INSPECTION
INTELLIGENCE

THE EVOLUTION OF ULTRASONIC INLINE INSPECTION

WHITE PAPER

INTRODUCTION

Inline inspection (ILI) by means of intelligent pigging has become a standard application to ensure the safe operation of pipelines worldwide. Ultrasonic inspection tools have proven successful for crack and metal loss inspections of liquid pipelines. The progress regarding inspection tools over the last three decades is tightly connected to the progress of electronics and data processing during this time period. By timely implementation of the available state-of-the-art technology in the field of data recording, data processing, and data storage, the performance of ILI tools has continuously improved. An important aspect of these improvements is the measurement resolution resulting in the detection of smaller defects as well as better sizing capabilities. Another instrument that is becoming more and more important for the proper design of ultrasonic ILI tools and their optimized application is ultrasonic modeling.

HARDWARE-RELATED IMPROVEMENTS

The progress of inline inspection tools is closely linked to the progress in electronics. Highly integrated electronic components allow for compact size and reduced power consumption at the same time. As a result, an increased number of sensor channels can be accommodated in less space, which is important for small diameter tools. The corresponding improvements for the ILI tools are:

- Increased sensor channels providing better circumferential resolution
- More parallel processing of receiving channels enabling higher inspection speed
- Less power consumption per channel thus increasing the inspection range

Data Digitization

For ultrasonic ILI, ultrasonic sensors are used as transmitter and receiver (so-called pulse-echo technique). The received ultrasonic signals are transformed by the piezoelectric effect into electric signals, which are digitized and further processed. For the digitization of the ultrasonic signals, analog-to-digital converters (ADCs) are used. The ADC itself is a source of error depending on its sampling frequency and its digitization depth.

Table 1 gives an overview for different ADC characteristics. Using state-of-the-art ADCs (e.g., 80 MHz sampling rate, 14 bit sampling depth), the amplitude error and the time error can be neglected for ultrasonic inspection frequencies of typically 5 MHz. Furthermore, the sampling depth of at least 14 bit provides a dynamic range adequate for the recording of ultrasonic signals.

Sampling Frequency (MHz)	Max. Amplitude Error* (dB)	Time Resolution (ns)	WT Resolution (mm)	Sampling Depth (bit)	Signal Dynamics (dB)
20	3.0	50	0.16	**8**	48 (**42)
40	0.7	25	0.08	**12**	72 (**66)
80	0.2	12.5	0.04	**14**	84 (**78)

**at ultrasonic frequency of 5 MHz, **if one bit is used for signal sign*

Table 1 - Maximum amplitude error, resolution and signal dynamics for ADC

Data Processing

After digitization, the inspection data is processed using field programmable gate arrays (FPGAs) in connection with state-of-the-art microprocessors. From 1990 to 2010 the clock speed of the microprocessors has increased by a factor of approx. 100 (Fig. 1.), while the progress in computer power as measured by the microprocessor transistor count has changed by a factor of 1000 in the same period (Fig. 2, Moore's law [1]). These improvements applied in ILI allow for advanced onboard data processing not possible in the past. Examples of application include:

- Less data reduction required as more data can be recorded
- Dynamic adaptation to varying medium properties
- Preprocessing of the inspection data to speed up the offline data analysis process

