

Advanced Stress Analysis & FEA

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Abstract

This report is the evaluation of ultrasonic testing, liquid penetration inspection, and visual inspection. Each method will be explained based on the theory of technique, process, sources of error, advantages and disadvantages, applications and the use in stress analysis. It was found that no matter how sensitive and reliable the test maybe it is still susceptible to human error.

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Introduction

In this report, non-destructive and destructive testing will be explained, and three types of non-destructive testing will be critically evaluated, the method explained, with an industrial example of application, the reason for such selection and how it can aid stress analysis.

Non-destructive Testing (NDT)

It is a technique to inspect, test or evaluate properties/form of material without causing any lasting damage (Louis, 1995). It is widely used in many industries such as ^Aaerospace, ^Aautomotive, ^Lcivil and ^Mmedical it is so widely used due to the accuracy, relatively low the cost and no alteration to the material. NDT checks are used in the manufacturing and creation of products, they ensure the integrity and reliability of the product. One of the greatest advantages of NDT is the repeatability of the test this gives the ability to measure the quality level of the product and correlate data from the test product (Dwivedi, et al., 2018). NDT is also widely used in asset integrity management where critical parts will have a periodic inspection to ensure the integrity of the material (Inspection Engineering, 2019).

Destructive Testing

Destructive testing is a method used to gather data on such physical properties such as impact resistance, ductility, yield, and ultimate tensile strength, fracture toughness and fatigue strength. The part will be tested beyond its limit until failures occur and then a conclusion of the values of each property can be drawn (Hull, et al., 1988). The part is no longer serviceable after testing due to being pushed to failure. This data can be used in the stress analysis of components and then verified with NDT to ensure the parts are to the required specification.

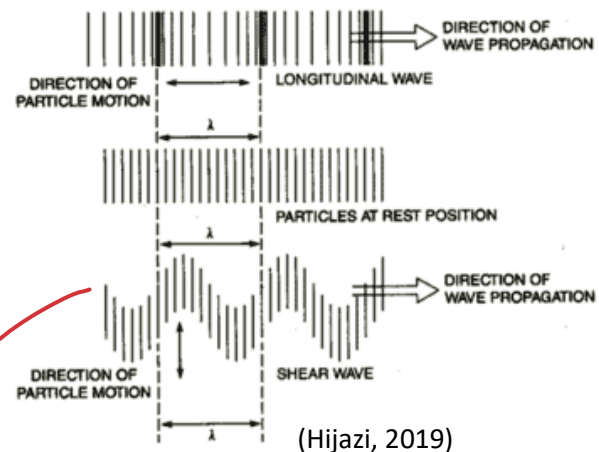
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Ultrasonic Testing.

Ultrasonic testing is the use of ultrasonic waves to gain a better understanding of the internals of the part. Ultrasonic is commonly used to detect subsurface defects or the dimensions of the sound conducting material (NDT Resource Center, 2019).

Theory

Ultrasonic is the measurement of vibration on an atomic level in a material referred to as acoustics. The atoms are forced to vibrate in harmony about their equilibrium position to form a mechanical wave. When a material is not stressed in tension or compression beyond its elastic limit the particles perform elastic oscillations (Hijazi, 2019). In solid materials, waves propagate in four principle modes but two are the most common in ultrasound which are longitudinal waves and shear waves.



(Hijazi, 2019)

Figure 1 Propagation of Waves

In longitudinal waves, the oscillation occurs inline with the direction of the wave. It forces the particles into compression and expansion as the waves travel through the material. Shear waves force particles to oscillate at a right angle to the direction of the wave (Olympus, 2019).

