Ultrasonic waves for materials evaluation in fatigue, thermal and corrosion damage: a review

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Abstract

Mechanical properties of materials tend to deteriorate over time and thus become responsible for cracks and malfunctions in mechanical components or civil structures. Non-destructive ultrasonic wave analysis has proven to be a successful investigation method for inspecting mechanical properties of materials. This review has highlighted the main results of research in the field of non-linear ultrasonic wave investigations for the inspection of fatigue damage, thermal damage and chemical damage. In all three cases, non-linear ultrasonic wave survey method was effective in detecting first-stage damage.

Key words: guided wave, non-linear wave, crack, failure, non-destructive evaluation, piezoelectric transducers, Rayleigh wave

1 Introduction

Mechanical properties of materials are degraded over time, due to the presence of microscopic imperfections caused by fatigue damage, thermal damage or chemical damage [1] [2] [3].
The stresses to which the material is subjected lead to breakage through two phases [4]:

- crack formation (Figure 1 (a));
- crack propagation (Figure 1 (a,b,c,d,e)).

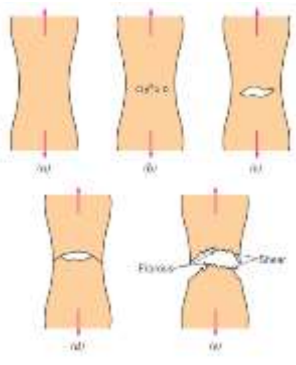

Figure 1 [5] – Crack propagation stages

More than 90% of metal structural failure during service is caused by fatigue failure [6].
The prediction of the structure fatigue life is based first and foremost on a good knowledge of material properties, loading conditions, geometry, etc... [7].
The capacity to withstand the load depends on [8]:
- how many trigger sites there are for crack generation;

- if such sites are or are not subject to sufficiently high stress.
It is therefore clear that there is a need to carry out a preventive investigation into materials in order to verify their actual state of damage [9].

2 Non-destructive control

Non-destructive control technique (NDT) is one of the best defect evaluation method [10], which makes it possible to identify first-stage structural damage, so as to prevent structural failure and reduce economic losses [11]. One of the advantages of this technique is the remote control, which reduces operating costs, downtime, etc… [12] [13].
It has been demonstrated [14] [15] that material defects (such as micro-cracks, delaminations, inclusions) are source of great non-linearity. To take advantage of this feature, non-linear non-destructive testing (NNDT) with ultrasonic waves has become established in NDT [16] [17]. It has been demonstrated [18] [19] [20] that NNDT have higher sensitivity in the detection of small damage than classical linear techniques [21] [22]. In fact, non-linearity indicators have wider dynamic ranges, often up to ten times greater than linear parameters [23] [24]. It can therefore be concluded that non-linear parameters are much more sensitive to defect detection than linear ones [25].
Ultrasonic waves have established as a valid choice in non-destructive testing technique.

3 Non-linear ultrasonic waves

Ultrasonic waves are highly sensitive to structural damage, propagate in all directions, spread quickly and have high penetration into materials [26] [27].
When a wave propagates in a medium, the phase and amplitude vary depending on material properties and has been shown [28] [29] [30] that elastic excitation of cracks leads to the generation of non-linear terms during wave propagation through damaged material.
The non-linear phenomenon manifests itself with second harmonic generation: when a sinusoidal ultrasonic wave of finite amplitude at the ω frequency crosses a non-linear elastic material, a second harmonic at the 2ω frequency is generated [31].
Breazeale and Thompson [32] were the first to discover that non-linear elastic materials distort an elastic wave and generate higher order harmonics.
The second harmonic provides useful information about the damage conditions of the material, by measuring the amplitude ratio of the fundamental waves and the second harmonic [33] [31].
In some parts of the world, such as Japan, the ultrasound method of investigation has been standardised as a test method for compressive strength and as an estimate of the cracks depth in materials [34] [35].
Interactions between propagated elastic waves and medium characteristics were found in both cement [36] [37] and metal fields [38] [39].
The appearance of non-linear terms is specifically related to the presence of damage and no other cause, so nonlinear ultrasounds are sensitive to mechanical properties degradation from the early beginning of damage [40].

