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STUDY OF COMPOSITE PIPELINES DAMAGED BY CORROSION: CONTROL BY NON-DESTRUCTIVE TESTING

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Since the degradation of material properties and defects often occur in engineering structures due to fatigue loading, it is necessary to develop non-destructive testing methods to assess the safety of engineering structures. In the aerospace industry in particular, the demand for early crack detection to ensure the safety and durability of engineered structures is growing. The automated inspection of pipelines using non-destructive testing (NDT) is desirable because visual inspections are not always consistent. In addition, automated inspections reduce the cost of the inspection process and improve its quality. Since the identification of cracks in engineering materials is very valuable for understanding initial and slight changes in the mechanical properties of materials in complex working environments, numerical simulations of propagating Lamb waves in a cracked pipeline were performed to study their non-linear behavior. Finally, the shapes of all the signal responses can be used to identify the depth, length, shape and orientation of cracks. The elapsed time before signal responses are received varies as a function of the orientation of a crack.

Keywords: composite material, pipeline, degradation, damage, non-destructive testing

1. Introduction

It is necessary to develop non-destructive testing (NDT) methods to assess the safety of engineering structures. In the aerospace industry in particular, the demand for early crack detection to ensure the safety and durability of engineered structures is growing. Linear ultrasonic testing has been widely used to detect cracks, holes, corrosion and other defects in materials, but is only sensitive to severe defects [1]-[4] through which ultrasonic waves pass [1]-[2]. Therefore, linear ultrasonic testing may well fail to detect closed cracks [2]. Compared to linear ultrasonic testing, long-range and highly sensitive Lamb waves propagate over relatively long distances (a few meters in composites), enabling each ultrasonic pulse to inspect the entire field between the transmitter and receiver, in contrast to traditional step-by-step inspection techniques. The proposed technique will therefore rely on the integration of sensors capable of generating and detecting such waves within or on the surface of the structures to be tested. Such a system must be capable of automatically acquiring, storing and processing data.

The presence of a fault will be identified by observing changes in the signal response relative to a reference response recorded before the structure was damaged. Due to the curvature of a tubular structure, the wave properties are more complex than through a plate. Theoretical and numerical analyses of higher-order harmonic generation were conducted on non-linear waveguides of arbitrary cross-sections in weakly non-linear cylinders and plates with large-radius pipes. The simulation showed that cumulative second-harmonic generation with longitudinal, torsional or flexural mode excitation was also observed in pipes when two conditions, namely phase velocity matching and non-zero power flow, as in plates were satisfied. Furthermore, the method of simulating material non-linearity in plates can also be applied to pipes. Experiments concerning material non-linearities in pipes also confirmed the phenomenon of cumulative second-harmonic generation with longitudinal or circumferential wave excitation [4]-[19].

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In this context, the theory and interpretation of the temporal characteristics of Lamb wave signals are mainly based on linear elasticity, i.e. signal characteristics are extracted within the frequency band at which they are generated. In this sense, the temporal characteristics, e.g. the ToF (Timer Off) delay, exhibit to some extent a linear correlation as the material or structural parameters are altered due to damage. Therefore, they are referred to as the temporal features of linear Lamb waves in this study and the associated signal-processing steps are referred to as temporal feature processing. In particular, the ToF delay, one of the simplest but informative linear temporal features, has proven to be effective in locating gross damage, i.e. damage with characteristic dimensions comparable to the wavelength of the sound wave such as open cracks, through holes and voids [5].

2. Experimental study

2.1. Types of defects in pipelines

Regarding the different types of defects, the Pipeline Operators Forum (POF) has classified the different existing defects into various categories [20]. It should be noted that since ultrasonic testing cannot detect cracks that occur perpendicular to a section of pipe, these types of defects are have been disregarded. The following four families of defects are predominant and generally detected during inspections:

- delamination;
- corrosion;
- geometric defects (sinking and ovalization);
- metal loss (arc cutting, scratching, grinding, spalling).

In the vast majority of cases, these are natural defects, so their characteristics, that is, size, depth, shape, residual texture, etc., vary significantly. The most common forms of pipeline defects are shown in *Figures 1a-e*.

Corrosion is the most frequent initial cause of damage in hydrocarbon pipelines [21] in which the condition of the pipeline deteriorates over time via a singular degradation mechanism. Corrosion degradation can be evaluated in many ways (phenomenologically [22], by making random adjustments [23], using stochastic mechanisms [24], carrying out numerical simulations [25] or conducting empirical studies). Based on these degradation mechanisms, the challenge is to predict how the condition of the pipeline will change between inspections to anticipate any possible internal damage. Given the importance of the fluids transported, containment can result in human, environmental or economic losses. Several factors that have an impact on the evolution of corrosion must be considered, e.g. the temperature in its current state, the initiation of degradation and the chemical composition of the steel. Most publications dealing with ultrasonic scrapers have focused on concrete pipelines [26]. However, the nature of the defects sought in this application is also different as in this type of pipeline only large cracks are dangerous.

