PHASED ARRAY TECHNOLOGY FOR AUTOMATED PIPELINE INSPECTION

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Abstract: State-of-the-art pipeline inspection tools with single element ultrasonic probes are limited with regard to their inspection capabilities because of the fixed arrangement of the sensors within a sensor carrier.
Phased Array Technology allows simultaneously performing different measurement tasks, e.g. crack detection and metal loss inspection; hitherto two measurement runs with different sensor carriers were required.
With Phased Array sensor system, as applied in the new UltraScan DUO™ ILI tool, the ultrasound beam generated by virtual sensors can be directed to different incident angles, its characteristics can be adjusted to match the actual pipeline medium and measurement task.
The sizes of the virtual sensors and the sensor overlaps can be optimized, e.g. for the measurement of small size pits.
The usage of Phased Array Technology allows higher inspection speed and improved defect detection capabilities.
The measurement principle and the inspection tool will be described. Prototype measurement results will be presented.

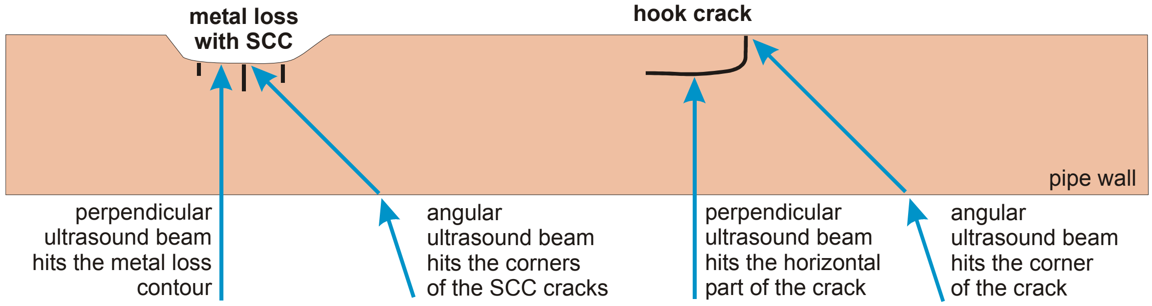
Introduction: Pipeline operators face many threats to the integrity of pipelines. Sophisticated non-destructive testing technologies and measuring devices are being used for diagnosing the pipeline condition, e.g. for detecting cracks and metal loss defects. Especially for older pipelines, hydrotesting is no longer accepted as an alternative to defect monitoring using non-destructive testing devices like ultrasonic inspection tools.
However, until now, different inspection tools with suitable sensor arrangements are required for the different measurement tasks resulting in high mobilisation cost and loss of pipeline throughput.
A further problem, quite often, is that the data recorded with different inspection tools need to be correlated. Otherwise, indications of defects present in the data sets of different inspection runs at same locations may be overlooked or not considered correctly.
These are the reasons why GE Energy started the development of the new UltraScan DUO™ pipeline inspection system based on Phased Array Technology. The main advantage of this technology is that the aperture, shape and direction of the ultrasound beam can be controlled by the electronics. This opens the following new possibilities:

- Crack detection and corrosion measurement can be carried out in one run.
- Size and overlap of virtual ultrasound sensor can be adjusted electronically to the individual measurement task.
- Incidence angle of the virtual ultrasound sensor can be adapted to the actual pipeline medium.

During the different development phases of the UltraScan DUO™ system, synergies from other GE applications of ultrasonic Phased Array Technology were used intensively, e.g. solutions for medical applications as well as for manufacture control during pipeline production.
One of the main motives for adapting the Phased Array Technology for pipeline inspection is the improved capability to interprete complex defect types:

- Identification of cracks and metal loss in SCC areas.
- Discrimination between lamination and SCC.
- Discrimination between metal loss and crack-like defects.
- Identification of hook cracks.

The benefits of a new pipeline inspection system like UltraScan DUO™ in connection with these complex defect types are demonstrated in the following Figure.

