ULTRASONIC GUIDED WAVE INSPECTION IN RIGID RISER

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Abstract. *The main objective of this article is to evaluate the potential of guided waves technique in rigid risers, production ducts used in the oil and gas industry. Experimental tests were conducted on a sample of these pipes, 2,10m long rigid riser specimen with 169,5mm external diameter, simulating its operational environment. Although this work is directed to the oil industry, results can be considered in maintenance efforts to other industries. Experimental tests consisted on create guided wave modes traveling at the sample riser in a pulse-echo configuration using a 0,5MHz ultrasonic transducer and a 70^o acrylic wedge . Two different inspection situations were simulated by varying the internal presence of oil and external presence of water. A defect was implanted and the procedures were repeated in order to evaluate its detection capacity under those situations. Results proved the crucial influence of the watery presence outside the pipe and its dependence with the internal condition (with or without oil). The way the defect reflected the energy conducted by the guided wave modes varied and, therefore, its detection became different under those two procedures.*

Keywords*: guided waves, rigid risers, guided wave modes, maintenance*

1. Introduction

Currently, one of the most important concerns of the Oil and Gas Industry is the preventive maintenance diminish the probability of failure of its installations. As the Industry operates hundreds of kilometers of pipelines, it is necessary to develop an inspection methodology that could reduce maintenance costs and improve the efficiency of discontinuities classification, detection and measurement.

Risers and flowlines have a crucial function due to either economic and environmental impacts associated to their operation. Hence, it is important to detect and control critical discontinuities that could eventually lead to their failure in a quick, reliable and less expensive way, allowing longer and safer operation.

Some of the main benefits the utilization of guided waves in NDT can bring to the industry are (Siqueira, 2002 and Rose, 2002):

- Testing over long distance ranges from a single probe position;
- Excellent discontinuity detection potencial by the tunning of the inspection variables like frequency or incident angle;
- Often greater sensibility than other NDT techniques;
- Ability to test difficult access areas;
- Direct detection and screening of the defect, leading to easier and quick repair.

The ultrasonic inspection by the guided waves technique does not require a point-by-point inspection, which is the main principle of traditional technique, avoiding some problems like accessibility, surface non-homogeneity and long inspection times. (Moon Ho Park *et al.*, 1995 and Siqueira, 2002).

This work aims to evaluate the capability of the guided waves technique on the detection of relatively small flaws (superficial or internal) in risers under an operational-like environment. It is also attempted to identify the modes detected at the different inspection scenarios. The influence of the internal and external fluids are studied as the investigation looks for a better understanding of the inspection limitations and benefits for a future field test.

2. Theory Review: Ultrasonics, Lamb Waves and Dispersion Curves

The mechanical vibrations necessary to carry the ultrasonic non-destructive testing are generated by electromechanical transducers, devices endowed with piezoelectric elements. Electromagnetic acoustic transducers (EMAT) lately have been given many scientific attention and practical applications. In solids, these waves can travel in many particular forms recognized by the relationship between the oscillatory motion atoms acquire and their propagation direction (Siqueira, 2002).

As the complexity of the vibrational displacement and propagation increases, other ultrasonic wave modes are observed and two other types can be distinguished between them:

- Surface waves;
- Lamb waves.

These are also called guided waves because they can propagate along the media. This property is exemplified in Figure 1, where only the surface waves (not studied in this paper) are illustrated. Therefore, the utilization of these waves on a material inspection can potencially detect a flaw in places far away from the sound incidence line.[13]

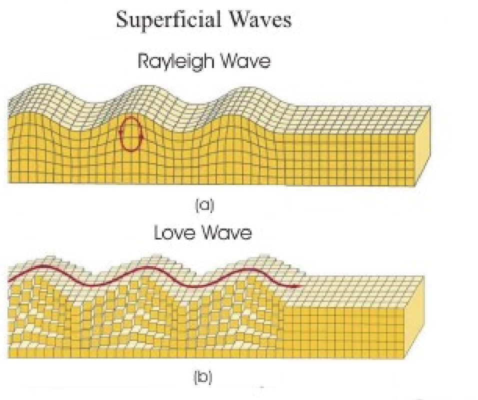


Figure 1. Superficial wave examples: (a) Rayleigh wave and (b) Love wave.