The wavelength is directly proportional to the velocity of the wave and inversely proportional to the frequency seen in the below equation. The velocity is the fixed value in the equation this is set by the materials, thus an increase in frequency will reduce the wavelength (Hijazi, 2019).

$$\lambda = \frac{v}{f}$$

λ : Wavelength (m), v : Velocity, f : Frequency (Acoustics Today, 2019)

The chosen wavelength has a massive effect on the detection of the discontinuity in the material (General Electric, 2018). In industry, a rule of thumb applies the discontinuity must be larger than one-half the wavelength (Hijazi, 2019). However, with increased wavelength, there are many repercussions such as loss of sensitivity and resolution. Sensitivity is the ability to identify small discontinuities to increase sensitivity the frequency must be high thus reducing wavelength. Resolution is the ability to identify discontinuities that are in proximity the same as sensitivity resolution is increased with higher frequency (Gupta, 2019).

Method

Ultrasonic Testing machines have several common functional units: pulsar/receiver, transducer, computer, and display device. The placement of the receiver defines the two common methods. The two ultrasonic methods are pulse-echo (reflection) and attenuation (through transmission) (Kumar, 2011). Pulse echo sends the ultrasonic energy through the material and measures the energy from the reflection at the end surface while attenuation has a receiver on the end surface of the material and measures the energy at that point.

Ultrasonic uses electrical energy which is applied to a piezoelectric crystal located on the transducer/probe which will vibrate for a small period of time. The electrical energy will be converted to soundwave energy which will propagate through the material until a discontinuity (possible defect) in the wave path occurs (Dwivedi, et al., 2018). Depending on the method some of the energy will be reflected at the point of discontinuity and the rest will reflect at the end of the material or the different energy levels due to the discontinuity will be measured at the end of the material. The energy can be displayed in a signal form, with the amplitude representing the size of the reflection and the distance representing the arrival time of the reflection (Kumar, 2011).

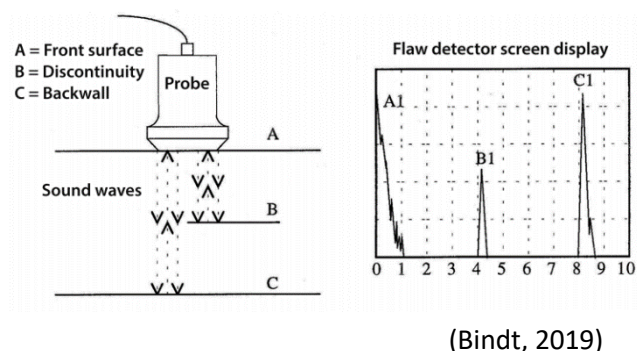


Figure 2 Ultrasonic Testing Output

The short pulse of high-frequency sound waves is passed through a part at a range between 0.5 and 15 MHz (Dwivedi, et al., 2018). The frequency will be the balance of detection probability and resolution/sensitivity. Other factors to be considered while selecting frequency are material grain structure and thickness, and the discontinuity type, size, and probable location (Nde-ed.org, 2019). High-frequency waves tend to scatter in large-grained materials such as cast iron and could be mistaken for discontinuities (Hijazi, 2019). While directional grained and forged materials can use a much higher frequency (Xu, et al., 2015).

Sources for Error

Ultrasonic can give inconsistent results if the grain size of the material is large and may be mistaken for discontinuities. The pressure applied to the transducer can give inconsistent results so it is important that the operator uses it correctly (Chapman, et al., 2006). Irregular geometries can be hard to measure and can be hard to interpret by an operator.

Advantages & Disadvantages

Advantages

- Excellent Penetration of materials can detect small defects.
- Results can be analysed almost instantly
- Can be used with limited access to part using pulse-echo
- Very sensitive so detect very small defects
- The shape of the defect can be determined
- Able to scan whole part to inspect the full volume
- Portable machines are available for infield inspection
- Measurements of material can be taken

Disadvantages

- Skilled operators are needed for use and interpret the output
- Irregular parts are difficult to test
- Can give incorrect readings with large-grained materials

- Favours smooth surfaces and good contact surfaces
- Couplant can become contaminated

(Bindt, 2019)

