Application of Ultrasonic Guided Waves in the Field of Cryogenic Fluids

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Abstract
The prevention of malfunction due to corrosion and defects in pipeline is one of the most important issues concerning the industrial plants, particularly oil & gas companies that control chemical plants and also transmission and distribution of gas and oil.
This paper presents a study of applicability of the guided-wave non-destructive inspection technique in industrial plants where the piping system for the transportation of cryogenic liquids is a critical component. In particular, the attention is focused on the control of the integrity of pipelines for the transport of fluids at temperatures between −33° C and −196° C. This temperature range includes the boiling temperatures at normal pressure of several gases used in industrial plants: −33° C for ammonia, −43° C for propane (LPG), −78.5° C for CO_2, −162° C for liquefied natural gas (LNG), −183° C for oxygen and −196° C for nitrogen.
A wide range of industries uses this type of pipes: the various petro-chemical plants and for production of plastic materials, the refrigeration systems, piping system for the transport of liquefied gases in general and in particular the transportation of LNG inside of LNG terminals.

Keywords: long range inspection; monitoring; guided wave; ultrasonics; magnetostrictive transducer; cryogenic fluids, liquefied natural gas.

1. Background

Several methods of non-destructive testing can be applied [1] in the safety management of pipelines in industrial plants, particularly oil companies, chemical and in transmission and distribution of gas and oil. Generally these methods such as visual inspection, MFL (Magnetic Flux Leakage), ultrasound, radiography, liquid penetrant inspection techniques are local and can only be applied to pipelines that are directly accessible. These characteristics imply a long time for the inspection of long pipelines, and in the case of plants that use pipes for the transportation of liquefied gas at extremely low temperatures, the need to remove the thermal coating and as a consequence stopping the production cycle, increases significantly the costs for the security management of the plant.
Ultrasonic guided waves (UGW) is [2], [3], [5] a type of non-destructive technique capable of verifying the integrity of a pipeline even if, as often happens, it is inaccessible for inspection because it is buried or insulated with a protective coating. The waves are generated in the form of impulses [4] from a sensor applied locally around the inspected pipe and propagate using the same pipe as the guiding structure. In the presence of defects due to corrosion and / or imperfections a reflected wave is generated that will be detected by the sensor itself. The technique allows to localize defects along the pipeline up to distances of tens of meters from the access point on the pipeline and to discriminate signals (still using heuristic methods that are only approximately accurate) due to defects from those produced by the joints, elbows and supports normally present in a pipeline.
At present, the UGW technique [6], [7] is spreading widely in the industry and amongst companies that provide preventive diagnostic services, as it:

- quickly provides information over long sections of pipeline;
- requires minimal preparation for its implementation;

- allows the inspection at distance on remote areas that are not accessible;
- reduces the cost of quantitative inspection with NDT conventional techniques, as it indicates precisely the critical points to be inspected by the local techniques;
- increases significantly the efficiency of inspection.

At the moment the research on the UGW technique is oriented towards:

- identification of defects;
- applications at extremely low and high temperatures.

There are two technologies for guided wave inspection based on collars made up of piezoelectric transducers (PZT) or magnetostrictive transducers (MSS) respectively. Both technologies are successfully applied for ordinary temperature in industry, in the petro-chemical plants, gas and water pipelines. In this paper the attention is focused on magnetostrictive sensors and on their application on extremely low temperature.

2. Magnetostrictive guided wave sensor

2.1 Basic elements

MSS transducer uses the direct and inverse magnetostrictive effect that occurs in ferromagnetic materials [7], [8]. The magnetostrictive sensor is applied locally on the section of the inspected pipe and consists (see Fig. 1) of strips of magnetostrictive material such as nickel or cobalt that are bonded on the pipeline, and transduction coils wrapped around the magnetostrictive strips and connected to the signal generator. The strips of magnetostrictive material are initially magnetized using a polarized static magnetic field. The signal generator sends the excitation impulse to the transduction coil that in turn, induces a correspondent vibration into the magnetostrictive strip that will propagate as a guided wave guided by and along the pipe. Thus, polarizing the magnetostrictive strips, it is possible to induce the propagation along the pipeline of the fundamental torsional modes T (0, 1) or longitudinal modes L (0, 1). Moreover, appropriately exciting the two coils, one can obtain the wave propagation along a direction making negligible the propagation in the opposite direction. The presence of defects due to corrosion and/or imperfections along the pipeline generates a reflected wave which will be detected by the same sensor that was used in the transmission using the inverse magnetostrictive effect. In this phase, the transduction system acquires the reflected signal that, when sent to the processing system, allows to locate the flaw.