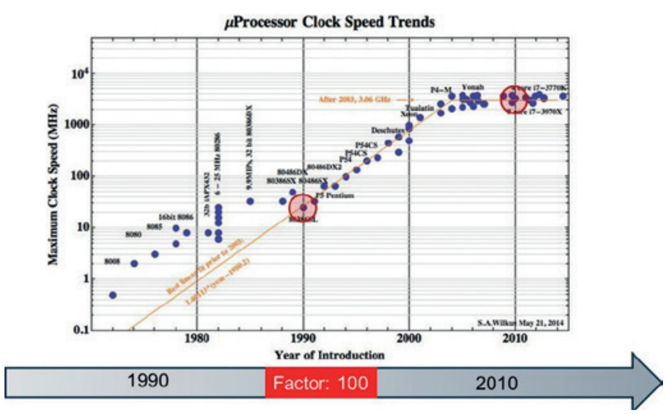


Figure 1 – Progress in microprocessor clock speed

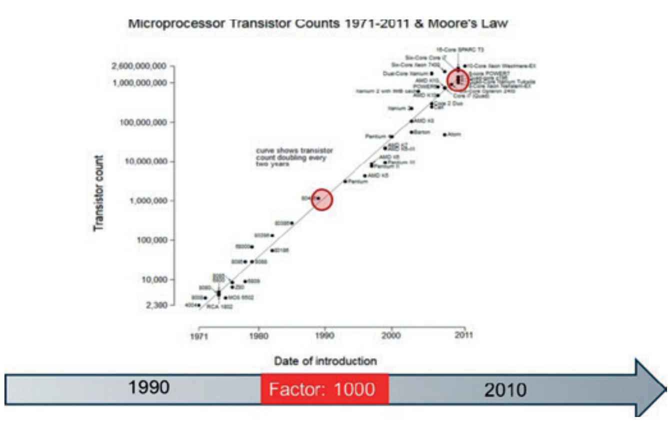


Figure 2 – Progress in microprocessor transistor counts

Data Storage

In the past, ILI had limited data storage capacity requiring the usage of data compression and data reduction algorithms in order to store a significant part of the data to ensure 100% inspection coverage. Due to the enormous progress in data storage technology, large storage capacities (several terabytes) can easily be accommodated in the current ILI tools. Here, the progress over the last two decades as measured in terms of capacity, size, and costs is estimated to be around $2x10^4$ (Fig. 3).

Figure 3 – Progress in data storage capacity

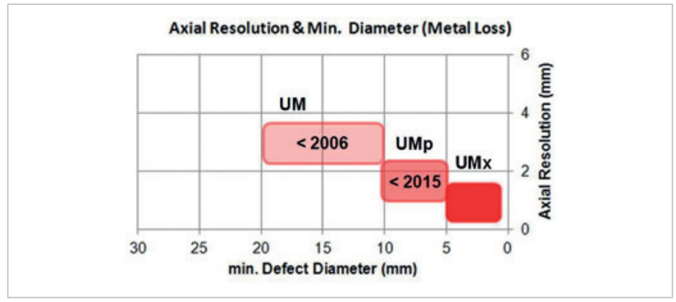


Figure 4 – Improvement of metal loss inspection regarding resolution and minimum

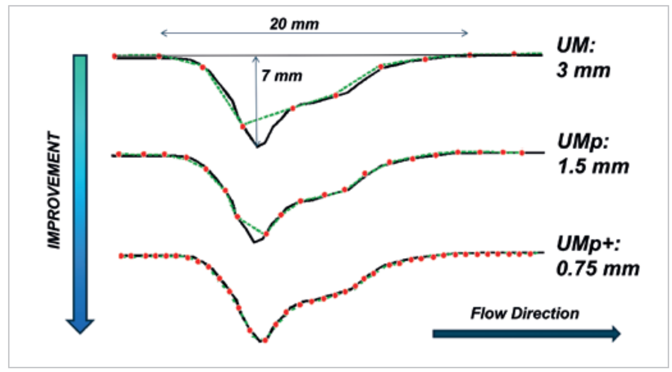


Figure 5 – Improvement of corrosion measurement by increasing the axial resolution

INSPECTION-RELATED IMPROVEMENTS

In the previous section NDT Global has described some of the progress in hardware used in latest ILI tools. In the following examples NDT Global will illustrate how this progress leads to improvements regarding the inline inspection performance.

Measuring Resolution

The measuring resolution is one of the most important characteristics of an ILI tool. It is related to the minimum defect size that can be reliably detected as well as the precision and accuracy of the defect profile that can be generated. There are three components of resolution:

- Axial resolution (distance between two ultrasonic recordings in axial direction)
- Circumferential resolution (distance between two adjacent sensors in circumferential direction)
- Metal loss inspection: resolution of depth measurement (Table 1)

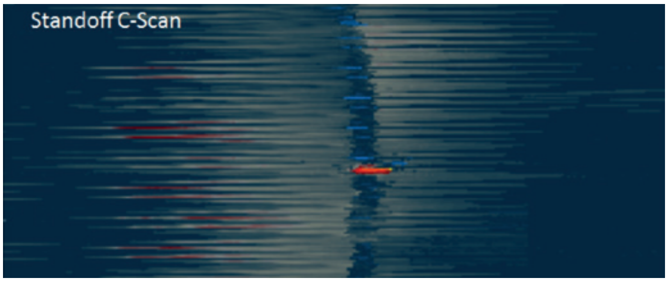
Regarding metal loss inspection, the requirements from the operator's side become more stringent all the time. These requirements are often based on problems related to pinhole corrosion characterized by small, but often deep, corrosion damage. This inspection challenge has led to the development of new generations of high-resolution tools during the last 10 years (Fig. 4).

