Long Range Ultrasonic Condition Monitoring of Engineering Assets

(LRUCM)

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Long Range Ultrasonic Testing – New Markets for New Technology

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Background

Long range ultrasonic testing (LRUT) is a new non-destructive testing (NDT) technology, which is being supported by the European Commission in a Collaborative project entitled ‘Long Range Ultrasonic Condition Monitoring of Engineering Assets’ (LRUCM).

LRUT is a new inspection method. Therefore a survey of European industry has been undertaken to assess both potential applications for the new technology and implementation routes to ensure its successful adoption. In addition, the Small and Medium Sized Enterprises (SMEs) that are participating in the LRUCM project, need to understand the potential capabilities for LRUT and therefore a survey was also conducted of their needs.

For over 50 years, the technologies used in inspection have relied on basic physical principles for detecting flaws, such as the reflection of ultrasound or leakage of magnetic flux from cracks and corrosion. Powerful computers have dramatically improved signal processing and analysis, but the technologies are still limited by the basic physics.

LRUT on the other hand represents a step change in inspection technology. Although using ultrasound it relies on a different physical principle; the refraction of ultrasound where the sound wave meets a change in wall thickness caused by a flaw. This opens up new possibilities for inspection, but also raises questions about inspection performance, because there is little experience on which to base conclusions. The limited knowledge must be carefully explained to potential users, otherwise the technology may become ‘oversold’ if emphasis is placed on benefits only. An ‘oversold’ technology can become an unused one, if customers are disappointed by inspection results.

The survey is therefore being used carefully as an implementation tool for LRUT technology. Although structured as a questionnaire, it has evolved into a dialogue between end-users, SMEs providing equipment and services and Industrial Association Groupings (IAGs) that are committed to providing information to their members. This report constitutes only the beginning of this dialogue.

Before discussing the survey, a brief description of the principles of LRUT is given.

Principles of LRUT

Ultrasonic testing (UT) is used extensively as a condition monitoring technique for detecting defects in a wide range of structures and components, both during manufacture and in service. Conventional UT uses so-called bulk waves with ultrasound frequencies in the MHz range, in which pulses propagate along a narrow scanning beam and echoes are detected from discontinuities in the beam’s path. The test range is measured in millimetres or centimetres. LRUT uses frequencies in the KHz range and wave modes that penetrate the whole wall thickness of the test object. Therefore in a plate for example, the plate must be thin enough and the wavelength of the ultrasound long enough for waves on opposite surfaces to interact. These are known as plate or Lamb waves. If the plate waves on the two surfaces are in phase,
asymmetric (A) plate waves are produced. If the waves are out of phase, symmetric (S) plate waves are produced (Figure 1).

A unique characteristic of plate waves is they change velocity with frequency. They are described as being ‘dispersive’, because a pulse of plate waves, containing as it does a spectrum of frequencies, will broaden as it propagates. The lower frequency components travel more slowly than do those of higher frequency.

In the case of pipe, they are known as Guided waves. The particle displacements are similar, but because the pipe acts as a wave-guide, the pulses can be propagated over even longer distances, exceeding 100m under some conditions. Figure 2 illustrates the principal wave modes that can be generated in pipe.
By looking along the pipe from the pipe end, the Longitudinal (L) wave can be seen as a bulge in the pipe wall travelling along the pipe. The Flexural (F) wave can be seen as a flexing of the pipe in any number of planes. The Torsional (T) wave as a twisting of the pipe (Figure 3).
The variation of velocity with frequency, wave mode, pipe diameter and wall thickness is illustrated by means of dispersion curves. A simplified illustration showing four wave modes only is shown in Figure 4. These are for a specific pipe diameter and wall thickness. Other diameters and thicknesses will have their own families of dispersion curves. It can be seen that the torsional T(0,1) wave is non-dispersive. That is its velocity is constant irrespective of frequency. The L(0,1) wave is highly dispersive with wide variations in velocity with frequency. The L(0,2) wave cannot exist at frequencies below about 20 kHz. However, at frequencies above about 40 kHz, the velocity becomes nearly constant with changing frequency. That is the wave becomes non-dispersive. There is a vast range of flexural waves. Only the dispersion curve for the F(1,3) mode is shown. This wave can only exist at frequencies above about 25 kHz. Like the L(0,2) wave it becomes almost non-dispersive at frequencies above about 50 kHz.