The appearance of non-linear terms in presence of cracks is due to breaking of proportionality between impacting ultrasonic wave and corresponding elastic response of the medium [41]. This break in proportionality is to be found in the following mechanisms [41]:

1) Nonlinear elastic energy loss;
2) Redistribution of energy through the various frequencies generated;
3) Dependence of the elastic constants on the amplitude excitation.

Non-linear effects increase with increasing material defects, resulting in reduced about strength, stiffness and material life [42].

The efficiency of the interaction between wave and defect depends on the defect size and on the degradation of linear properties due to the damage [43].

Two basic non-linear effects may be used to assess the condition of the materials [1]:

a) Acoustic-elastic effect, based on the dependence of ultrasonic wave velocity on external stress applied to the material;
b) Harmonic generation. This method requires more specific instrumentation and more complex adaptability than point (a).

2 Nonlinear ultrasonic detection principles

Breazale and Ford (1965) gives the one-dimensional longitudinal non-linear wave equation:

$$\rho_0 \frac{\partial^2 u}{\partial t^2} = k_2 \frac{\partial u}{\partial x^2} + (3k_2 + k_3) \frac{\partial u}{\partial x} \frac{\partial^2 u}{\partial x^2} \tag{1}$$

Where,

ρ_0 is the density of the medium;
k_2 is the second order elastic coefficient, $k_2 = \rho_0 v$;
k_3 is the third order elastic coefficient;
v is the longitudinal wave speed.

Using the method of perturbation with progressive approximation, the approximate wave solution is:

$$u = A_0 \sin(kx - \omega t) + \frac{1}{8}\left({A_0}^2 k^2 \beta x\right) cos2(kx - \omega t) \tag{2}$$

Where,

k is the wave number, $k = \omega / c_p$;
ω is the angular frequency;
c_p is the phase speed.

If the fundamental amplitude is $A_1 = A_0$ and the amplitude of the second harmonic is $A_2 = \frac{1}{8}\left({A_0}^2 k^2 \beta x\right)$, then the non-linear ultrasonic coefficient β can be written as [44]:

$$\beta = \frac{8}{k^2 x}\left(\frac{A_2}{{A_1}^2}\right) \quad (3)$$

A_2/A_1^2 is the measurement of acoustic non-linearity, A_2 is the measured amplitude of the second harmonic and A_1 is the measured amplitude of the fundamental wave. The ratio A_2/A_1^2 is used as a measure of the non-linear acoustic parameter with respect to its initial value and it is proportional to the non-linear parameter β. So, to obtain the value of the non-linear ultrasonic coefficient β is necessary to measure the absolute amplitude of the ultrasonic wave A_1 and A_2 [45] [46] [47].

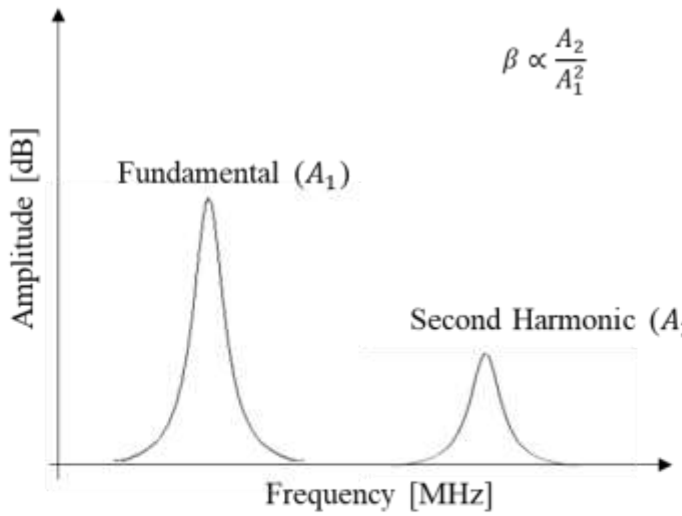

Figure 2 – Graphical representation of the proportionality ratio β

Previous studies [48] [49] [38] have demonstrated that parameter β is closely related to the amount of damage accumulated in the material. Parameter β has been shown to be effective in inspecting fatigue damage [50] [51] [52], thermal damage and micro-crack [53] [54].