2.1. Lamb Waves

Lamb waves are typically induced by oblique incidence of ultrasonic waves generated by common piezoelectric transducers or by EMATs with wavelengths corresponding to approximately the third part of the structure thickness, as shown in Figure 2 (Siqueira *et al.*, 2004). They are directly linked to the natural resonance modes of the structure and their guided propagation depends on the structure geometry (Meeker and Meetzler, 1972 and Pavlovic and Lowe, 2001).

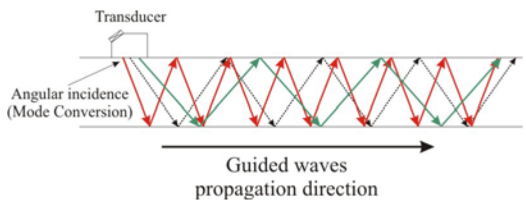


Figure 2. Generation of guided waves by angular incidence of ultrasonic waves.

There is close relationship between the generation of guided waves in a structure and the phenomena of refraction and reflection of acoustic waves, as illustrated in Figure 2. The incident ultrasonic beam is refracted on the structure surfaces and propagates at a new angle (governed by the Snell's law). After that there is a region where intense interference takes place caused by consecutive reflections of the beam between the two surfaces (Rose, 1995). Therefore, packets of travelling energy along the structure are created when majority constructive interference (in relation with destructive interference) takes place inside the media thus generating guided waves (Kenneth and Rose, 2003).

The main characteristics of the guided waves are determined by the media density, elastic properties (Young modulus, Shear modulus and Poisson's ratio), geometry parameters, transducer frequency band and incident angle (Rose, 2002).

The complete behavior of travelling guided waves in a structure is obtained by numerical or analytical solution of the partial diferential equation that rules the propagation of acoustic waves inside a medium. The result brings to the conclusion that infinite guided wave modes can be generated depending of the variables chosen, specially transducer frequency and structure thickness (Victorov, 1967).

When the propagation media has a plate geometry, it´s well known that two forms of propagation can be presented. As illustrated in Figure 3, they are defined by the symmetry between the motion of the particles:

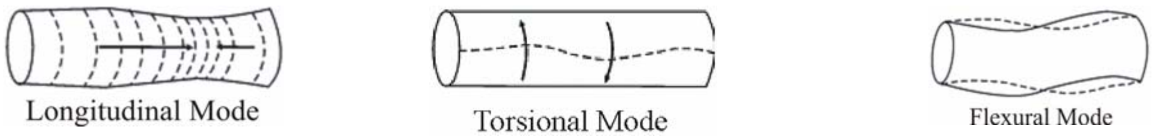
- Symmetric waves;
- Assymmetric waves.

(a) (b)

Figure 3. Guided wave modes in plates

This behavior can be quite different when the waves travel in media with different geometries. For the cylindrical geometry, there can be induced guided wave modes with three different propagation displacements, as illustrated in Figure 4. They are:

- Longitudinal Modes, or L modes;
- Torsional Modes, or T modes;
- Flexural Modes, or F modes.



(a) (b) (c)

Figure 4. Guided wave modes in pipes.

Each mode is labeled with an indicial nomination in the *N(n,m)* form, in accordance with Lowe, Alleyne and Cawley[3], where *N* represents the letters L, T or F. The first index *n* consists of the number of complete wave cycles along the circumferential direction, or the u_θ magnitude of displacement. That is, n equals 0 if there is no θ displacement, n equals 1 if the displacement along this direction corresponds to a complete first harmonic vibration (or just one point where u_θ equals zero at the circumference) and so on. The index *m* represents the order of the mode, so the first longitudinal mode with a *n* equals to 0 is L(0,1), the second is L(0,2) and so on (Lowe *et al.*, 1998).

The first index is dependent of the excitation type used to produce the guided waves. If the excitation is done with equally spaced transducers, in a quantity higher than the highest order of modes that can be present, than only symmetric modes (*n* index equals zero) are excited. This selectivity has an outstanding influence in the characteristics of the signals acquired and shows great efficiency on detecting different types of defect (Lowe *et al.*, 1998).

The main properties of the guided waves, evidencing this work, are the phase velocities, group velocities and incident angle of the ultrasonic excitation. All three, together with propagation characteristics, vary with the frequency and the thickness of the material in a behavior called *dispersion*. All ultrasonic probes do not produce a single frequency wave but a wave with a range of frequencies (Siqueira, 2002 and Lowe *et al.*, 1998). Hence, it is important that modes with low dispersion (short velocity variation along the propagation frequency) are used in non-destructive tests (Siqueira *et al.*, 2004 and Rose, 2003).