Applications

Due to the versatility of ultrasonic testing and the ability to analyse results almost instantly the applications of ultrasonic is endless. However, there are many industries which use it extensively due to the type of parts they are testing. For instance, some critical aerospace engine components have a one hundred percent check rate. An example of this is the compressor and combustion blades in the turbine engine. The blades are a nickel alloy with directional grains to form a single crystal (Nathan, 2017). These blades operate in an extreme environment with the temperature around 1700°C and spinning at 12,000rpm it is imperative that these blades are defect-free otherwise the outcome could be catastrophic from a failure (Rolls Royce, 2019). Using ultrasonic testing allows each blade to be tested to see if there are any imperfections in the grain or the material itself. This scenario can be applied to many industries that need one hundred percent testing components where the integrity of the part is safety-critical and failure could lead to loss of life. Ultrasonic testing can be also used to check the integrity of materials such as billet blocks from the casting/forging process. It can find defects such as porosity in the materials which would only be clear after the billet has been machined (Starsman, 2019).

The Use in Stress Analysis

Ultrasonic testing can be used to calculate the principal stress of a part while the part is exerted to a force. It is done by using a very high-frequency sound-wave. The pulse pattern of the reflected echoes gives the ability to calculate the directions of the principal axis of the stress. The pulse-echo-overlap method is used to measure the velocity of the two shear waves. Then the difference in the principal stresses is calculated from the velocity measurements (Hsu, 1974). By knowing the principal axis stress of the object it gives the ability to understand how

a defect will act. It has been shown that the path of a crack is defined by the trajectory of the maximum principal stress (Aliabadi, 2003). This will give the ability to control failures in the design. For example, a jet plane engine is designed to fail in a certain way to limit the damage to the plane. By being able to control how it fails and also be able to verify that the part is made to specification could be priceless. Ultrasonic testing can also be used to test the integrity of parts after testing. For example, parts that have gone through fatigue testing can then be inspected using ultrasonic testing to see if there are any defects that have occurred. The findings can be then cross referenced with the stress analysis calculations to see if the part acts as calculated (Takahashi & Takeshi, 2008).

Liquid Penetration Inspection (LPI)

Dye penetrant inspection is a type of NDT that is used to check defects on the surfaces on non-porous materials such as ceramics, metals, and plastics. LPI can be used on ferrous and non-ferrous materials however, magnetic-particle inspection is used due to its subsurface detection (Di Gianfrancesco, 2017). LPI is used to detect surface defects such as hairline cracks, surface porosity, and fatigue cracks.

Theory

Liquid penetrant inspection is a capillary action which identifies surface discontinuities by using fluorescent or visible dyes to highlight defects. The dyes can be further highlighted by the use of UV lamps to give a better probability of identification. The fluorescent penetrant can be split into two type one which deposits into the discontinuity and when dries becomes fluorescent and the second being a fluorescent liquid (Halmshaw, 2006). However, for a greater probability of detection, the penetrant must be able to penetrate the discontinuity in the material and be visible for detection.

The penetration process can be split into two categories the ability to wet the material and the ability to fluoresce the penetrant. Each has contributing factors to increase the success rate of each and should be taken into consideration.

Wetting the material has many contributing factors and has two main factors. The viscosity of the penetrant which is the speed of which penetrant enters the discontinuity. This will influence the effectiveness of the test if there is not adequate time for the penetrant to penetrate the discontinuity. There are equations that will calculate the fill time of however they don't consider the release of gases for the discontinuity (Deutsch, 1979).

The second factor is a capillary force, which is the driving force of the fluid into the discontinuity it is a function of the surface tension of the liquid-gas interface, the contact angle, and the size of the defect opening (Tugrul, 1997).

Capillary force can be expressed as:

$$\text{Capillary Pressure} = \frac{2(s_{SG} - s_{SL})}{r}$$

s_{SG} = the surface energy at the solid-gas interface.

s_{SL} = the surface energy at the solid-liquid interface.

r = the radius of the opening.

As seen in the capillary force equation the surface energy is what defines the wetting characteristics is important to fill the discontinuity void. The penetrant will fill the discontinuity until an opposing force brings the capillary force into equilibrium this force will usually be the pressure of the trapped gas in the discontinuity and will compress at the closed end of the void (Tugrul, 1997).