The measurement of the ratio between second harmonic amplitude and fundamental harmonic has been investigated by several authors to understand the relationship between non-linearity degree of the material and mechanical and microstructural properties of the material [55] [56] [57].

In recent years, the third order non-linear parameter for the inspection of material degradation has also been studied and has been shown to be more sensitive to creep [58] [59].

3 Fatigue damage

All materials subject to cyclic loads are at risk of sudden fatigue failure, even if the material is still in the elastic range [60] [22]. This is because alternating stresses σ_a stress the material in such a way that it has a fatigue life of approximately 10^6 cycles, estimated value in mechanical engineering applications [61] [62].

Cantrell [63] has studied and identified the contribution of non-linearity provided by fatigue cracks as fatigue parameters vary and as a percentage of fatigue life.

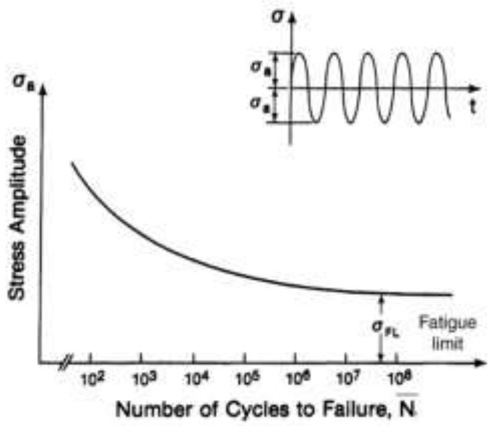

Figure 3 [64] – Life fatigue cycles

Given that the number of load cycles responsible for fatigue failure in the presence of a macro crack is much smaller than the load cycles required to generate a micro crack, it is necessary to be able to detect fatigue cracks before they arrive at failure [26].

For both high cycle fatigue and low cycle fatigue, it has been found that plasticity occurs near the onset of the crack, due to dislocations and slippages, and this phenomenon is responsible for the appearance of non-linear terms in ultrasonic waves [26] [65].

So, the NNDT detection with ultrasonic waves is effective for the detection of fatigue damage in materials subjected to cyclic loads, also thanks to the ability of this type of wave to reach long distances and inspect parts to which access is not possible [66].

Rayleigh waves are the most commonly used for fatigue crack monitoring [67] [68], which is based on the generation of the second harmonic from a monochromatic source at the fundamental frequency that crosses the material to be analysed [69].

For Rayleigh non-linear ultrasonic wave measurements, the effects of diffraction should be considered because measurements depend on the propagation distance and have a significant amplitude reduction over long distances [69] [70].

It has been shown [67] [71] that spectral analysis with Rayleigh waves can be effectively used for crack detection: the signal energy drops drastically in the presence of cracks. It has also been verified [67] that in the presence of painted metal elements there is a significant loss of signal amplitude.

Hirase and Achenbach [72], by the boundary element method, have studied the increase of higher order harmonics on the surface.

Another method that has proved effective for fatigue cracks determination is the investigation with linear-acoustic effect [1]. Through an experiment involving the application of a long-term fatigue load to metal samples, Nagy [1] has continuously monitored the non-linearity measured by the linear-acoustic effect, in order to study the relationship between degree of damage and fatigue.

Experimentally, results that the non-linear parameter, just before the failure, reaches a value six times higher than the initial value. The increase of the non-linear parameter indicates the degeneration of the material resistance. Nagy [1] has experimentally demonstrated that, shortly before failure, the excessive non-linearity caused by fatigue cracks can be an order of magnitude greater than the intact intrinsic nonlinearity. Non-linear parameter increases as resistance deteriorates, but stabilises when the further accumulation of fatigue damage is negligible.