Complete analysis of guided waves traveling along a system is obtained through by tracing graphics that relate these essencial properties to the propagation frequency of the waves. This is reached according to the mathematical results mentioned prior in this section. The program DISPERSE, developed at Imperial College, was used to trace the dispersion curves for the systems tested in this work (Pavlovic and Lowe, 2001).

Physically, the different fluids change the amount of energy transferred at the contact interfaces. This phenomenon of energy leakage takes place by radiation of longitudinal guided waves that propagates on or with the pipe surface when the phase velocity of the longitudinal waves generated in the fluid is less than the guided wave in the pipe (Rose, 2003).

3. Experimental Procedures

The experimental tests were conducted on a steel pipe. The ends were sealed by welded steel plates. All the experimental tests were carried out with the pipe in the vertical position. The dimensions of the pipe are listed in Tab. 1.

Table 1. Rigid riser dimensions

External Diameter	Thickness	Length
169,5 mm	11,7 mm	2100 mm

The experiments comprised four different procedures on both intact pipe and pipe with machined defect, as indicated in Table 2.

Table 2. Experiment procedures

Stage	Id.	Description
1	A	Inspection of the rigid pipe without internal fluid and no defect.
	B	Inspection of the rigid pipe containing oil and no defect.
2	C	Inspection on the rigid pipe without fluid and a superficial defect.
	D	Inspection on the rigid riser containing both oil and superficial defect.

The pipe were inspected in a 1,5m depth water tank. The ultrasonic pulse generator/receiver was connected on the emerged pipe region.

Aiming at observations on the influence of the water depth on the attenuation of the guided waves and the defect detection probability with respect to the pipe total length, every procedure was followed by signal records corresponding to external depth changes of 10cm each.

3.1. Integrity Condition

The integrity risk simulation of the pipe (critical situation that has to be detected by the inspection) was machining a superficial defect at mid length.

The defect depth of 40% the pipes nominal thickness and approximately 2mm wide.

3.2. Experimental Aparatus and Signal Processment

The ultrasonic equipment used was a ECOGRAPH 1024 model from *KARL DEUTSCH*, connected by a coaxial cable with LEMON type ends to a 500KHz normal transducer model B0,5SL manufactured by *KRAUTKRAMMER*. The angular incidence was made by connecting the transducer to a 70^o acrylic wedge.

The signals were digitalized at an oscilloscope *TDS420A* from *TEKTRONIX* and then saved on a diskette for post processing. All signals were Normalized and the DC was reduced.

No signal/noise reduction process was utilized in order to maintain the signal form and test the real capability to immediately find any defects in the pipe just by observing the ultrasonic spectrum changes.

4. Experimental Results and Discussion

4.1. Dispersion Curves Investigation

The usual procedure to conduct the guided wave inspection consists of identifying the best wave that can be used to detect the defects first, to then arrange and set the experimental apparatus to practice the test, as done for exemple by Lowe, Alleyene and Cawley[3]. Differently, this work first analyses the dispersion curves, identifying the detectable guided waves, and then the practical results are compared.

High angles of ultrasonic incidence typically brings the best results as concluded by Siqueira, Gatts, Silva *et al*[15]. Therefore, experiments with different incident angles is not conducted.

The different inspected systems were simulated by the DISPERSE program and the dispersion curves were traced. Unfortunately, it is not possible to simulate different levels of external surrounding fluid (just full of external water or empty) and the presence of discontinuities in the structure, so the dispersion curves analyzed were only related to 4 distinct situations where the pipe does not have any defect. These are designated as procedures A and B, with and without external fluids each.

In Fig. 5, the graphics for phase velocities versus frequency are illustrated and the Fig. 6 relates the graphics for incident angle versus frequency. It is clear that the internal presence of oil makes a complete confusion on both the dispersion curves showed for procedure B. In Fig. 6, graphics 6.c and 6.d are approximated at the area of interest, so that only the detectable modes could be obtained.

It can be seen in Fig. 5 that for situations A and B, just a few modes have low dispersion. Again, the high angle of incidence chosen filters the high dispersive modes and the modes related on Tab. 3 are the ones with lowest dispersion among those that can be generated with a 0,5MHz transducer.