Figure 4 Typical dispersion curves

The dispersive nature of the wave modes used in long-range ultrasonics makes the test procedures more complicated than those used in conventional ultrasonics. For most ultrasonic tests, the results are interpreted from the A-scan (Figure 5), which is a display of signal amplitude against time. In conventional ultrasonic tests, the time-base is calibrated to read distance by using the bulk velocity for shear or compressional waves. In long-range ultrasonic testing, not only are there many more wave modes, but the velocity of each will vary to a greater or lesser degree according to frequency.
In pipes, there is the added complication of the guided wave mode being dependent on the pipe diameter and wall thickness. In practice, the instrumentation used in long-range ultrasonic testing uses software to calculate the velocity from the given test frequency and for the specific pipe diameter and wall thickness. Also, from the dispersion curves shown, it can be seen that over certain frequency ranges the curves are flat, that is to say the propagation is not dispersive. NDT is therefore conducted within these frequency ranges.

Because their velocity is influenced by wall thickness, guided waves exhibit their most important characteristic for NDT; that of being sensitive to changes in wall thickness. They are therefore sensitive to corrosion or erosion, whether it is on the inside surface or the outside surface of the pipe. They are also sensitive to cracks provided that they present a significant area transverse to the axis of the pipe. This characteristic is based on the physical phenomenon that whenever ultrasound velocity changes at a boundary, a small proportion is reflected. The effect can be caused by an increase in wall thickness, at a pipe girth weld for example, as well as by a decrease in wall thickness (Figure 6). Indeed, because of they are consistent reflectors, pipe girth welds are usually used as reference reflectors.

**Figure 5 Ultrasonic test A-scan display**

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Long-Range Ultrasonic Testing – New Markets for New Technology

Application of LRUT

Until recently, long-range ultrasonics has been applied to the detection of corrosion in components of simple geometry, that is to say plates and pipes. New techniques for generating plate and guided waves, by using Electro-Magnetic Acoustic Transducers (EMATs) for example and a better understanding of how the various wave modes propagate, through the use of advanced computer simulations, has led to interest in developing long-range ultrasonic techniques for a wide range of test piece geometries. These include wire cables, railway rails and sheet piling. Moreover, new signal processing techniques has improved performance for detecting small defects, such as fatigue cracks and for testing through heavy coatings that normally absorb the ultrasound, such as concrete.

Long-range ultrasonic testing is therefore an expanding condition monitoring technology, which will be of major benefit in the inspection and therefore maintenance of pipelines, railways and other vital parts of Europe’s infrastructure. The European Commission is sponsoring LRUCM among Industrial Association Groups (IAGs) and Small-to-Medium Enterprises (SMEs) across Europe, supported by Research and Technology Organisations (RTOs), in order to develop new long-range ultrasonic sensors and systems. These will take the LRUT technology into a new range of industrial applications including:

- Pipes and pipe-work in process and power plant.
- Pipe-lines carrying oil and gas between production fields, plants and customers.
- Small diameter pipes in heat exchangers.
- Rails used in railway lines.
- Wire cables used in stays and hangers for suspension bridges.
Sheet piling used in harbour walls and other civil engineering structures. It is anticipated that the technique will have an increased functional capability in terms of range of test, defect detection capability, and defect positioning and sizing capability.

The project includes a significant effort in technology transfer to ensure proper implementation of the technology. These include work-shops and seminars and the introduction of training and certification for test operators and technicians.

**Survey of market for LRUT**

The introduction of any new technology requires a thorough knowledge of its market. A market survey has therefore been conducted by the IAGs across Europe, from Portugal to Russia. They have surveyed potential users of the technology and perhaps more importantly, because of their own knowledge of the condition monitoring business, the Non-destructive Testing (NDT) service companies that provide equipment and services to owners and operators of engineering assets.

The specific objectives of the survey have been:

♦ To survey the specific needs for LRUT with SMEs in the project.
♦ To survey the general needs for LRUT within industry in countries covered by IAGs in the project.

A questionnaire was used in both surveys and was translated into German, Russian, Bulgarian, Ukrainian and Spanish. A survey was also conducted in Italy, but in English.

The Ukrainian IAG conducted the survey in Russia.

Gathering information from the survey is on-going. In particular, more detailed information is being gathered about some of the new potential applications by way of personal interviews, in which specific test-piece dimensions and defects sought are discussed.

**Results**

In the survey, respondents were asked for some background information about their companies and then asked to rank a list of answers to questions in order high, medium, low or not relevant.

- **Respondent activity.**
  
The majority of respondents (31%) were inspection service providers (Figure 7).
Inspection service providers are generally SMEs. They provide an inspection service to the owners or operators of engineering assets and to their equipment and component suppliers. They may also provide services to engineering contractors that manage construction projects and later maintain the assets.