Another confirmation [1] of the correlation between the increase in non-linearity and the deterioration in material strength is given by hardening materials such as nylon. The inherent plastic

non-linearity was found to be relatively high and rather temperature sensitive. In metals and metal matrix composites intrinsic non-linearity is significantly lower and less temperature sensitive.
These results confirm that non-linear measurements are particularly suitable for the early detection of fatigue damage.

4 Thermal damage

Thermal damage is a type of damage that occurs during service [33] and generates thermal stress in material, resulting in the formation of new cracks or the propagation of existing cracks [2] [73].
Thermal damage due to propagation of micro-cracks that reduce service life [74] [33], leads to degradation of the mechanical properties of materials. Micro-cracks change in volume and size according to the level of thermal stress applied [75].
In case of high temperatures, it is not easy to quantify thermal damage induced in material [42].
Ultrasonic waves are able to evaluate the extent of damage variations by evaluating longitudinal ultrasonic wave velocity, because they have a good sensitivity to temperature [75] [33].
The effects of temperature variation on ultrasound were considered in [76] [77] and it has been demonstrated that the main effect of temperature variation is to lengthen or compress the wave signal and the secondary effect is to distort its shape. Due to the primary effect, the root mean square error measured between waves at a few degrees difference in temperature is of the same magnitude order as the root mean square error measured between waves measured on a structure before and after damage [78].
Empirical studies have highlighted the relationship between ultrasonic parameters in the time and frequency domain and the extent of thermal damage in rocks [79].
Due to the presence of micro-cracks and heterogeneous mineral components, the rocks behave like low-pass filters, progressively decreasing the high frequencies of the ultrasonic wave propagating in the medium [80]. As a consequence, it is not possible to obtain a general relation between the degree of damage and the ultrasonic response, because the frequency spectrum varies with the different microstructural properties of the rocks as well as with the degree of thermal damage [81].
H.J. Yim *et al*. [54] has shown that in concrete impact-modulating method allows earlier detection of thermal damage than linear ultrasound method (phase speed and dynamic modulus measurement).
The impact-modulation method is based on the generation of a resonant vibration mode by percussion hammer, rather than by harmonic vibrations. Non-linear parameter D can be described by proportional relation between spectral energy of high frequency wave (E_h), low frequency vibration (E_l) and lateral components (E_s) [82] [83] [84]:

$$\frac{E_s}{E_h} \propto DE_l$$

H.J. Yim *et al*. has experimentally verified that non-linearity, originating from contact defects, increases proportionally to thermal damage.
It is therefore concluded that ultrasound method for investigating damage conditions in stone materials is effective due to simultaneous variation of temperature in mechanical and acoustic characteristics [85] and provides a reliable measure for deciding on continued use of thermally damaged materials [42]. In fact, deformation parameters of materials that have suffered thermal damage are closely related to the characteristics of ultrasound in the time domain [80].

5 Corrosion damage

In metal structures subject to aggressive environments there is a corrosion steel risk. Solving this problem induces repair costs, sometimes higher than the initial construction cost, and where it is not possible to intervene in time with maintenance interventions, structural failure occurs [86] [87].

For the control of surfaces subject to corrosion, visual inspection is still widely used, which allows large areas to be checked, but is an inspection applicable only to open surfaces [88].

Non-destructive non-linear ultrasonic wave testing has been successfully used for the analysis of metal damage conditions in the presence of corrosion [88] [89].

Zhong *et al*. [90] has studied intergranular corrosion in stainless steel pipes as the level of corrosion varied. The results of the experiment have shown that non-linear coefficients increase with increasing corrosion, which confirms that assessment of ultrasonic wave nonlinear coefficient is suitable for the investigation of corrosion level in material. However, it was found that tube length affects the measurement of non-linear coefficient.