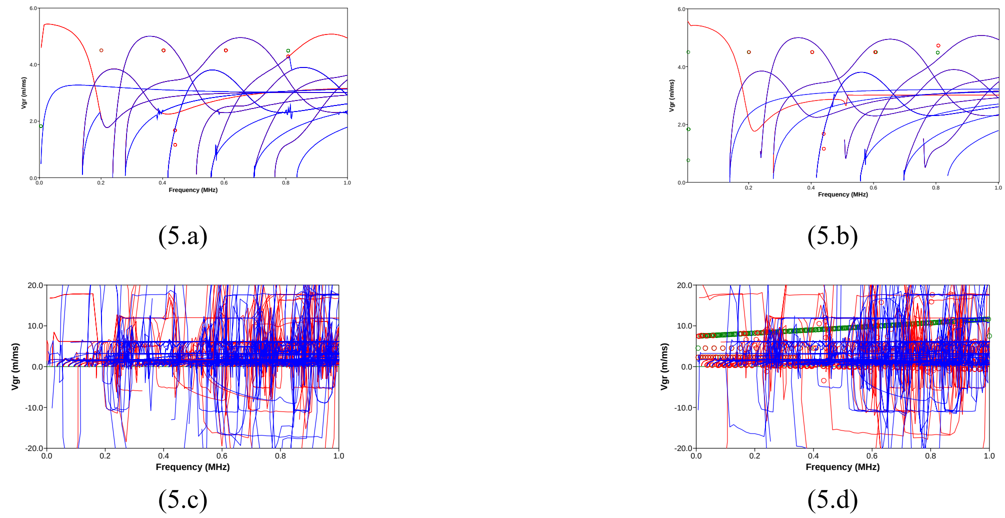


Figure 5. Frequency x group velocity for: (5.a) procedure A without external fluid, (5.b) with external fluid, (5.c) procedure B without external fluid and (5.d) with external fluid.

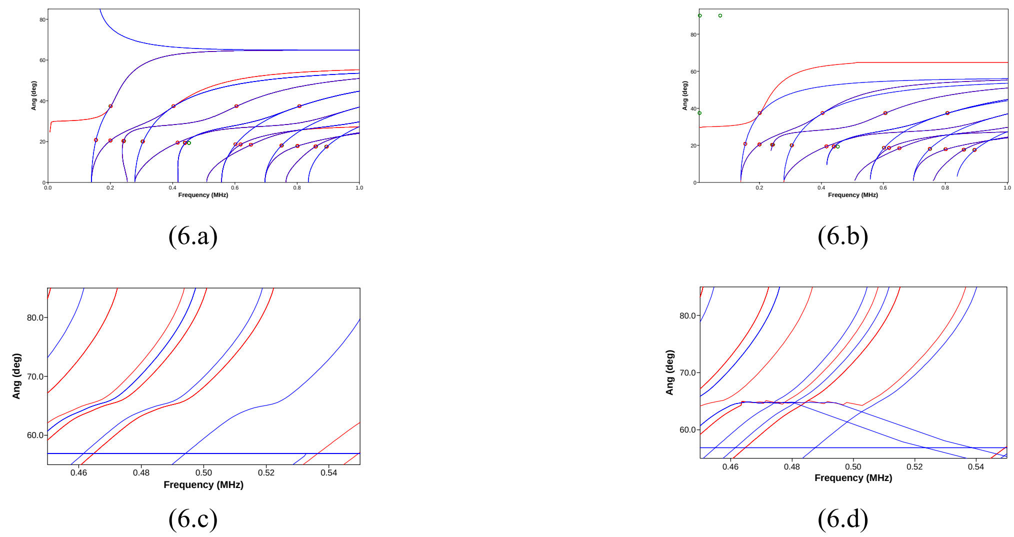


Figure 6. Frequency x incident angle for: (6.a) procedure A without external fluid, (6.b) with external fluid, (6.c) procedure B without external fluid and (6.d) with external fluid.

Table. 4 Related guided wave modes with possible detection at the experimental inspections. They were identified by the dispersion curves analysis. 1 indicates no external water and 2 indicates presence of external water.