Starting with NDT Global's UMp tool in 2007, the minimum detectable defect size could be reduced to 5 mm using an axial resolution of 1.5 mm. Current tools can operate at axial resolutions of 0.75 mm (UMp^{+}) providing precise defect profiles even for small corrosion defects (Fig. 5). The result of these developments is an increase of a factor of two in the number of ultrasonic sensors from the old UM standard to the UMp standard. Compared to the former UM tools (8 mm circumferential resolution, 3 mm axial resolution) the current tool generation with 4 mm circumferential resolution and up to 0.75 mm axial resolution generates 8 times more inspection data (UMp^{+} version).

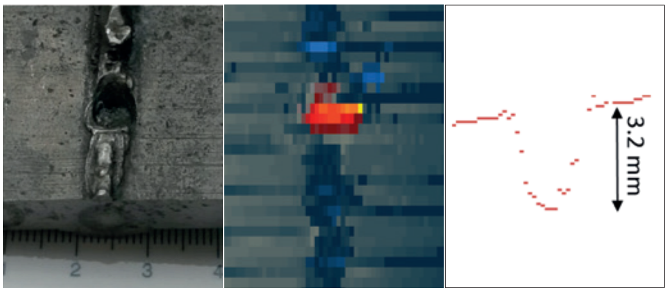
Examples from wall thickness inspection

High-resolution tools can detect and size tiny corrosion spots (pinholes with dimension < 10 mm, see [2]) even in welds. An example recorded with an axial resolution of 0.75 mm is depicted in Fig. 6. The comparison of the ultrasonic image (Fig. 6c) with a picture of the cut-out defect exhibits a very good alignment (Fig. 6b). The depth profile of this internal pinhole as shown in the B-scan in Fig. 6d is clearly visible, providing a highly accurate depth measurement. Such small pinhole defects are usually not detected with legacy, standard-resolution tools. Using the higher resolution tools, however, such defects are found quite frequently in many pipelines. This special type of metal loss is mainly related to the welding of the girth welds. Many of those have been confirmed by several verification campaigns in different countries exhibiting defect depths up to 80% wt.

NDT GLOBAL OFFERS AN ADVANCED SOLUTION FOR DENT ASSESSMENT



6a – Ultrasonic C-scan



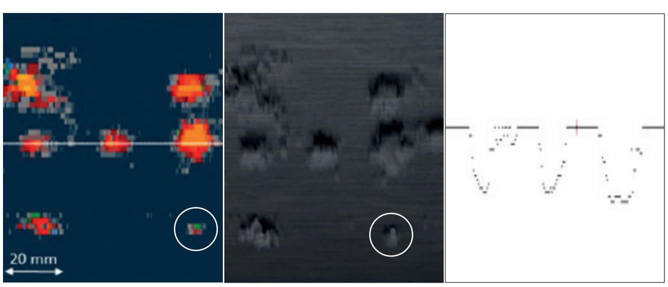
6b – Picture of defect

6c – Zoomed C-scan section showing pinhole defect

6d – B-scan along centerline

Figure 6 – High-resolution ILI data showing an internal pinhole in a girth weld (axial length 6 mm, width: 9 mm, depth: 3.2 mm)

Another example of a group of external pitting including pinholes in the base material of a pipe joint is shown in Fig. 7. Fig. 7a shows the ultrasonic C-scan of the defects while Fig. 7b provides a 3D image as reconstructed from the ultrasonic wall thickness data. Here, the smallest defect has a length of approx. 5 mm (see encircled spots in Fig. 7a and 7b). A depth profile of the three defects along the white horizontal line in Fig. 7a is depicted in Fig. 7c. Based on an axial resolution of 0.75 mm, one obtains a very accurate information about the defect shape.