Fig. 1 - Magnetostrictive strip and coils applied on inspected pipeline.

Tab. 1 shows the main features of MsS2020® diagnostic system developed by SWRI, San Antonio, TX, USA and based on magnetostrictive technology.

Tab. 1 – Main features of MsS2020® diagnostic system.

Sensitivity	2% of “cross-sectional area” change
Frequency	5 ÷ 250 kHz
Wave – operating mode	Torsional and longitudinal - Pulse-echo/Pitch-catch
Pipe size	Tested up to 60-inch diameter pipe, up to 1-inch-wall pipe
Inspection range	10 ÷ 120 m for every direction; the effective range depend on pipeline geometry (diameter, number of joints, elbows, branches) and pipeline state (pipeline suspended or buried, pipeline coated or uncoated)
Time required for inspection	A few minutes once the magnetostrictive strips are bounded

Maximum temperature of the outside pipeline	At present, the MsS probes are used for relatively low temperature (up to 65°C) applications; tests on magnetostrictive probes for high temperature (up to 300°C) have been executed
Permanent installation of the sensor	Possible for the monitoring

The system has a good sensitivity, a range of inspection comparable to those of other systems and can easily be used on pipes of different diameters.
An improvement [9], [10] of the diagnostic capabilities of the MSS sensor can be obtained using the magnetostrictive collar shown in Fig. 2, developed by DSEA, University of Pisa, Italy. The new system allows the extraction of the flexural component in the acquired signal and consequently the discrimination between symmetrical feature (welds, joints, branch joints, and elbow joints) and asymmetrical features (corrosion, notches, cracks). More details on defect identification are provided in [11], [12].

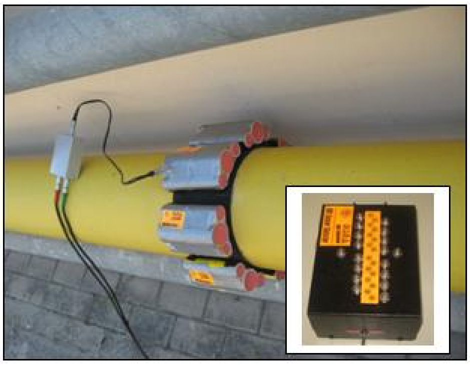

Fig. 2 - Magnetostrictive collar and multiplexer

2.2 Monitoring of coated pipelines

The strength of MSS technology lies in the simplicity of the sensor in terms of installation and adaptability to different types of pipes. Moreover, in the case of coated pipes as thermally insulated ones, the inspection set-up can have a specific configuration, with the insulating material positioned between the strip and the magnetostrictive coil transducer. In this way it is possible to perform repeated acquisitions in successive periods or continuous monitoring of the pipeline without damaging the coating. By the test illustrated in Fig. 3, related to a 10-inch pipe, 12 m long and PE coated, it has been shown [11], [12] that the acquired signals don't change significantly in the following two cases:

1. acquisition with the coils directly placed on the nickel strips bounded and magnetized;
2. acquisition with the coating between the strips and the coils.

The results obtained shown that five reflections from the end of the pipe are detectable so that 60 m of coated pipeline can be monitored.
Like this the test suggests the possibility of

- removing a short coating (20 cm) from the pipeline;
- bounding and magnetising the strips;
- coating the strips;
- measuring without removing the coating.

It is important to underline that this monitoring is made possible by the sensor simplicity (the magnetostrictive strips are 0,25 mm thick and 25 mm wide for 32 kHz test frequency) and inexpensive (about 13 euro for the strips used in the test).