Figure 1: The studied types of pipeline defects

Finally, many publications have focused on the ultrasonic technology [27].

2.2. Principle modeling?

Leaks and ruptures in pipelines due to ageing and rapid deterioration cost millions of dollars per year, which underlines the necessity of continuous, automatic safety monitoring systems capable of rapidly detecting and warning of defects. Before a major catastrophe occurs, this article examines how sensor networks can detect these problems.

Ultrasonic guided waves (Lamb waves) can be employed to transmit energy along the length of the pipeline, making it possible for energy to be transferred wirelessly over a longer distance without being hindered by the electromagnetic shielding of the structure [28]. Research has shown that it is possible to detect defects over a large area using active detection devices for simultaneous actuation and detection.

Sensors can be mounted on the surface of the curved pipeline to generate and measure guided waves propagating along the curve [29]. Lamb waves follow the curvature of the structure and detect subsurface defects by measuring the structure on one side and allowing subsurface defects to be detected by measuring the inclination on that side.

2.3. NDT of cracked pipelines

Since the application of Lamb waves in the real world is extremely complex, numerical simulations are one of the best ways to understand their behavior and implementing the ABAQUS model is invaluable.

This simulation can yield the distribution of displacement and the displacement field, where (see *Figure 2*):

- Geometry: R_{in}=0.09mm; R_{ex}=0.10mm;
- Carbon/epoxy composite material.

3. Results and discussion

In this study, two models were used: the first without any

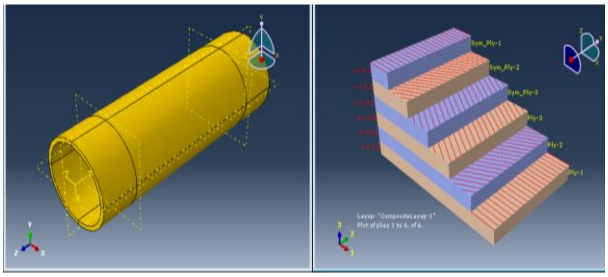


Figure 2: Composite Pipeline

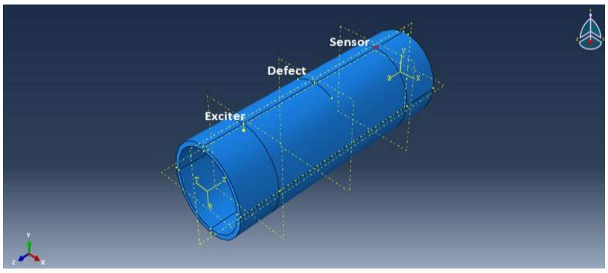


Figure 3: NDT of the pipeline

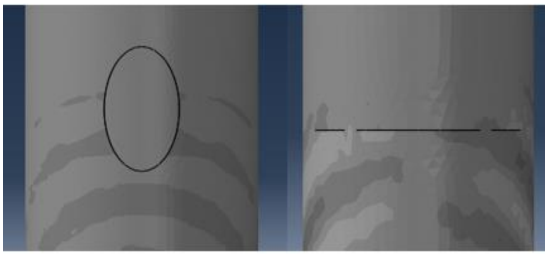


Figure 4: Crack formation

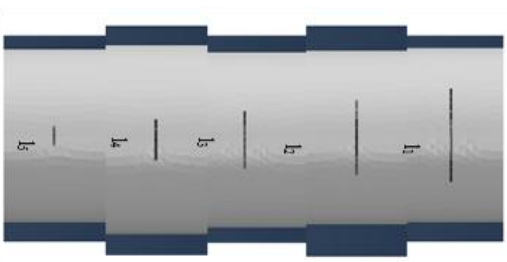
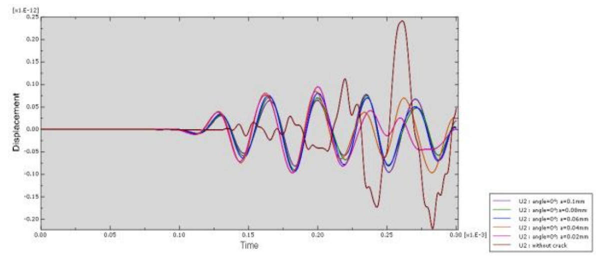