Maddumahewa *et al.* [91] has studied ultrasonic wave behaviour through steel bars incorporated in concrete and experimentally verified that, in the presence of bars affected by corrosion, wave speed decreases. This confirms ultrasonic investigation as an effective method for detecting corrosion damage even in reinforced concrete.

There are also some cases, such as pipes used in the petrochemical industry, where large lengths need to be monitored and a fast and precise method of investigation is required to identify the areas where corrosion has occurred. In these cases, guided ultrasonic waves are used, which are ultrasonic waves requiring boundary borders for propagation [92]. Typical examples are wave propagation in a platter, tube, or multilayer structure.

Ultrasonic guided waves have the advantage of being able to inspect hundred meters of pipe without having to reposition the transducer [93]. Ultrasonic guided waves also couple the advantages of non-linear ultrasonic waves, such as great sensitivity to detection of small defects, with the advantages of guided waves, such as volumetric coverage, long propagation distances, one-sided access and inspection speed [94].

Imperial College's NDT laboratory has developed a system that uses ultrasonic guided waves to control corrosion on long pipe lengths [95] [96]. In this system the waves propagate along a tube and are reflected when they encounter characteristics that modify the geometry of the tube (corrosion zones, welding, etc.). This technique was initially designed to test 2-24 inch tubes, but both larger and smaller tubes can be tested [97]. This technology has been put on the market [98]. This method of investigation is suitable for all applications where external access to the pipeline is limited. For the investigation of corrosion damage, cylindrical Lamb waves were also considered. Initially [99] this method aimed to detect corrosion defects on areas wider than 3Tx3T and deeper than T/2, indicating tube thickness with T.

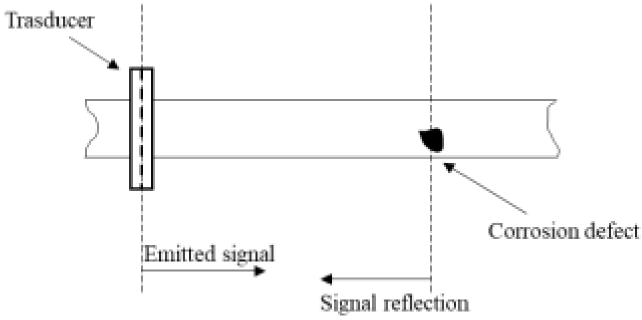

Figure 4 –Ring transducer emits guided wave that runs through the tube. When wave encounters a defect on the pipe walls it is reflected and returned to transducer.

Defect presence and location on pipe wall is determined by the wave reflections and the time it takes to return to transducer [100] [101].
In this field, it would be interesting in the future to analyse interactions between propagation properties of guided wave through the tubes and geometric discontinuities.

6 Measurement methods

As mentioned in the previous paragraphs, non-linear parameter β is sensitive to microstructural changes caused by damage and to the presence of micro-cracks. Recalling that the parameter β is proportional to A_2/A_1^2, fundamental and secondary frequency shall be measured to provide an estimate of β.
There are various measurement methods to achieve this, among the most used techniques: contact piezoelectric transducers [102], laser [103] and capacitive techniques [104].

6.1 Contact method: Piezoelectric Transducers

Contact piezoelectric transducers are readily available at low cost and ready to use. These transducers require a poor surface preparation of the sample on which they must be applied, in fact a hand polishing of the contact surface is enough. Transducer must be firmly glued to the sample surface and therefore the variations that this encumbrance may cause to the measurement result must be considered [105].
Two transducers are required for the inspection of material defects: a receiving transducer and a transmitting, on the opposite sides of the sample [106]. Transmitting transducer has a centre frequency equal to about the first harmonic value and receiving transducer has a centre frequency value equal to about the second harmonic value [107]. The most common materials for piezoelectric transducers are lead–zirconium–titanate (PZT) and lithium niobate. PZT transducers are more advantageous in ultrasonic applications than other materials because their good acoustic impedance [108]. However, the defect of PZT transducers is that their high efficiency is non-linear. Lithium niobate is less efficient than PZT, but has less non-linearity.
To be efficient, the piezoelectric transducer must be able to generate and receive acoustic pulses with a high sensitivity in the range of 1-10 MHz. The high sensitivity of the transducer is closely related to the electromechanical coupling coefficient [109].