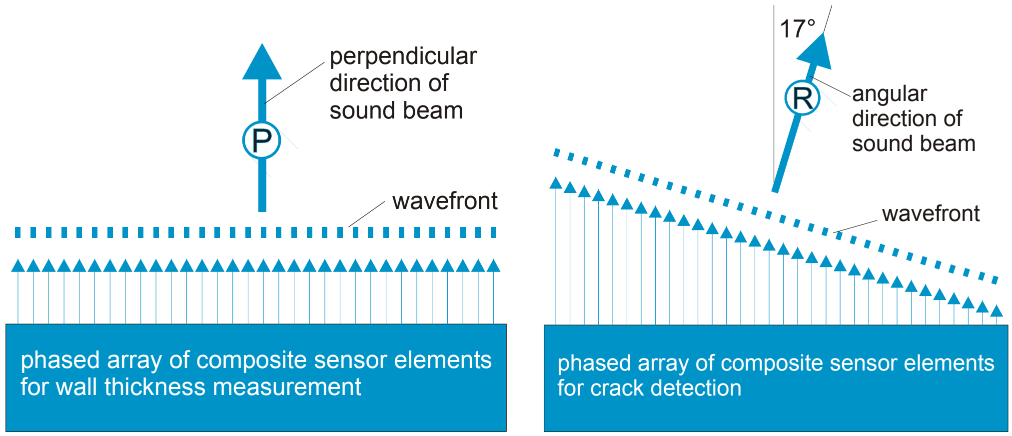


Defects like "metal loss with SCC" or "hook cracks" are detected with optimum POD and POI if both perpendicular and angular ultrasound beams are used.
The perpendicular beam targets the flat horizontal parts of the metal loss contour and the hook crack. However, the interpretation of the ultrasonic data would lead to the conclusion that these might rather be pure metal losses or laminations near the surface than anything crack-like.
The angular beam hits the corner reflections of the cracks and the interpretation would quite safely lead to the conclusion that these are really cracks. However, determination of the metal loss part in the first case or the determination of the extent of the flat horizontal part of the hook crack is not always possible with the necessary accuracy.
An ultrasonic tool with WM and CD capabilities, with perpendicular as well as angular sound beams, would give best oportunities to detect, identify and size such defects with maximum confidence. Hitherto, the state-of-the-art method for such a combined inspection is accomplished in two individual inspection runs. The practical limitation of such an inspection is a tremendous amount of correlation work costing a lot of time and effort, perhaps in some special cases considered to be worthwhile.
An inspection using the UltraScan DUO™ tool provides the ultrasonic data of the different measurement types simultaneously and in the same data format. Correlation is therefore not necessary.

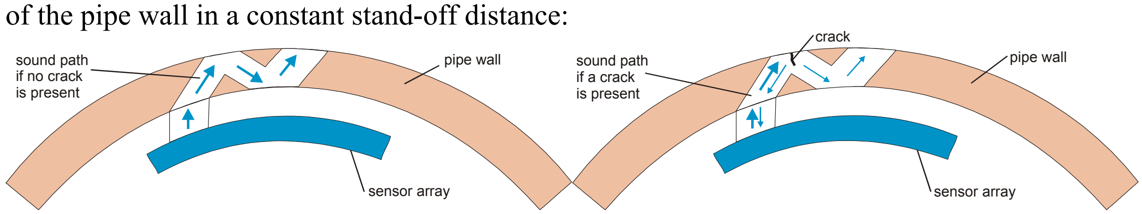
Nomenclature:

CD	= Crack Detection
ILI	= Inline Inspection
POD	= Probability of Detection
POI	= Probability of Identification
SCC	= Stress Corrosion Cracking
WM	= Wall thickness Measurement

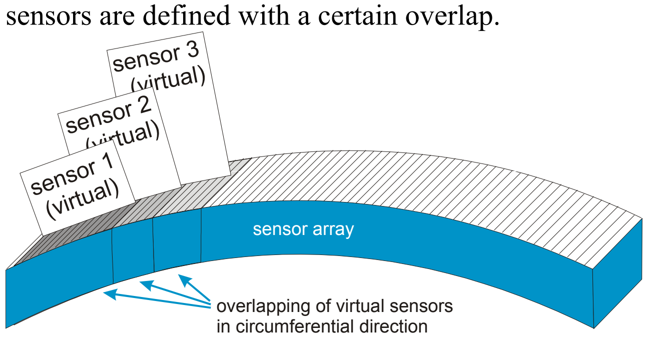
UltraScan DUO™ Operating Principle: The UltraScan DUO™ uses Phased Array Technology. The central elements of this technology are arrays built up of composite sensor elements, which are controlled individually by the ultrasound electronics. The way how these composite sensor elements are triggered determines the kind of sound beam that is generated and the direction in which the sound pulse travels.
If a set of neighbouring composite sensor elements is triggered simultaneously, a perpendicular sound pulse is generated. The following picture (left part) shows such a "virtual" wall thickness measurement (WM) sensor built-up by a group of composite sensor elements.