Inspection equipment manufacturers and suppliers are also generally SMEs. Their market is not only inspection service providers, but also to some owner/operators and suppliers that have retained their own inspection departments. The trend is towards sub-contracting of inspection services by large enterprises, whether they are owner/operators or suppliers, to SMEs. They can then concentrate on their core business.

Many inspection equipment manufacturers and suppliers are also training organisations, when training provides an integral part of their service to customers. Research and development is also a key activity of some equipment manufacturers, if they are to develop new products and find new applications for their equipment.

18% of respondents were owner/operators of engineering assets. These include oil refineries, power stations, railways and bridges. As they ultimately procure the NDT that is used to monitor condition, either as equipment they use themselves, or as a service, they are the ultimate arbitrators of whether a new NDT technology is successful or not. However their involvement in maintaining engineering assets is becoming increasingly distant, as the day-to-day operation of plant is sub-contracted.
Long Range Ultrasonic Testing – New Markets for New Technology

13% of respondents were engineering contractors. Their view of NDT technology is increasingly important, though more from the point-of-view of short-term cost benefit than long-term investment.

16% of respondents were research and technology organisations, many of which are developing new NDT technology. NDT is supported by research in many universities, because the underlying technology in sensor development is at the leading edge of research.

- **Products relevant to company**

Respondents were asked to score the relevance of products in a table on a scale from 3 (High importance) to 1 (Low importance).

![Figure 8 Products relevant to respondents](image)

Respondents were mainly interested in pipes (Figure 8); those used in process plant (34%), in transmission lines (46%) and in plant equipment, such as heat exchangers (19%). The interest in rails was restricted to specialist companies involved in railways. Only one respondent had a strong interest in steel cables, because he owned a suspension bridge, although there was moderate interest among some inspection service providers, who saw a need that was not satisfied with current technology. Like steel cables, sheet piling is another example of an application in civil engineering, where there is currently little demand for inspection services through lack of satisfactory technology.

- **In-service inspection methods**

In a table of methods, respondents were asked to score on a level of use from 3 (High) to 1 (Low).
The principal inspection methods in use by the respondents are magnetic testing (MT), penetrant testing (PT), electro-magnetic testing (ET), ultrasonic testing (UT) and radiographic testing (RT). These five methods are covered by national and international standards and by schemes for training and qualifying test operators. Visual inspection is an integral part of all the other inspection methods, but is often used on its own, if defects are all surface breaking and large enough to be detected unaided by the human eye. Surface breaking discontinuities are generally the more serious, although sub-surface flaws may grow to the surface and then quickly cause failure. MT and PT are used to increase the visibility of surface breaking flaws and are therefore very common inspection methods. ET increases the sensitivity to surface-breaking flaws even further and ET sensors are even able to access surfaces that are not visible because they are coated. UT and RT are used to detect internal flaws. Recently they have been automated. Automated UT uses mechanical scanners to guide the sensors over the test piece and computer software to gather, display and, increasingly, analyse the data. Automated RT uses sensor arrays to gather data in place of radiographic film and digital techniques to enhance the images.

![Figure 9 Current usage of NDT](image)

From the survey however, there is still a low uptake of automated methods (Figure 9). Only 25% of respondents had a high level of interest in automated UT, in contrast with the 51% who had a high level of interest in manual ultrasonics. This low level of interest in automated UT remains, despite the generally accepted reduced level of costs and the recent introduction of national standards and codes of practice for automated UT of pipe-lines and pressure vessels, where it replaces radiography. Digital radiography is a very new technology, there are no codes of practice and procedures have to undergo qualification trials before they can be implemented. Therefore only 8% of respondents had an interest in digital radiography, compared with 40% in film radiography.
Among the few other NDT methods mentioned by respondents were thermography and acoustic methods. But 85% of respondents had no interest at all in other new NDT methods.

- **Confidence in inspection methods**
  
  From their usage of NDT methods, respondents were asked to rank their level of confidence.

![Confidence in inspection methods](image)

**Figure 10 Level of confidence in inspection methods**

Between one third and one half of respondents had a high level of confidence in the inspection method they used, which is more than the number who had only moderate confidence (Figure 10). The number with low confidence was negligible. However in the case of digital radiography and electro-magnetic methods, there were almost double the number with moderate confidence than with high confidence. On the other hand with film radiography, there were four times as many with high confidence than with only moderate confidence, which is a higher level of confidence than even with visual inspection. It is significant, that the three methods that provide an image of the test results (visual inspection, magnetics and penetrants testing and film radiography) are treated with the more confidence than the methods that do not (manual ultrasonics and eddycurrent testing).

