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INVESTIGATIONS OF MECHANICAL GUIDED WAVES PROPAGATION IN PIPES REPAIRED LOCALLY BY COMPOSITE PATCHES

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Abstract. *Mechanical guided waves are frequently used to non-destructively test and/or monitor large structures, such pipes. These pipes, which are used to transport fluids, are vulnerable to structure defects, such as corrosion and crack. For mainly economic concerns (save time and cost), the areas where defects had occurred are sometimes repaired. The material used for reparation is often composites, which cause a hug attenuation of guided waves. This attenuation can limit drastically the distance of inspection (i. e. the distance between the transducer and the smallest detectable defect). The current work aims to investigate numerically, through finite element method, the influence of composite reparations on guided waves propagation. Various parameters such as the shape of the reparation and the operating frequency are studied. The final purpose of this work is to propose some recommendations on guided waves setup to ensure an efficient use of this nondestructive testing technique.*

1 INTRODUCTION

The need to pipelines for transporting liquids, gases and any chemically stable substance is in continuous increase [1]. The material of most pipelines is Carbone steel. Due to its cost, this material is preferred to stainless steel. However, it is much more vulnerable to corrosions. In order to save maintenance cost and avoid interrupting production, composite repair (see an example given in Figure 1) is used to reinforce the strength of the segments of pipes where corrosions had occurred. Using composite repair, in lieu of replacing pipes or at least the damaged areas especially when a leak is assessed to be imminent, can yield significant economic and environmental benefits [2]. Note that the panel of defect types is large and includes internal and external corrosion, external damage such as dents, gouges, and cracks, as well as manufacturing defects. The problem is that these defects continue to progress even after reparation, but maybe with lower velocities. Assessment of the evolution of the said defects is not a straightforward item since it depends of various factors such as geometry and material characteristics of the repair, the tube as well as the transported fluid, the environmental and operational conditions. Consequently, the remaining lifetime is unpredictable and so, non-destructive testing techniques, which should be adequate with this kind of structures, are needed.

Figure 1 : Photography of a composite pipe repair example

Ultrasonic guided waves (UGW) technique seems to be a good candidate to reach this aim (*i. e.* testing periodically this type of structure). Indeed, UGW technique well-adapted for tubular and large structures [3], and showed its efficiency in detecting defects especially in bare pipes. The application of UGW technique on composite repaired pipe segments should however not be trivial because the propagation of these waves is closely linked to the characteristics of the surrounding medium, more particularly the damping. The aim of the project, from which the current study is extracted, aimed to study the feasibility of the monitoring of the said structure. In other words, is UGW technique able to follow the evolution of the “repaired” defect? If a new defect occurs after reparation, is UGW able to detect it?

The problem of attenuation is accentuated by the lack of other required information such as thickness, composite modulus, filler materials, fiber orientation, shape of the repair, etc. The aim of this paper is to investigate numerically the influence of the main parameters which are the material of the repair, its shape and the frequency of excitation.

The paper consists of 3 sections except the first one which is the introduction. Section two concerns the models built in this study. Section three is devoted to present the main obtained results and their discussions. The last section deals with the conclusions gained from this work.

2 MODELS CONSTRUCTION, AND PROBLEM STATEMENT

2.1 Model setting

One among softwares which are available in our laboratory, and which permits to simulate complex configurations is Comsol Multiphysics [4], which is based on Finite Element Method. This software allows simulating wave's propagation in:

- two dimensions structures (2D) in Cartesian coordinates,
- axisymmetric structures (which is 2D, but in cylindrical coordinate), and
- three dimensions structures (3D)

In all cases, simulations can be carried out in:

- frequency domain, or
- time domain

A post-processing, based mainly on Fourier Transform, is then used to analyse results in the suited domain. There is always preference for 3D simulations for its advantage to mimic the true-life phenomenon. However, the models size is too big, which needs high memory calculators, and the computing time is large. 2D models (whatever in Cartesian of Cylindrical coordinates) are preferred, when it is possible, to overcome this problem. In the present case, 2D calculation permits obtaining quick access to representative results, as well as the ability to run high exciting frequency cases (i. e. small mesh size).

In the present study,

- the piping element possesses an axisymmetric geometry,
- homogeneous material
- the sensor (to receive waves) is axisymmetric, and
- the actuator (to generate waves) is axisymmetric.