If a set of neighbouring composite sensor elements is triggered with a certain time shift from element to element, an angular sound pulse is generated. The direction of this sound pulse depends on how the time shift increments.
The right part of the above picture shows a "virtual" crack detection (CD) sensor built-up by a group of composite sensor elements transmitting under a right angle of 17°. This is caused by positive time increments, i.e. the left sensor element is triggered first and the right one is triggered last. If the time shift would be negative, i.e. the right sensor element is triggered first, the sound pulse would be transmitted under a left angle.
For the ultrasonic measurement of a pipe wall, the Phased Array is led along the internal surface of the pipe wall in a constant stand-off distance:

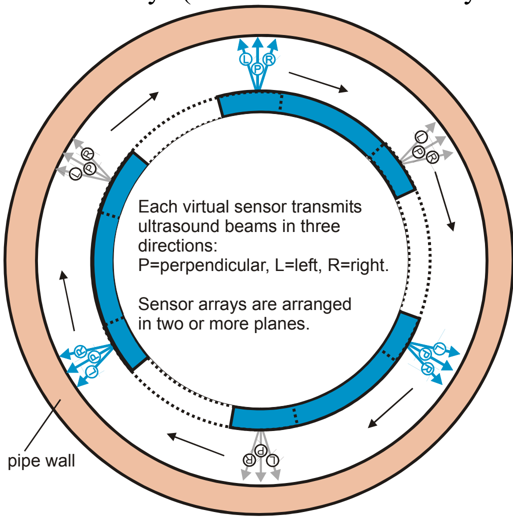


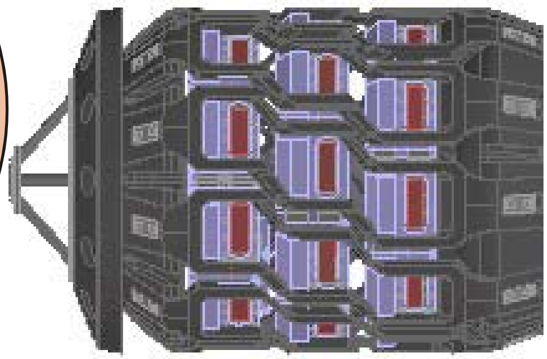
A virtual sensor is activated by the ultrasound electronics to shoot in the desired direction.
In the case of crack detection with angular sound beam, the sound wave propagates through the liquid and is then coupled into the pipe wall where it continues to propagate (left part of the above Figure).
If a crack is present in the pipe wall, part of the sound energy is reflected and received by the same virtual sensor (right part of the above Figure). The position of the crack within the pipe wall is calculated using the time-of-flight of the signal echoes.
Each sensor element is individually controlled by the ultrasound electronics. Therefore, any set of sensor elements can be used as a virtual sensor. In the practical application, neighbouring virtual sensors are defined with a certain overlap.



With the sensor overlap, an optimum circumferential coverage of the pipe wall is achieved. Moreover, depending on the inspection tasks the number of sensor elements to be combined to virtual sensors can be varied. A pitting inspection, for example, can be carried out with much "smaller" virtual sensors than a general corrosion inspection.

The sensor carrier of the UltraScan DUO™ tool consists of two or more sections with rings of Phased Arrays (number of Phased Arrays depends on the pipe diameter).





The Phased Arrays on the sensor carrier sections are arranged in a way that each array covers a certain section on the circumference including minimum overlaps with the neighbouring arrays.

Conventional Ultrasonic Technology vs UltraScan DUO™ Phased Array Technology: Both technologies are based on time-of-flight measurement of ultrasound pulses that are generated by a sensor system and coupled into the pipe wall via a coupling liquid.

Conventional Technology:

The general shape of a sound beam and its travel direction are fixed for each sensor in the conventional technology. This means that for each application an individual sensor arrangement must be provided mechanically.