The fluorescing of the penetrant is down to the dimensional threshold of fluorescence. The dimensional size of the discontinuity directly corresponds to the dimensional threshold of fluorescence response which are characteristics of the penetrant (Nde-ed, 2019). To gain a fluorescence response from the penetrant there must be satisfactory levels of absorption of ultraviolet radiation, this is dependent on the concentration and thickness of the penetrant. Therefore, for the dye to be detectable it must be able to fluoresce as a very thin film (Larson, 2002).

The performance of penetrant can be calculated using Beer's law however the equation is not always true for very thin layers on penetrant (International Atomic Energy Agency, 2000)

$$I = I_o \cdot x \cdot e^{-Ict}$$

I = Transmitted light intensity

I_o = Incident light intensity

e = Base of natural log (2.71828)

I = Absorption coefficient per unit of concentration

C = Dye concentration

t = Thickness of the absorbing layer trolled to a certain degree by the concentration of the fluorescent tracer dye in the penetrant.

(Nde-ed, 2019)

The equation proves that the intensity of the transmitted energy is directly proportional to the intensity of the incident light and varies exponentially with the thickness of the penetrant and its concentration (Nde-ed, 2019).

Method:

Pre-cleaning of the part is a vital part of the success of the test. If contaminants are not removed it will greatly reduce the chance of the penetrant filling the discontinuities or contaminating the penetrant so it will not fluoresce. The cleaning process is commonly done by using a cleaner such as a solvent-based fluid to remove grease and oil (Magnaflux, 2019).

Penetrant is applied and allowed to dwell to ensure that the penetrant fills all discontinuities and has time to dry.

The excess penetrant is removed by rinsing the part commonly in an emulsifier to aid the removal of the penetrant.

The developer is applied to draw out trapped penetrant out of discontinuity and can amplify the fluorescence by controlling the thickness of the penetrant.

The part is then inspected by using an ultraviolet light in a dark room and discontinuities in the part can be identified.

The part is then cleaned, and all penetrant is removed before final processing or the defect process. (Bindt, 2019)

Sources for Error

In LPI testing there are factors in the process that might give errors or inconsistent results. As stated previously the cleaning process is a vital part of the process. Contaminants will give

errors in the inspection process by either stopping the penetrant fluorescing or the penetrant will not stick to the material. Another possible cause for an error is not allowing enough time to dry which will allow the penetrant to be washed off.

Advantages and Disadvantages

Advantages

- Material versatility (metals and non-metals)
- High sensitivity to small surface discontinuities
- Detect wide shallow discontinuities
- Can be used in mass production
- Automated detection possible
- Penetrants available in Aerosol so can be used in service

Disadvantages

- Pre-cleaning must be carried out correctly
- Materials need to be relatively non-porous
- Limited to surface discontinuities
- Rough or coarse surfaces produce inconsistent results
- Cleanliness of part must be high due to contamination
- Must have direct access to surfaces

(Bindt, 2019)

Applications

Due to the versatility of the LPI, the industrial applications are endless. As with most non-destructive testing techniques it is heavily used in the aerospace industry. LPI is no different and is used to check many components in the manufacturing, repair and over hall of turbine engines (General Electric , 2019). The use of LPI in aerosol cans gives the ability to inspect in service parts to see if any defects have occurred. This is used often used to detect discontinuities on the aircraft fuselage commonly it is used after lightning strikes to ensure there are no small cracks (British Airways, 2019).

The Use in Stress Analysis

LPI can aid in the verification of stress analysis by ensuring components after the experimental test or in service have performed as calculated. LPI can be used to detect surface discontinuities such as fracture cracks (Jolly, 2003) this complied with other data such as principal stress can help understand the crack and possibly find the root cause of the discontinuities. LPI is used throughout the manufacturing process due to tasks such as machining causes discontinuities in material. It allow inspectors to make improvements in the process which could not of been calculated in the stress analysis of the machining process (Magnaflux, 2019).

Visual & Optical Inspection

Visual inspection is a method of checking surface condition and geometry of parts by human vision or with the use of optical systems. It is the simplest form of NDT and can be performed at all most any point in the process. Experienced inspectors will be able to detect small nonconformities with easy in optimum conditions (Bindt, 2019).