Situation	Guided Wave Modes	Velocities (*Km/s*)
A1	F(1,1)	3,071
	F(1,2);L(0,1)	2,932
A2	L(0,1)	2,822
B1	F(1,25);L(0,46);L(0,47);F(1,47)	-
B2	F(1,45);L(0,45);L(0,46);L(0,47)F(1,47);L(0,44);F(1,55)	-

4.2. Inspection Results

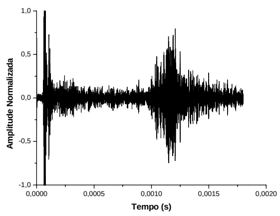
The inspection procedures were conducted at the riser under different scenarios shown in Tab. 2. Only the most relevant signals are presented as the great majority show the same appearance.

4.2.1. Pipe Without Defect in Air

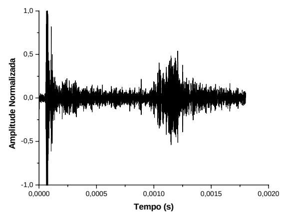
Fig. 7 relates the signals obtained for water depths up to 30,00cm, where total attenuation was observated and the signal remained with the same form until the total filling of the tank. This evidences great attenuation. The graphic shown on Fig. 8 relates the water depth with the highest amplitude of the echo generated by the guided wave. The echo represents a great energy packet traveling along the pipe and it is received by the ultrasonic pulser between the time interval from $10x10^{-4}$ s to $13{,}6x10^{-4}$s. This represents a wave group velocity of, approximately, 3,08*Km/s*, what shows great equivalence with the velocities obtained in the dispersion analysis, specially for the F(1,1) mode.

It would be very difficult to detect good separation between the predicted F(1,1) and F(1,2)/L(0,1) modes for this inspection because of their almost equal group velocities. The L(0,1) mode is a fundamental longitudinal mode and has a low wavelength (directly linked with phase velocity). Therefore, as only one transducer was used, good excitation of the L(0,1) mode was securely done. Higher excitation energies are usually required to excite modes F(1,1) and F(1,2) but, although phase velocity dispersion curves have not been analyzed, it can be said that they were generated by the high energy packet observed in the signal received.

The last situation of this inspection procedure is related to the situation A of the dispersion curves analysis with external fluid, but no results can be found because of the total attenuation provoked by the surrounding water medium.



(7.a)



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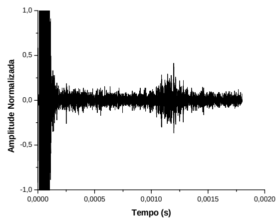
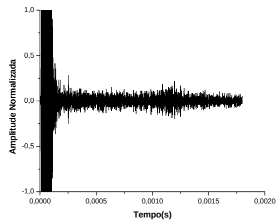


(7.c)



(7.d)

Figure 7. Signals for stage 1 procedure A for (7.a) 0,0cm, (7.b) 10,0cm, (7.c) 0,20cm and (7.d) 0,30cm external water.

4.2.2. Pipe in Air Without Defect and Containing Oil

This procedure showed waves with no attenuation along the water depth variation. It means that the oil reduces the leakage of energy through the internal interface. This observation indicates that the presence of oil can be helpful at the inspection results when inspecting a defective pipe.

The echoes in Fig. 8 represent guided waves with 15,6*Km/s* and 8,8*Km/s*. Certainly they refer to the same mode, because the velocity of the first one is two times the velocity of the second one. Its not possible to securely determinate the mode that these echoes represent because it was not possible to determine the group velocities of situation B with and without external water, on section 4.1.

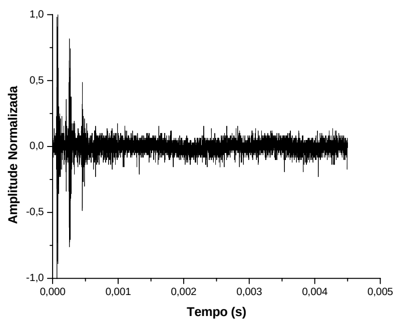


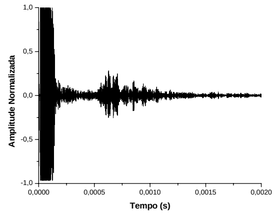
Figure 8. Signal acquired in stage 1 procedure B.

4.2.3. Pipe in Air With Defect

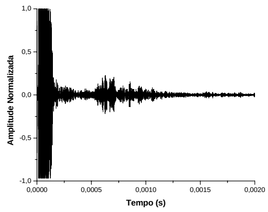
The defect was inserted at the mid section and then measured with the ultrasonic signals acquired from the inspection. Fig. 9 shows the ultrasonic signals acquired. The first one (Fig. 9-i) represents water depths up to 100cm where no signal attenuation happened. The other ones (Figs. 9-ii, 9-iii and 9-vi) show signals with attenuation, corresponding to water depths from 110cm to 130cm.