If measurement conditions are changed, a different mechanical solution for the sensor carrier including a new selection of suitable sensor types is necessary.

Phased Array Technology:

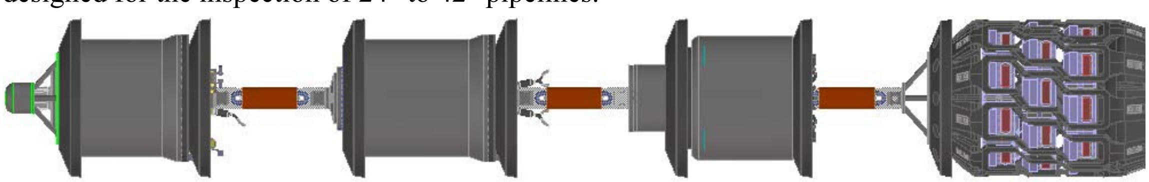
With the Phased Array Technology, virtual sensor arrangements are programmable.

This enables the individual virtual sensor to shoot in different direction and with different sound beam characteristics, e.g. smaller sound beam for pitting inspection.

For inspection jobs where the measurement characteristics of the pipeline medium are not clear during the job preparation phase, the ILI tool settings can be left undefined until the arrival of the GE technicians onsite. As the sound beam settings are all performed via computer interface, there is no need for mechanical changes on the sensor carrier or manual calibration work on the sensors and sensor electronics.

Even if the measurement conditions change during an inspection run, the ILI tool is able to adapt the current tool settings to the new situation.

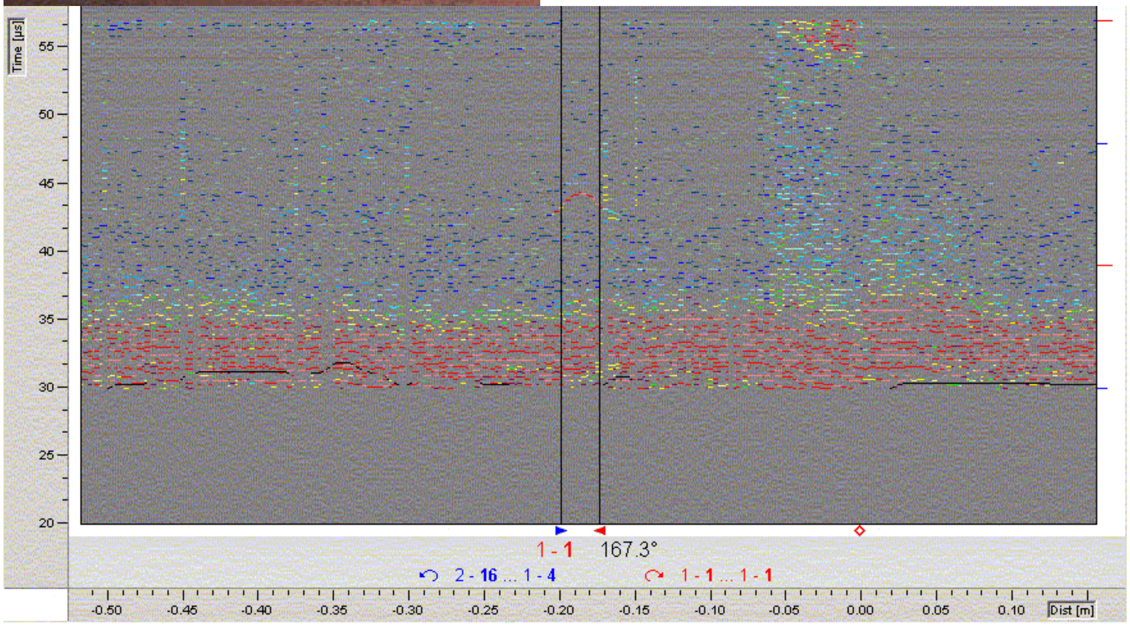
Development Program for UltraScan DUO™: The first UltraScan DUO™ generation was designed for the inspection of 24" to 42" pipelines.



power supply and tool control | ultrasound electronics and data storage | sensor carrier

The Phased Arrays are approx. 100 mm long and comprise about 200 composite sensor elements.