Hence, the modelling can be performed in 2D axisymmetric medium. However, we cannot use 2D axisymmetric model by exciting the displacement of T(0,1) mode, which is u_θ-displacement component (the radial and axial displacement are null). The 2D axisymmetric dimension is defined by these displacements.

The solution is to build 2D model combined with unique variable wave equation (similar to the case of wave propagation in liquid, where the acoustic pressure p is the only variable). The plane of propagation is x-y plane, while the only displacement component has distribution dependent on x and y, but supposed uniform along z. Besides, the material properties linked to the shear SH wave (T(0,1) mode in circular tubular structures) should also be carefully set, especially those of anisotropic materials (as different elastic matrix component should be taken into account for wave propagating in different directions). For this reason, the detailed wave equation should be developed to check which parameters should be set to study the influence from composite repair.

2.2 Equations formulation

Based on the Hooke's law which can be described by:

$$\sigma_{kl} = C_{ijkl} e_{ij} \quad (1)$$

Associated with the law of conservation of momentum, the general wave equation is written as below:

$$\rho \frac{\partial^2 u_i}{\partial t^2} - c_{ijkl} \frac{\partial^2 u_l}{\partial x_j \partial x_k} = f_i \quad (2)$$

So for x-y plane SH wave (with z-displacement component) propagating, the wave equation concerning z displacement component is:

$$\rho \frac{\partial^2 u_z}{\partial t^2} - \left(\frac{\partial \sigma_{zz}}{\partial z} + \frac{\partial \sigma_{xz}}{\partial x} + \frac{\partial \sigma_{yz}}{\partial y} \right) = f_z \qquad (3)$$

As it is assumed that it is uniform along z direction, so $\frac{\partial \sigma_{zz}}{\partial z} = 0$, the equation can be simplified as:

$$\rho \frac{\partial^2 u_z}{\partial t^2} - \left(\frac{\partial \sigma_{xz}}{\partial x} + \frac{\partial \sigma_{yz}}{\partial y} \right) = f_z \qquad (4)$$

The nonzero stress components σ_{xz} and σ_{yz} can be calculated with the Hooke's law, associated with material anisotropy. It can be simplified as following:

$$\begin{pmatrix} \sigma_{yz} \\ \sigma_{xz} \end{pmatrix} = \begin{pmatrix} C_{44} & \\ & C_{55} \end{pmatrix} \begin{pmatrix} e_{yz} \\ e_{xz} \end{pmatrix} \qquad (5)$$

So the final wave equation is written as:

$$\rho \frac{\partial^2 u_z}{\partial t^2} - \frac{1}{2} \left(C_{44} \frac{\partial^2 u_z}{\partial y^2} + C_{55} \frac{\partial^2 u_z}{\partial x^2} \right) = f_z \qquad (6)$$

C_{44} et C_{55} describe the materials to used hereafter.

2.3 Results extraction

We choose to show, as results, the circumferential displacement u_θ and its spatial waveform at different frequencies. The former gives an immediate idea about the distribution of the displacement through the thickness of the pipe as well as the repair. It is a fictitious C-Scan in the axial (z) – radial (r) plan. It is an easy way to show qualitatively the influence of the repair on wave's propagation. The spatial waveforms are however collected in the outer lateral surface to show clearly the u_θ displacement amplitude, as shown by Figure 2. Both representations are complementary. Reflection coefficient will also be plotted.

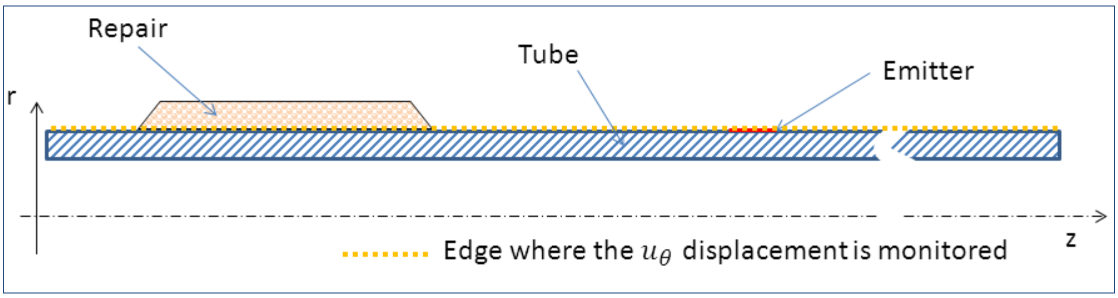

Figure 2 : A not scaled schematic showing the area where the shear displacement u_θ is monitored (along the tube including the repair/tube interface)

3 RESULTS AND DISCUSSIONS

3.1 Displacement monitoring

The first model was a bare pipe. This model simulates also a limit case of pipe with repair (thickness = 0). The analysis of this case will be revisited afterwards, but for the moment it serves to validate the calculations.