7a – Ultrasonic C-scan

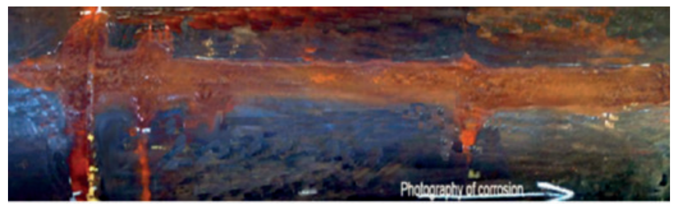
7b – 3D image reconstructed from UT data

7c – B-scan showing corrosion profile

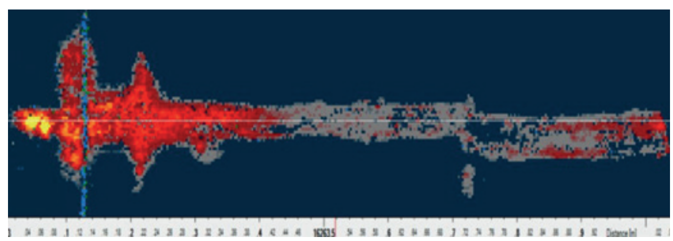
Figure 7 – High-resolution inspection data showing an area of external corrosion with pits and pinholes in the base material

Fig. 8 gives an example of general corrosion at the external side of the pipe. The corrosion damage extends over a large area exhibiting quite a complex structure with some very deep local pits (depth up to 62 % wt). Furthermore, it is crossing over a girth weld as can be seen at the left side of the pictures.

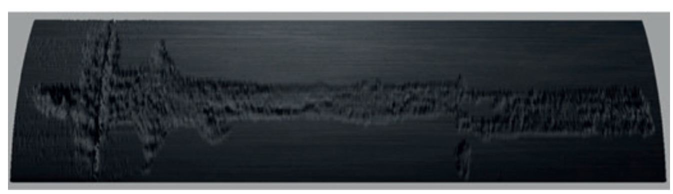
Fig. 8b shows the ultrasonic wall thickness data that match very well with the photography of the damaged area shown in Fig. 8a. The ultrasonic wall thickness data can be used to reconstruct a 3D image of the pipe section, which gives a realistic impression of the corrosion damage (Fig. 8c). This type of data is ideally suited for Level 3 defect assessment. Therefore, the 3D data can be imported into an appropriate FE-software for calculation of the maximum allowable operation pressure (MAOP). Based on the high-precision sizing information in combination with the best resolution available in ILI today, this approach provides the most advanced solution for defect assessment.



8a – Photography



8b – Ultrasonic C-scan



8c – 3D image generated from ultrasonic data

Figure 8 – High resolution ILI data showing complex external corrosion crossing a girth weld; the maximum depth is 62% wt

Inspection Speed

The issue of resolution cannot be discussed without taking into account the relationship between axial resolution and the maximum inspection speed that is acceptable to ensure a specified axial resolution. This relationship is given by the simple formula

$$v_{max} = a_R / (N_m * t_{\mu s})$$

with:

v_{max} – max inspection speed at given resolution a_R
N_m – no. of multiplexed ultrasonic receiving channels/unit
$t_{\mu s}$ – time window for recording a single A-scan.

As the time window to record the ultrasonic signal is more or less fixed (typically < 100 µs), the main option to increase the maximum inspection speed for a given axial resolution is to parallelize the data processing on the receiving side; i.e., to reduce the number N_m of multiplexed channels. The corresponding design is implemented in NDT Global's Evo Series 1.0 electronics. Compared to previous electronics, this design allows for an increase of inspection speed by a factor of up to four depending on the total number of sensors used. Consequently, the high-resolution tools can now be operated at inspection speeds that, in most cases, do not require the pipeline operator to reduce the pumping speed and thus the throughput of the pipeline.