Piezoelectric transducers are part of the survey method that involves contact between detection element and sample surface. This means that transducer and sample must be well coupled with a medium that guarantees good impedance: oil or grease. It is necessary to consider the variations that the encumbrance can involve in the measurement. Furthermore, this type of analysis does not allow measurement at high temperatures and in hostile environments, such as corrosive environments, or on hidden or geometrically difficult to reach surfaces [110].
Non-contact investigation techniques are therefore needed.

6.2 Non-contact method: Laser Ultrasonic

Ultrasonic laser methods have the advantage that measurement is carried out without sample contact and allow punctiform detection, but require sample finish surface like a mirror [111]. Until now only two studies have been conducted on the effect that surface roughness produces on β [112] [111]. Because of the need to prepare surface specimen under examination, ultrasonic laser technology has a lower SNR than contact techniques.
This technology can work at high temperatures and pressures and also has the advantage of having the ability to scan at high resolution [113] [114] [115].
Hess et al. [116] have been recently reviewed in detail laser methods in the field of ultrasonic guided waves for non-destructive testing.
Laser detection method is used in vibration-acoustic measurements [117] [118].
Ultrasonic laser technique can analyse moving surfaces even in hazardous environments [119] [110].
Jian et al. [120] has studied surface cracks with Rayleigh waves generated by laser technology.
Choi et al. has investigated the relationship between crack width and ultrasonic wave excited by masking laser beam with line arrayed slit [121].
Ni et al. has studied crack breaking angle by means of a double laser source generating ultrasound and thus gave a new method for crack orientation angles calculation [122].
T. Wan et al. [123] has investigated damage induced by erosion with ultrasonic laser technique and demonstrated that this technique, combined with Wavelet differential analysis, quantitatively indicates damage depth dependency.
To date, new proposals are being searched for ultrasonic laser survey techniques in situ [124].

6.3 Non-contact method: Capacitive Ultrasonic Transducers

This method has been extensively discussed in [125] [126] and, more recently by Cantrell and Yost and co-authors in [127] [128] [129].
Compared to piezoelectric transducers, this method allows to measure absolute displacements of the first and second harmonics, but sample preparation is cumbersome and requires careful preparation.
Capacitive ultrasonic transducers are made of many small membranes. Inductances are inserted between the membranes in order to establish an electrical transmission line. The transducer is capable of both emitting and receiving ultrasonic wave. Incident ultrasonic wave vibrates membrane and this vibration modulates transmission line signal. The signal of the transmission line is proportional to the total capacity and frequency of the signal passing through it [130].
Transducer is kept at a distance of approximately 1-10 µm above the sample.

This detection system has a sensitivity of about 10^{-16}m, more than sufficient to detect first and second harmonic displacement amplitudes of the propagated wave [131].

7 Conclusion

Micro-cracks, inclusions, delaminations induce non-linearity in materials. This feature has made NNDT valid for defect investigation. Detection of these structural defects is fundamental: it avoids premature and catastrophic breakages and reduces costs of intervention, thanks to preventive and targeted maintenance. Ultrasonic methods are very sensitive to structural damage, thanks to their ability to propagate in all directions and to their ability to penetrate deep into the materials. When a wave propagates in the sample its phase and amplitude vary depending on the properties of the material. In material damage there is a non-linear behaviour that leads to the formation of the second harmonic, which provides useful information about the conditions of material damage.
We have reviewed the main studies and results of the application of the non-linear ultrasound survey method in cases of fatigue damage, thermal damage and corrosion damage, concluding that this survey technique has proved effective in the early detection of damage.
Finally, we have reviewed some measurement methods, reporting that non-contact methods are more efficient than contact methods.

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