After validating the model, we focus now on the investigation of the T(0,1) mode propagation in repaired pipe. As explained previously the shape of the repair is trapezoidal. To understand better the effects of this repair on T(0,1), and be able to analyse properly the obtained results, we add in first step a steel repair. Note that in this case, we make only one change, which is the geometry of the waveguide. The main results are given by Figure 3 and Figure 4.

For the ease of the reader, we recalled the drawing of the repaired tube, as it can be seen in Figure 4. The monitored displacement contains 7 regions, which correspond to:

- (1) ➔ Set of absorbing region, near field and reflected waves by the repair. By comparison with the case of the bare pipe, which can be token as benchmark (not shown here for the sake of brevity), we can see that:
    - o the amplitude is slightly different,
    - o the amplitude of the reflected signal is not proportional to the other zones, where the displacement amplitude decreases with frequency,
    - ⇨ This confirms that the current repair caused a reflection but it is not too big. Note that reflection coefficient depends at least of:
        - ▪ Acoustic impedance of the reflector with regard to that of the main waveguide (tube wall in our case), and
        - ▪ Reflector shape.

    In the current case, the acoustic impedance doesn't have any impact, since the repair has the same material as the pipe. So, the reflection should be driven only by the shape, and more particularly by the angle of this conical form ($\emptyset$ in Figure 3). To verify this ascertainment, we studied the case where the repair is rectangular ($\emptyset = 90°$). The correspondent result is not shown here, for the sake of brevity. As it can be seen effortlessly, the reflection coefficient is too big, as what is expected. The other extreme case is where $\emptyset = 0°$, which corresponds naturally to a bare pipe.

- (2) ➔ zone of the pipe just before the repair. The displacement amplitude is constant in whole this zone. Waves reflection is too weak as explained before, otherwise this amplitude should be bigger,
- (3), (4), and (5) ➔ displacement amplitude at the repaired region. They are lower in these zones. However, the transmitted wave amplitude remains almost the same as the incident one. In this case, a little energy was reflected.
  The phenomenon of the decrease of the amplitude at these zones can be explained by the energy flow density (or Poynting Vector). Indeed, the same energy flow density travel in the waveguide (pipe + repair). When the surface increases, the flow decreases.
- (6) ➔ zone of the pipe just after the repair and just before zone (7). Amplitude displacements are constant along this zone, and approximately equal to that of zone (2). This is normal because:
    - o waves reflection is quasi-absent, and
    - o The medium is non-absorbing.

- (7) ➔ absorbing region

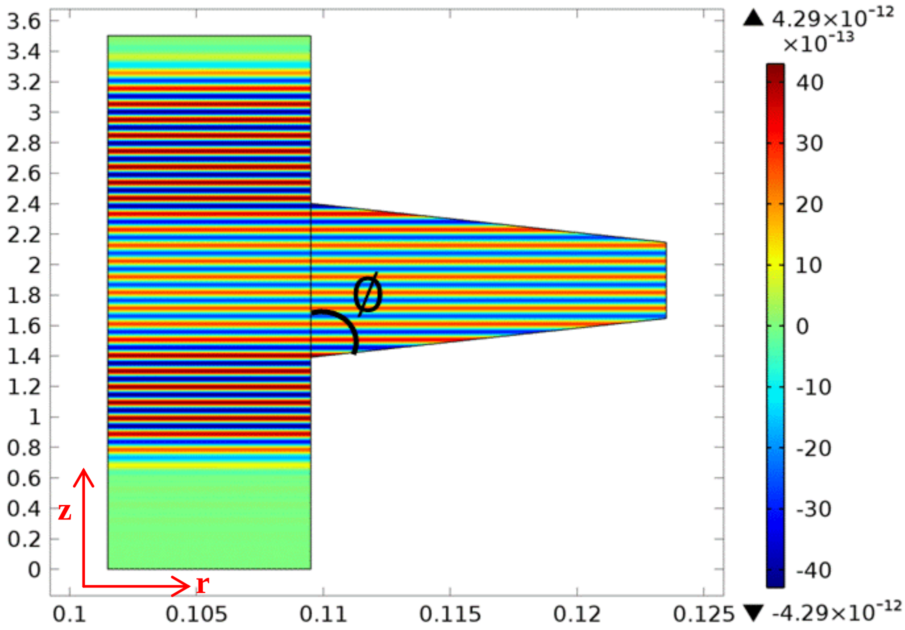

Figure 3 : distribution of u_θ-displacement, at frequency of excitation = 30 kHz, not-scaled figure.