THE ROLE OF ULTRASONIC MODELING

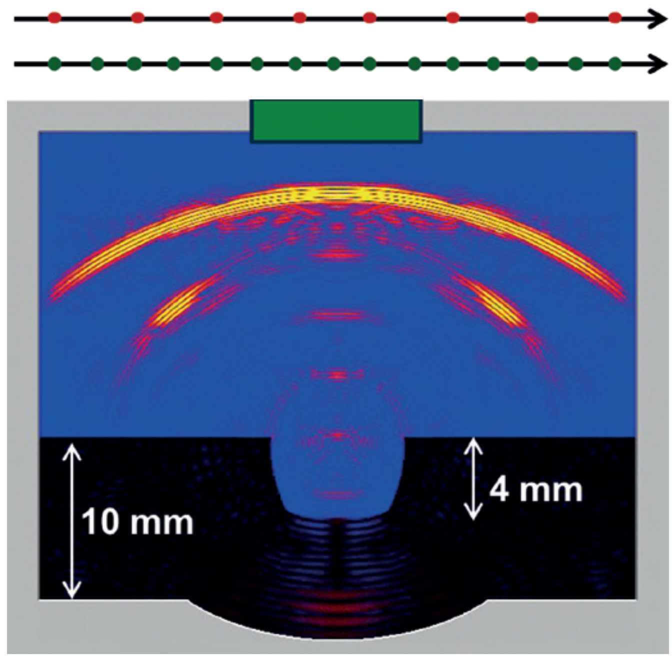
Ultrasonic modeling is being used more and more as a powerful tool for supporting and optimizing inspection solutions. Commercial products and proprietary developments are available using a variety of physical approaches. The most accurate tools from a physical point of view are based on finite element (FE) or finite difference (FD) methods. Using the latest computer technology, even 3D-modeling can be performed in acceptable time frames (minutes to hours depending on the testing scenario). Other tools using approximations such as ray tracing allow even faster calculations. However, the intrinsic limitations of these methods need to be kept in mind.

Type of Inspection	Axial Resolution (mm)	Max. Inspection Speed (m/s)
Metal loss inspection		
UM	3.00	4.0
UMp	1.50	2.0
UMp+	0.75	1.0
Crack inspection UC	3.0	3.0
	1.5	1.5

Table 2 – Maximum inspection speed obtained with Evo Series 1.0 depending on axial resolution for different inspection types

NDT Global has developed its own modeling software based on the FD approach. The software allows for the precise modeling of many testing situations. In particular, the testing parameters (geometry, defect type, defect size, ultrasonic sensor characteristics, medium etc.) can be easily modified to enable parameter studies in a much faster way compared to experimental studies. For special situations, it is recommended to verify the modeling results by selected experiments. However, the appropriate usage of ultrasonic modeling can reduce costs and time. In the foreseeable future, its application will become more and more a convenient part of the development process for ultrasonic inspection solutions.

For example, Fig. 9 shows a modeling result obtained for the ultrasonic inspection of a pinhole in a girth weld. Here, the defect width is 5 mm and the depth is 4 mm. The situation can be compared with the pinhole defect shown in Fig. 6. The ultrasonic probe is scanned across the weld with axial resolutions of 3 mm (probe diameter 10 mm) and 0.75 mm



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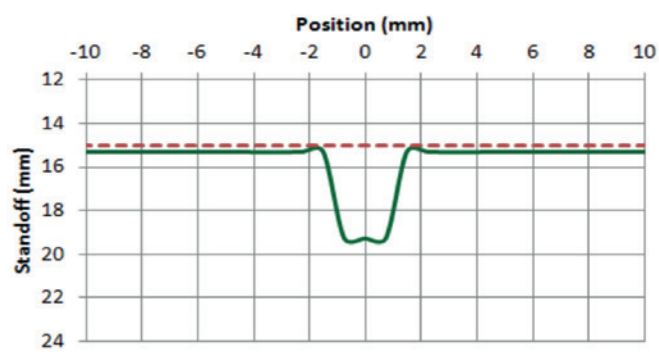


9b

Figure 9 – a) Ultrasonic modeling of a pinhole in a girth weld. b) Result of standoff measurement when scanning across the weld (axial resolution: red: 3 mm, green: 0.75 mm)

(probe diameter 6 mm). The first scan corresponds to the former standard UM, whereas the second scan is simulating the UMp standard. Fig. 9.b shows the results of the standoff recording obtained from 24 simulations. Using the UM resolution, the pinhole is not detected (no change of standoff signal measured) while the UMp simulation yields an accurate profile of the defect with the correct depth. The simulation can be easily extended to test the influence of wall thickness, defect shape, probe size, probe focusing, medium properties, etc., which would obviously require much more effort if would be performed experimentally.