The attenuation started due to the fact that total wave energy is reflected by the defect, so it stays at a distance interval from 100*cm* and 110*cm*. This is not the common response obtained from guided wave tests. It can be explained by analyzing wave displacements along the pipe and the mode wavelengths, but for simplicity this discussion will be omitted in this paper.

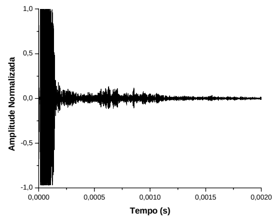
The arrival echo time is $7,28 \times 10^{-4} s$ and its velocity, calculated with the defect distance from the transducer, is 3,03*Km/s*. Therefore, comparing with the velocities calculated in section 4.2.1, it can be concluded that the presence of a notch at the pipe without internal oil does not change the guided wave characteristics, what is very useful concerning future field applications of the practiced method.



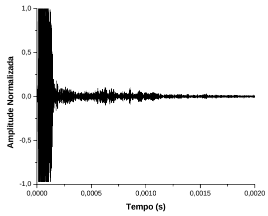
(9.a)



(9.b)



(9.c)



(9.d)

Figure 9. Signals for stage 2 procedure C for (9.a) 100cm, (9.b) 110cm, (9.c) 120cm and (9.d) 130cm external water.

4.2.4. Pipe in Air With Defect Containing Oil

This procedure is the closest from a situation where the pipe is inspected without having its operation stopped. The signal resulted from this experiment is showed in Fig. 10.

Similarly to the previous results where the same situation was utilized to test a pipe without defect, there was not observed signal attenuation while inserting water in the tank. The first echo detected corresponds to a $2,54 \times 10^{-3} s$ arrival time and the second one to a $4,75 \times 10^{-4} s$.

It can not be said that this signal represents a reflection from the defect, because of its similarity shows the signal presented in Figure 10. It does not mean that the defect was not detected or that it can not be detected. The presence of oil internally at the riser does affect the guided wave displacements along the riser and therefore affect the defect sensitivity to the guided waves generated.

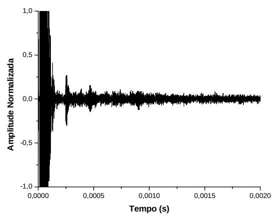


Figure 10. Signal acquired in stage 2 procedure D.

The velocities calculated by the echo arrival times and the defect distance from the transducer are 8,65*Km/s* and 4,63*Km/s* respectively for the first and second arrival times. As these are half the value of the velocities obtained in section 4.2.3, the echoes does come from the opposite riser extremity reflection.

Although the different results obtained in this experiment, concerning the way the defect was detected in section 4.2.3, the amplitude difference is proportional to the defect distance from the transducer and it consists a good way to calculate this dimension, but it can only be possible when the attenuation relationship between the traveling waves and the riser length is known, which is the following step of this research.

5. Conclusions

The dispersion curve analysis was able to predict the wave modes for the different systems tested. However, at the cases which the riser was filled with oil, it was observed an increase at the complexity of the traced curves, disabling the measurement of the group velocities and, as a consequence, diminishing the precision. Additionaly, it was observed a considerably lower wave attenuation comparing with the results where only external water was used.

The results obtained in the case which the pipe was placed in air (section 4.2.3) confirm the good potential of this method for detecting defects. This is also evident when one compares the results for the pipes with and without defects (sections 4.2.2 and 4.2.4). Although the analysis of the wave modes are yet to be improved, there are clear differences between both cases.

An intensive analysis of the frequency x group velocity curves for the systems where the riser is filled by oil and of the relationships between the different attenuation levels observed between these procedures correlating with the defect presence are under way at COPPE in order to better understand the problem and to enhance the capabilities of the method.

6. Acknoledgements

The authors acknowledge the technical the National Petroleum Agency, ANP (*Agência Nacional do Petróleo),* for the financial support needed to conduct this research as well as the technical staff of the Submarine Technology Laboratory (PeNO) and Non-Destructive Testing Laboratory (DEMM) at the Federal University of Rio de Janeiro for the valuable support on the execution of this work.

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