- **Inspection issues**
  
  The respondents were asked to rank the issues that affected their confidence in inspection.
Operator performance is the dominant inspection issue, with 88% declaring it had the highest importance and only 4% the lowest importance (Figure 11). This was followed by equipment performance (72% and 3% respectively). Inspection coverage was still regarded by 60% of respondents as of high importance, despite the introduction of risk based inspection methodologies, which limit inspection coverage to areas where there was a high risk of failure. Surprisingly, the majority of respondents thought that cost of inspection was of only moderate importance (51%). A strong inter-dependency between costs and rate of inspection is evident. The importance of finding the smallest flaws is highlighted by the 53% of respondents who thought it had high importance although this was tempered by the knowledge that as flaw the test sensitivity is increased, so the likely number of false calls will increase. This was of high importance among 39% of respondents. The management issues of quality assurance through proper documentation systems, good working practices and health and safety of test operators was recognised by about one third of respondents.

- **Perceived benefits of LRUT**

From their knowledge of LRUT, respondents were asked to rank a list of potential benefits in inspection of engineering assets.
The benefit with the highest importance (69%) perceived by the respondents was ‘100% coverage’ (Figure 12). The benefit with the lowest importance (36%) was ‘Range greater than 100m’. Screening for flaws was also regarded as of high importance by 63% of respondents. Slightly more respondents thought that crack detection (58%) was more important than corrosion detection (53%), which is the current preferred use of LRUT on pipes. The accurate positioning of flaws and the critical sizing of flaws were regarded equally, with slightly more placing high importance of flaw positioning (42%) than flaw sizing (36%). Less importance was placed on flaw monitoring, with the majority (36%) believing it was only of moderate importance.

One of the original aims in developing LRUT was the detection of flaws in areas of pipe that were inaccessible, because they were under insulation, buried in road crossings or below the water-line. Buried test pieces are still of high importance (36%) among respondents, but there is also a need to test inaccessible areas (38%), which may be above ground and need scaffolding to reach.

In contrast to the high level of importance placed upon operator performance in the question about inspection issues, ‘ease of operation’ of LRUT equipment, an important contributor to operator performance, was only regarded by 35% of respondents as of high importance.

‘Reduction of inspection costs’ was regarded as an important benefit in LRUT by only 42% of respondents.
Conclusions

A start has been made to gathering information about interest in LRUT across Europe.

The dominant interest is still in pipes, which were the original application for LRUT. These are a critical engineering asset in the oil, gas, petrochemical and power generating industries, where there is high usage of NDT and a strong interest in developing new technology. In civil engineering on the other hand (railways, cables, steel piling), there is much less awareness of NDT.

The five primary methods of NDT are penetrant testing, magnetic particle inspection, eddy-current testing, ultrasonics and radiography, but visual inspection is still the principal method of assessing the condition of an engineering asset. Visual inspection underpins all NDT methods, even ones that are intended to detect internal and subsurface flaws. For example, surface features on the test object may affect an ultrasonic test for internal flaws. Any new NDT technology, such as LRUT must also pay due regard to visual inspection in test procedures.

There is still a low uptake of advanced NDT techniques. Only 57% of respondents had used any automated UT at all, compared with 83% who had used manual ultrasonics. With digital radiography, the uptake was even worse, with only 27% having used the method compared with 68%, who had used film radiography. However of those that used automated UT, there was a greater proportion with high confidence in test results (64%) than with manual ultrasonics (47%). The linkage of higher confidence to imaging mentioned earlier is important. LRUT bases test results on the interpretation of signals in A-scans. Greater confidence would be attained if these signals could be translated into images of the test piece.

The industries that employ NDT techniques are therefore conservative and many barriers have to be overcome, over and above recognition that the method detects defects. The most important of these is inclusion of the method in national codes and standards.

The dominance of test operator performance over all other inspection issues (88% of respondents regarded it as of high importance) underpins the importance of the approach adopted by LRUCM in developing LRUT technology. When introducing a new technology, there is a tendency among developers to concentrate on equipment performance, without due regard to how the equipment will be used in the field. Much NDT is done under conditions that are far from ideal, where test operators work under stress-full conditions among dangerous plant and machinery. LRUCM will address this issue by developing training programmes for LRUT and running workshops and seminars that explain the limitations as well as benefits.

The most important perceived benefit of LRUT is 100% coverage and screening for flaws. This complements conventional NDT, which aims to detect and evaluate the smallest flaw in specific critical areas. These areas are often inaccessible, and can be dangerous for test operators, but could be reached by LRUT.