TRENDS

The progress of ILI will continue in the future although the performance capabilities of latest ILI tools have already reached a very high level compared to the first generation tools. There are several improvements that are already apparent today. Some of these were driven by developments resulting from other applications that needed additional development steps in order to be implemented into an ILI tool; others were driven by new challenges from the pipeline side where, for example, more difficult environmental conditions have to be faced. Some of the trends are briefly touched upon in the following sections.

Combined Solutions

Based on the continuous miniaturization of electronic components as well as the progress in the development of sensors used in ILI tools, a combination of several independent inspection technologies in a single tool will be one of the next targets. NDT Global used a combined metal loss and crack detection tool for the first time in 2007 [3].
Such combination tools may also be equipped with additional inspection modules providing, for example, geometry inspection and inertial navigation systems (INS) all in one inspection. Combined inspections offer several benefits for the pipeline operator:

- The mob/demob and cleaning activity is required only once.
- The different data sets are perfectly aligned. This is very helpful for data analysis (feature discrimination, evaluation of combined defects).
- Applying two independent inspection technologies for the same feature type improves the POD as well as the sizing accuracy [5].

Challenging Applications

Some of the most challenging applications of ILI are related to the inspection of offshore pipelines. These challenges can be categorized according to:

- Environment: High pressure, high temperature
- Materials: Clad pipe, lined pipe, austenitic alloys, thick wall
- Type of line: Flow lines, injection lines, production lines, risers, dual-diameter lines
- Medium: Crude oil, condensate, seawater

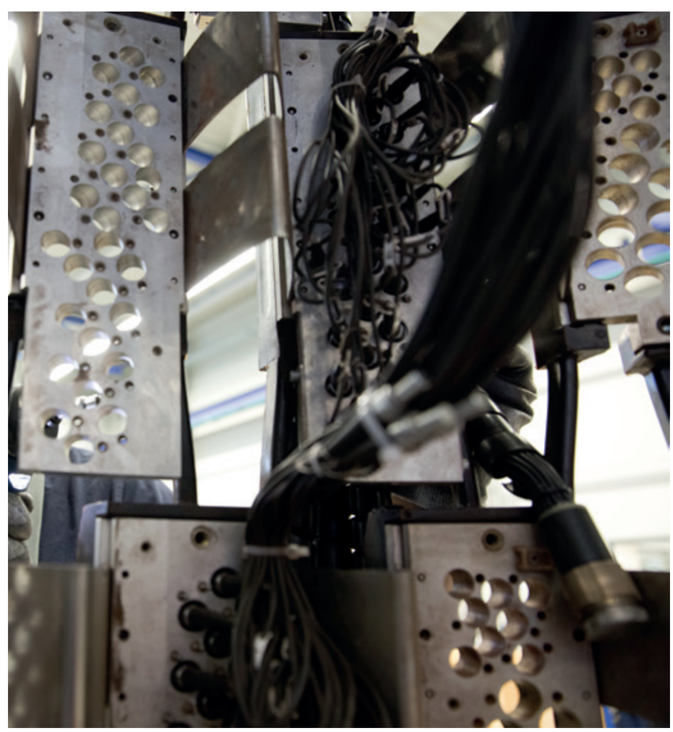
The challenges become even more demanding when the oil and gas production will proceed from deep sea into the area of ultradeep sea (depths > approx. 2000 m). NDT Global is prepared for these challenges having developed a variety of tools for the inspection of deep sea pipelines [6]. These tools are frequently applied for metal loss and crack inspection on a routine base in offshore production fields worldwide.

SUMMARY

The main task of inline inspection is the early detection of potentially hazardous pipeline anomalies (e.g., metal loss) as well as their precise sizing thus providing reliable input data for integrity assessment. For the inspection of liquid pipelines ultrasonic tools offer specific advantages with regard to resolution as well as to measurement accuracy. Since their start in the early eighties, these tools have been considerably improved by taking advantage of the progress in electronics, data processing technology, and data storage capabilities made available from other application areas.

For example, the current achieved measuring resolution allows for the reliable detection of tiny pinholes at higher inspection speeds than available before. Apart from progress regarding the inspection tools, ultrasonic modeling is becoming more and more important as a supporting tool for a better understanding of ultrasonic signal behavior as well as for optimizing inspection solutions.

SOME OF THE MOST CHALLENGING APPLICATIONS OF ILI ARE RELATED TO THE INSPECTION OF OFFSHORE PIPELINES



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