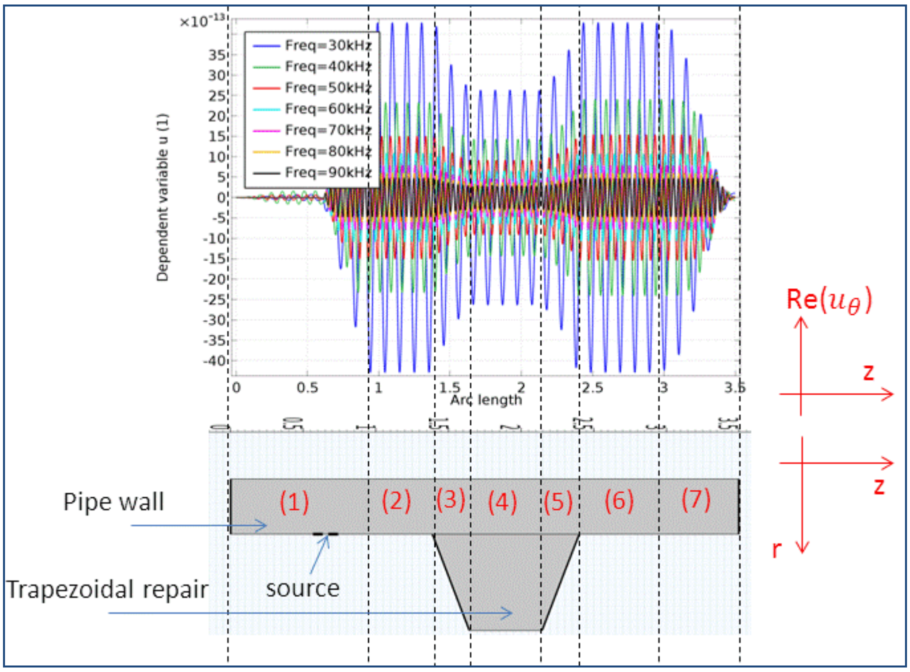

Figure 4 : u_θ-displacement monitored at outer surface of the pipe, for different frequencies (top), and drawing of the repaired pipe (bottom).

Up to this stage of the numerical calculations, the cases studied are: bare pipe and pipe with rectangular and trapezoidal repair shapes. Both the pipes and the repair were steel. From numerical simulation point of view, the material is not absorbing. So, if there is any attenuation, it should be linked to reflection. Hence, and as it was remarked, the waves reflection by the trapezoidal are too weak in front of that caused by the rectangular repair. This was ex-

plained by the repair shape, which is gradually increased in one case (trapezoidal shape) and sudden in the other one (rectangular shape).
Once these studied are achieved, we spent to investigate the case of viscoelastic composite repair. The pipe wall covered by a composite repair will make a bilayer structure. So the relative wave properties will be changed, such as dispersion and attenuation. Concerning the dispersion properties, what will be taken into account are:

- o Cut-off frequency for higher order mode
- o Mode shape affecting the displacement distribution through thickness (of detected signal)

While the attenuation is mainly linked to the viscosity of the composite material, especially the resin of the fibre reinforced material. The viscosity can be pretty low or extreme high.
To understand the influence of the material on T(0,1) waves propagation, and achieve a more reliable analysis, the investigation will be performed in two steps:

i. pure elastic material, that means non-absorbing material but different from steel. It is the lower limit of damping (viscosity component = 0),
ii. viscoelastic material ➔ absorbing material. The damping is supposed equal *0.15 * 408MPa*, which represents high viscosity.

For the sake of brevity, the obtained results are not shown in the current paper. In the displacement distribution, the maximal amplitude in the elastic case is around 5 times that in the viscoelastic case. This argues the expected influence of the viscoelastic material.

3.2 Reflection coefficient

The final results are gathered in Figure 5. These results confirm what it was already concluded previously. As it can be seen:

- reflections are small in the case of:
  - o steel repair with gradually increasing thickness (trapezoidal shape), as well as
  - o trapezoidal high damping composite repair, while
- reflections are large where:
  - o the composite repair is purely elastic, even with trapezoidal shape
  - o and rectangular steel repair,

In all cases, reflections vary greatly with the exciting frequency. It can be easily remarked where they have large coefficient.