Figure 5: Crack size propagation

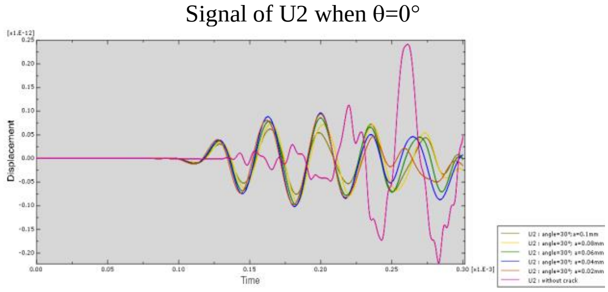
cracks and the second with. One sensor was created to check the data along the circumference of the model (see *Figure 3*). This figure also presents the form of the investigated crack. *Figure 4* shows that the crack size increases.

In the first part of our experiments, we investigated how response signal changes with crack size propagation. 5 sizes of cracks are considered in each model: $a1$=0.10 mm, $a2$=0.08 mm, $a3$=0.06 mm, $a4$=0.04 mm and $a5$=0.02 mm. In order to highlight the response behavior, the crack angle θ (orientation of the crack) was fixed and the crack size varied as described above as well as shown in *Figure 5*.

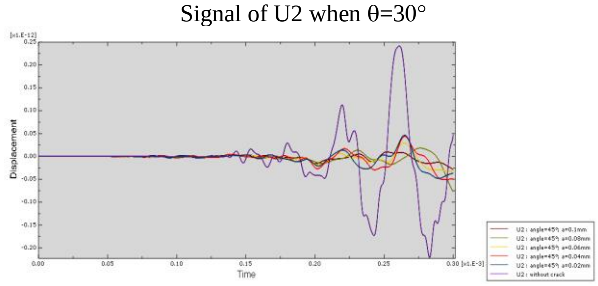
The response signals detected during NDT are presented in *Figure 6*. It was noted that when θ=0°, crack initiation causes the amplitude of the signal response to decrease. The same is true when θ=30°, *Figure 6* shows that the amplitude decreases as a function of the increase in crack size. When θ=45°, significant decreases in amplitude following crack initiation can be observed. In the case of θ=60, the difference between the signals responses is negligible. Logically, when θ=90°, the signals are identical, which is one of the limitations of the ultrasonic testing of perpendicular cracks.



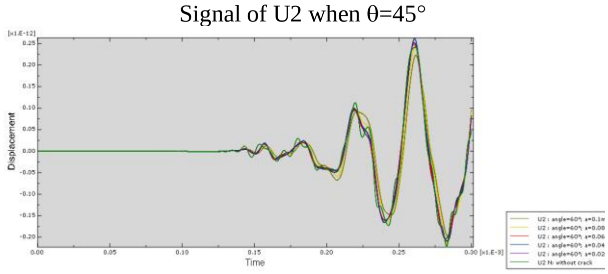
Signal of U2 when θ=0°



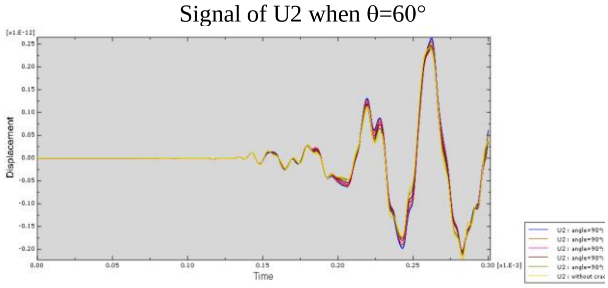
Signal of U2 when θ=30°



Signal of U2 when θ=45°



Signal of U2 when θ=60°



Signal of U2 when θ=90°

Figure 6: Response signals detected during NDT when measuring the crack orientation

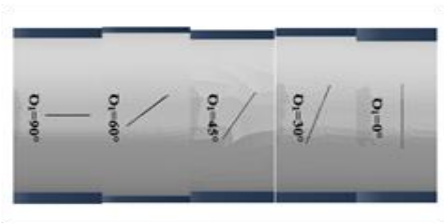


Figure 7: Crack propagation

In the second part of our study, with a fixed crack size, crack orientation was changed in each model as follows: θ=0°, θ=30°, θ=45°, θ=60° and θ=90° as shown in *Figure 7*.

The results obtained are given in *Figure 8* for each crack size studied. This field data shows the importance of global coordinates. Some positive and negative U2 signals at the excitation source can be seen because the global coordinate was located in the y-z plane.

It should be noted that the time that elapsed before the signal responses were received varies as a function of the angle of crack orientation.