Theory

A key aspect of visual inspection is the environment of which inspection is taken place. The human eye is biologically adapted to perform best in natural sunlight so replicating such conditions would be thought of as optimum conditions. However, when inspecting alloy materials, it is imperative that there is a reduction of glare which could lead to missed defects (Asnt, 2019). Having a sunlit inspection environment may not be possible and due to there being no one day the same therefore artificial light must be used. By using artificial light standardisation can be achieved and become part of the process.

Illuminance is the light level required to do such inspection it is measured in lux. One lux is the illuminance of a surface one meter from a light source of one candela (Bindt, 2019). Most inspection processes will have a minimum illuminance that is required to perform the inspection. Newer methods of automated visual inspection are becoming more and more used in the industry. Automated visual inspection allows a standardised method of inspection, cameras/sensors are in fixed positions and can detect the smallest defects. It also gives traceability of each part and data can be compiled and trends were seen (Ford Motor Company, 2019).

Equipment can be used as part of visual inspection such as video cameras, these could be attached to probes, drones, submarines and stream live video to a human inspector. This can be used if the access is limited or dangerous for a human.

Method

To increase the probability of discontinuities detection the process must be carried out in optimum conditions. For instance, having a clean, contaminate free inspection area with the correct lighting would be said to be optimum conditions (Hull, et al., 1988).

To further increase the probability of detecting discontinuities a process should be followed to ensure all areas are inspected and visual aids of previous or reoccurring faults should be on hand.

Having an experienced inspector will be the greatest asset in the visual inspection process. Experienced operators would have a mental library of the previous inspections and mentally cross-reference the inspected part against what they have in their mind as a defect-free part (Halmshaw, 2006).

Pre-cleaning should be carried out before inspection. This will be done in the same way as LPI the use of solvents/cleaner to remove grease, oil, etc. The part can then be inspected this could visually by an operator or autonomously.

Sources of Error

Due to visual inspection being subjective by a human's judgment there are many possible sources for error the main one being a human error (HSE, 2019). Human factors are the method of trying to reduce human error by designing with humans in mind. It takes into consideration human interaction with the task, equipment, and the environment. It is used to optimise human and system efficiency and effectiveness, safety, health, comfort, and quality of life (The National Academies of Science Engineering & Medicine, 2019). If human factors are applied to the visual inspection process then the human error can be greatly reduced.

Advantages & Disadvantages of Visual Inspection

Advantages

- Simple and effective of inspecting for discontinuities
- Can be carried out anywhere in the process
- Multiple discontinuities can be seen at one time
- Operators discontinuities/defects knowledge is always expanding
- Almost everything can be inspected, not limited to a certain material, etc
- Training costs are low

Disadvantages

- Human factors *EXPAND*
- Limited to surface detection
- Variables lead to missed discontinuities

Applications

As human beings, we visually inspect everything subconsciously in everyday life. The use of it in NDT is a more process-driven method. Standards are put in place and inspection is carried out against the standard. Visual inspection is used extensively in automotive manufacturing example of this would be the inspection of surfaces faces after CNC machining. This gives an indication of the quality of the surface finish, if there are defects such as porosity, and the condition of the tooling. The experience of the operator can detect imminent failures or nonconformities before they happen. Tooling life is a perfect example of this, as the tool wears the surface finish will deteriorate this could be very difficult to identify using an automated system.

The Use in Stress Analysis

Visual inspection is can be used in stress analysis after however due to it being subjective and hard to quantify it is very opinion-based. The experience of the inspector is a key role, but it will need to be coupled with an evidence base test.

Conclusion

After extensive research into three different techniques, it is clear no matter how accurate, sensitive and reliable the technique maybe it is still susceptible to human error. By factoring in human factors it can be greatly reduced however due to the repetitiveness of the task it will never be eliminated. No one technique had the full package and the implementation of multiple techniques will be the best practice. It was clear to see that the experience of operators played a pinnacle role in the success of defect detection.

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