In conclusion, reflections depend on:

- o material of the repair,
- o shape of the repair,
- o excitation time frequency.

4 CONCLUSIONS

A numerical study was performed in healthy waveguide (i. e. without any defect). The aim was to investigate the T(0,1) wave mode in a steel pipe coated locally by a composite repair. Due to lack of some characteristics of this material, which were needed as input of the built models, some assumptions were considered:

i. pure elastic repair : this is the lower limit of damping,
ii. viscoelastic repair with high damping.
iii. for both cases (i and ii), the density was token, basing on the literature, the density was token (1000 kg/m3). However, this value depends critically on fiber/matrix ratio, and fiber and matrix types.

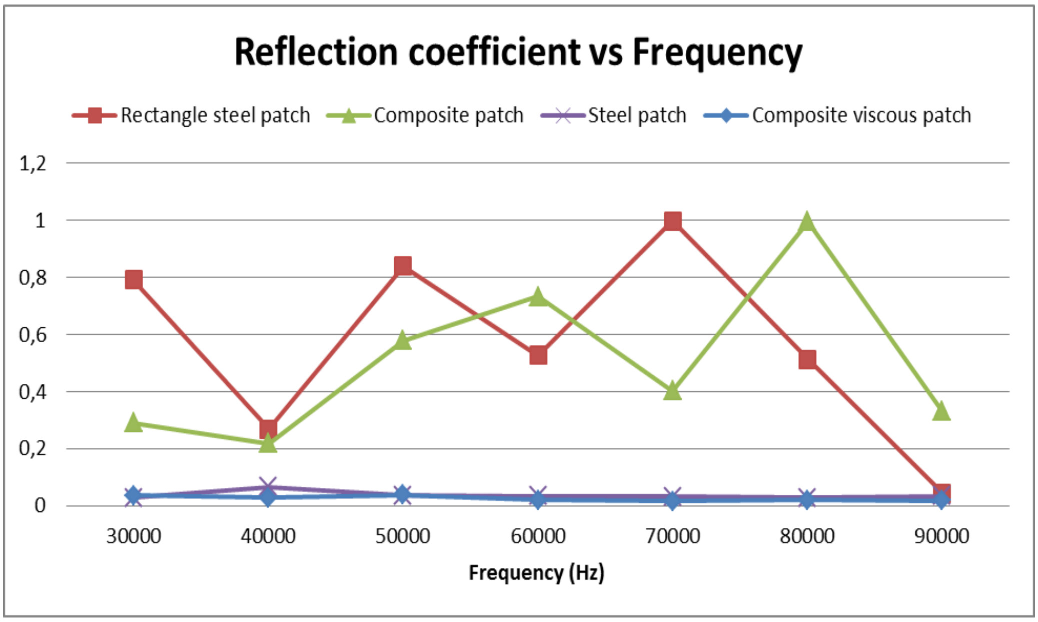

Figure 5 : Reflection coefficient versus frequency for different studied cases : rectangular steel repair, trapezoidal pure elastic repair, trapezoidal steel repair, and trapezoidal high viscoelastic repair.

The repair material, used in this current study, should be between that described in case (i) and in case (ii).
To help verify the results, additional models were built and run:

- Bare pipe
- Pipe with trapezoidal steel repair
- Pipe with steel repair in rectangular form

The main conclusions were found concerning the reflection coefficients based on different models:

- For pipe with pure elastic composite repair (case i), the reflection coefficient may be big as 1 at some exciting frequencies,
- For pipe with high viscoelastic composite repair (case ii), there is few reflections.

The results cited from literature [] are consistent with our results. Note that parameters of this study are different from ours, such as:

- dimensions and the material of the pipe, and
- dimensions, material and shape of the composite repair.

Even both studies are achieved with different parameters, the main conclusion is unique and common: reflections (and consequently transmitted waves) depend considerably and non-linearly (as one can think) of the frequency. Reflection coefficient versus the frequency consists of alternating bands: pass-band where the reflected waves are weak and forbidden-band where they are large. Attention should be paid to this point, since it impacts the attenuation and so, the sensitivity. For future study, it is necessary to have more information about the material properties (elastic or viscoelastic), to perform simulation in smaller frequency step if need.

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