Fig. 3 - Test of PE coated pipelines: a) acquisition without the coating; (b) coating of the pipe; (c) acquisition with the coating between the strips and the coil; (d) results.

3. Testing of magnetostrictive sensor for low temperature applications

It is known that magnetostrictive materials can operate at higher temperatures compared to piezoelectric sensors, being limited in this respect by the characteristic Curie temperature. For the lower limit of temperature at which the magnetostrictive sensors can work, there are theoretical studies that predict the possible use at extremely low temperatures [13], [14] while an experimental confirmation is not available in the literature.
In the following, preliminary tests performed at −80°C and −196°C respectively show that the MSS technology can be applied also when the temperatures are extremely low.

3.1 Test at –80°C

A special freezer was used to chill the pipe sample down to about −80° C. The pipe was 20 cm long, 4" in diameter, with the magnetostrictive strips already bonded to it. The pipe was left in the freezer at −80 °C for more than 24 hours in the first phase and for more than 6 months in the second phase.
After about 25 hours at −80 °C the magnetostrictive strips were still attached to the pipe and the pipe was ready to be tested.
In less than 5 minutes after the frozen sample was taken out the freezer, the coils (protected from cold) were applied over the strips and the first data set was acquired. In the acquired signal the first reflection and several reverberations of the pipe ends can be noticed at every 20cm (which is the length of the sample).

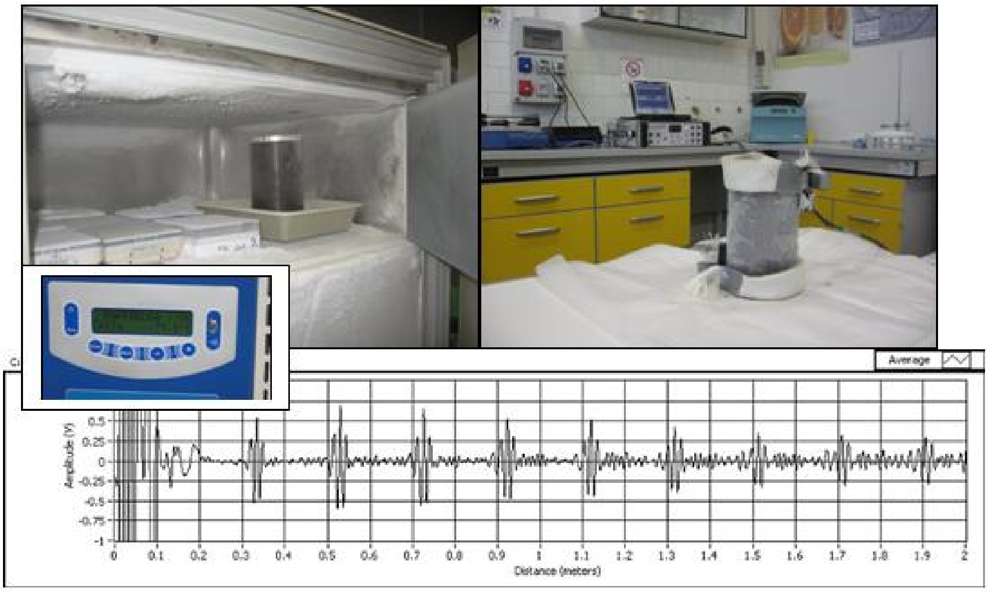

Fig. 4 – Test at −80 °C.

A further test has been executed using another pipe sample with the same geometric dimensions. The pipe with the bonded nickel strip and coils have been kept inside the freezer: the acquired signal were stable even after 6 months at the same temperature.

3.2 Test at –196°C

The test was performed by immerging the sample pipe that was mentioned before into liquid nitrogen. As we show in Fig. 5, the magnetostrictive sensor has been kept outside the liquid. Since the metal is a good thermal conductor, in this experiment the temperature of the sensor has been considered near to −196 °C, the boiling point of pure nitrogen. The pipe sample has been monitored during 12 hours obtaining stable signals (see Fig. 6).

Fig. 5 – Test at −196 °C: (a) filling the Dewar; (b) piece of pipe and magnetostrictive guide wave sensor inside liquid nitrogen; (c) data acquisition.

