurs in glass fiber and natural fiber composites by using a microwave-based NDT.

3.5 Testing of Spot Welds

The region of spot weld is called nugget and this region is responsible for the distortion or reduction in strength of a high frequency wave [18]. Lamb waves are a type of high frequency ultrasonic waves. The experiment was carried out by transmitting the lamb waves across the nugget cross-section by the transmitter, and the wave is received at the other end by the receiver.

Study on spot weld inspection by immersion method:

Hajime and Tomoyuki [16] decided to conduct a study on evaluation of spot weld (see Figure 4) by studying the weakening of wave strength. The alloy part (weld) has a dendritic structure and a lamb wave passing through such area results in weakening of the signal strength [16]. The quality of the weld is related to the attenuation or distortion of the ultrasonic wave passing through it.

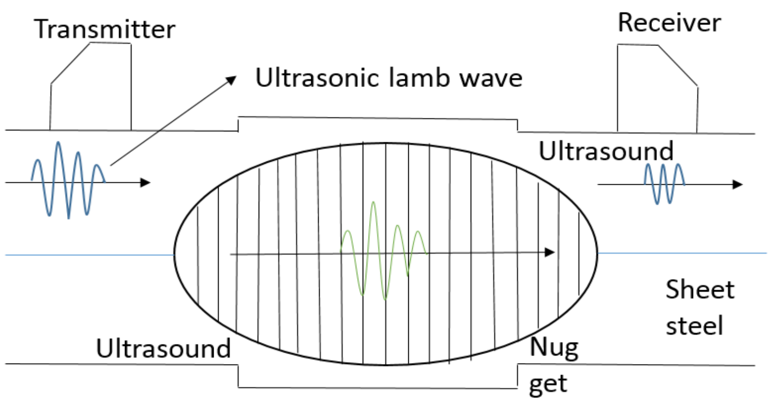

Figure 4. Ultrasonic testing of spot weld.

4. Conclusion and Future Research

UT being a non-destructive method results in a lot of reduction of losses caused by destructive method earlier. It is utilized in rail testing defects smaller than 0.8 mm in size; the quality of spot welds (nugget) can be inspected by ultrasonic testing. UT plays an important role for defect detecting in CFRP, GFRP, and BVIDs. UT helps in maintenance of aircraft. Now a day, UT is utilized during online monitoring systems of manufacturing systems. The future potential of non-destructive ultrasonic testing will be tremendous fruitful for manufacturing systems. An automated system of testing should be developed in case of testing of rails, complex geometry, severity of corrosion, fruits, and medical science. An effective and efficient methodology for fault detection using UT is a need of our society. Hopefully, in few decades UT will helpful in almost all areas like engineering, medical, geographical, service sectors, etc.

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