For the purpose of an experimental comparison, the measurements were made in both damaged as well as undamaged areas on flat structures and pipelines. A reference signal was first obtained in the undamaged areas before being received in the damaged ones [28]-[33]

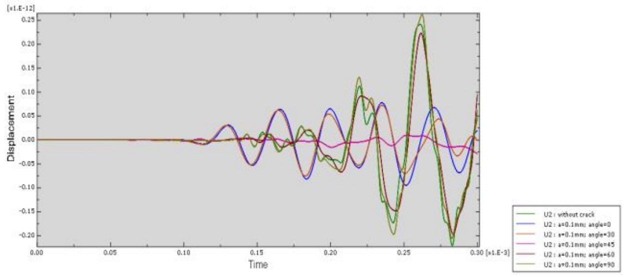
The two time signals were superimposed and when the two signals were compared, the signal from an area where a defect is present was amplified, resulting in a frequency shift between the two areas. The characteristics of the Lamb wave time signal were compared using a sensor when different defects were detected in an aluminium tube. Two damage indices were applied based on respective characteristics of Lamb waves.

4. Conclusions

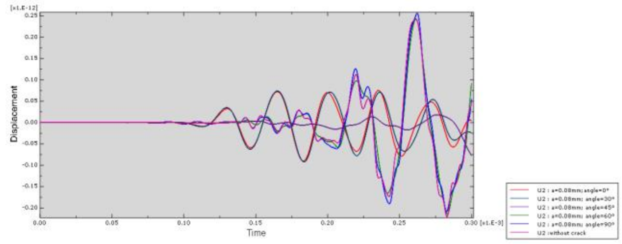
It can be concluded that this difference in amplitude is due to the absence of matter (a discontinuity) preventing a part of the waves from propagating through the pipeline walls, resulting in significant attenuation of the signal amplitude of the waves. This phenomenon is referred to as the scattering of Lamb waves. When θ=0°, crack initiation causes the amplitude of the signal response to attenuate.

When θ=30°, the amplitude decreases as the crack size increases. From the graph depicting θ=45°, a significant reduction in the amplitude is observed during crack initiation. However, when θ=60°, the difference between the signals responses is negligible.

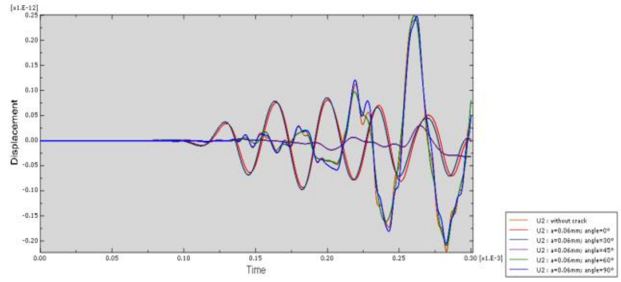
Logically, when θ=90°, the signals are identical. This phenomenon, known as perpendicular cracking, is one of the limitations of ultrasonic testing. The signal responses when no cracks are present and when θ=0º are identical. The time elapsed before signal responses are received varies as a function of the angle of crack orientation. Finally, the shapes of all these signal responses can be used to identify the depth, length, shape and orientation of cracks.



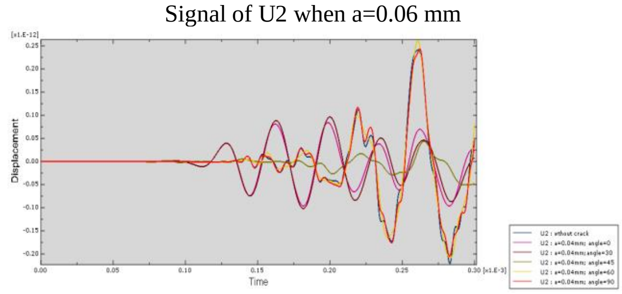
Signal of U2 when a=0.10 mm



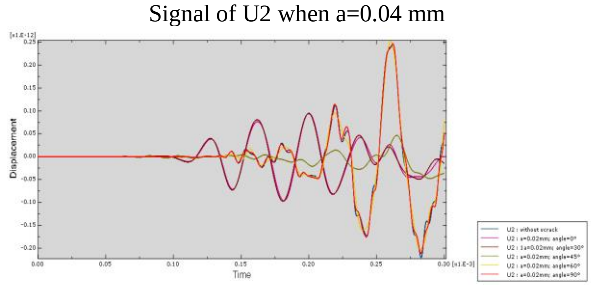
Signal of U2 when a=0.08 mm



Signal of U2 when a=0.06 mm



Signal of U2 when a=0.04 mm



Signal of U2 when a=0.02 mm

Figure 8: Response signals detected during NDT when measuring the size of the cracks

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