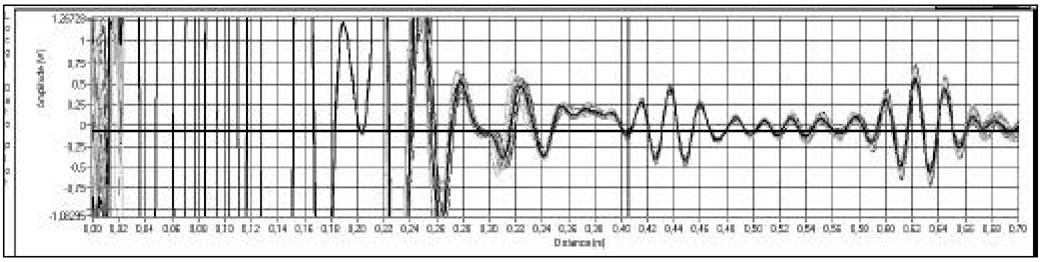

Fig. 6 – Test at −196 °C: acquired signals.

4. Further developments and industrial applications

The experiments just shown are the first step towards the development of an innovative sensor for guided-wave monitoring. The application field is related to the integrity of pipelines for the transport of cryogenic fluids at temperatures below –30ºC. Amongst the various industries that use this type of pipes are the industries of refrigeration systems, piping systems for the transport of liquefied gases and in particular for the transportation of LNG - Liquefied Natural Gas – inside regasification plants (see Fig. 7).

The boiling temperature at 1 bar pressure for several gases used in industry for cooling or as fuel is ranging from -33ºC for ammonia, to -43ºC for propane (LPG) to the -162ºC of the LNG. Since most of the pipelines transporting liquefied gas at these temperatures are coated with insulation materials, their integrity cannot be assessed by visual inspection even in the case of external corrosion unless the coating is removed, which is considerably expensive.

Fig. 7 – LNG Offshore, Porto Levante – Rovigo - Italy

Moreover, in continuous-cycle facilities such as petrochemical plants, a technique that allows inspection of the pipeline without interrupting the normal operation would allow huge savings.

Among the two existing technologies for guided wave inspection the magnetostrictive technology seems to be the most attractive.

At the moment, the piezoelectric collars present as a matter of fact some drawbacks that do not allow their application to pipelines carrying fluids at extremely low temperatures. Among these limitations, the most important is the temperature limit for which they are operable, declared by the producer as being -40ºC [15]. Moreover there is the fact that the transducer collar must by applied in direct contact with the pipeline and therefore the coating must be removed at the point of application for every inspection.

It is different the case of magnetostrictive sensors [6], [12]: the magnetostrictive strip can be applied before the start of the plant activity or with the occasion of periodic inspections when the coating is removed and plant activity is temporarily stopped. The electromagnetic nature of this sensor allows the transduction coils to be positioned a few centimetres distant from the magnetostrictive strip, therefore, above the thermal insulation. Moreover, it is of obvious importance the resistance of the components of the magnetostrictive sensor at extremely low temperatures. In this way, it is possible to perform periodic inspections or long-term monitoring of long pipelines without having to remove the thermal insulator, and, therefore, without interrupting the cycle of activity of the plant.

5. Conclusions

The ultrasonic guided wave technology can be applied to the non-destructive testing of pipes or pipelines that are not directly accessible due to their position or because they are coated. Normally the temperature of the inspected pipeline is higher than 0°C. The application of the UGW technology in the field of the cryogenic fluid is innovative.

The good results of the tests illustrated in this paper can bring a significant contribution to the innovation in the specific case of monitoring of the integrity of pipelines for the transport of fluids at temperatures below –40ºC. At the moment this is possible only with magnetostrictive sensors.

The new sensor prototype consist of the two essential parts: the strip of magnetostrictive material bonded around the pipeline under test and a transducing coil or coils disposed around the strip, above the coating. These characteristics imply a short time for the inspection of long pipelines, and in the case of plants that use pipes for the transportation of liquefied gas at extremely low temperatures, the need to remove the thermal coating only once before the start of the plant activity or with the occasion of periodic inspections when the plant activity is temporarily stopped.

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