Virtual sensors of any size can be formed, transmitting a steered beam at a predefined incidence angle. This angle can be chosen for perpendicular or inclined incidence onto the pipe wall.
Appropriate definition of virtual sensors in reception mode allows the acquisition of measured data representing defects and anomalies as well as the thickness of the pipe wall.
To cover the complete pipeline circumference, a suitable number of Phased Arrays are positioned along the internal circumference of the pipe wall with sufficient overlap.
Data generated by the Phased Array sensors are reduced and compressed onboard the inspection tool.
Measurement data are being analyzed off-line by means of A-, B- and C-Scan representations.



The tool performance of the UltraScan DUO™ system is better or at least as good as the specifications of ILI tools using conventional measurement technology, especially the POD, POI, sizing resolution and accuracy.
The arrangement and the triggering of the virtual sensors are continuously varied for the different defect types and continuously adapted to the current measurement conditions.
Therefore, a stable inspection quality is achieved for all kind of defect types.
The main inspection figures are:
- Min. detectable crack size of 25 mm length and 1 mm depth,
- Pits of approx. 5 mm diameter detectable,
- Wall thickness measurement resolution of 0.1 mm,
- Direct wall thickness measurement down to approx. 1 mm thickness.
The compact dimensions of the Phased Arrays and the associated electronics together with the lower power consumption allow the UltraScan DUO™ tool to be of short length and to pass 1.5Dx90° bends.
The multi-mode measurement capability (combined CD and WM inspection with high tool speed) causes minimum flow disruption for the regular pipeline operation.

Notes on Some Development Challenges: For inline inspection, the measuring system must cope with the extreme conditions present inside the pipeline. Therefore, the following design criteria had to be followed for the new UltraScan DUO™ tool:
- Low power consumption and little heat dissipation.
- Small mechanical sizes.
- Resistance against harsh mechanical, thermal and chemical environment (temperature, pressure and aggressive pipeline media).
- High accoustic emission and sensitivity of single transducer elements.
- Minimum cross-talk and interaction between the individual signal channels.
- High array homogeneity.

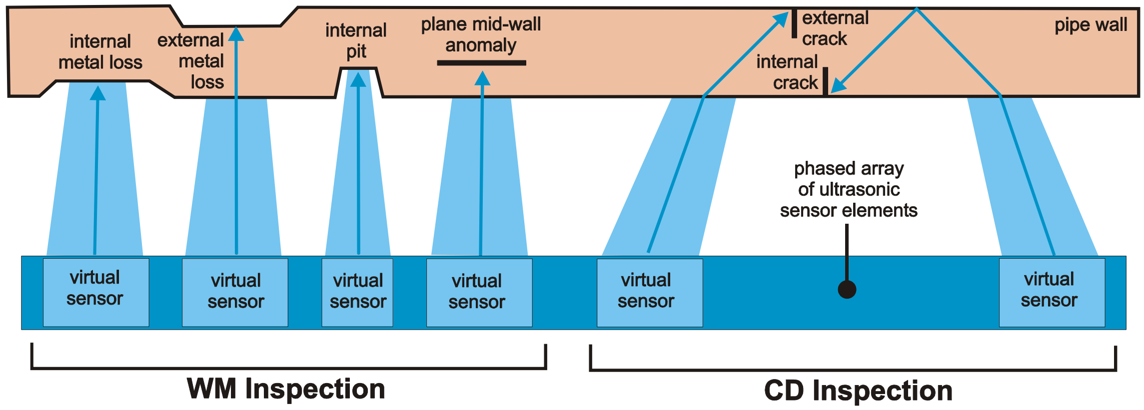
The main functional elements of the measuring system are as follows:
- Phased array probe
- Multiplexer
- Phasing electronics
- Data processing electronics

At the end of the development phase the following achievements were reached:
- Total power consumption of one phased array probe including multiplexer and phasing electronics was measured to be in the order of 10 W only.
- More than 5000 transducer elements are steered and read-out for a 24" pipe application, compared to about 500 channels in a conventional pipeline inspection tool. Therefore, a high degree of miniaturization and parallelization of the measuring electronics was necessary. Furthermore, the "front-end" of the excitation and data acquisition electronics had to be located close to the phased array probe.
- Small cross talk and inter-element variations were achieved by the selected design.
- The measured signal-to-noise ratio is significantly above 30 dB, even with small virtual probe sizes.
- The phased arrays were designed for harsh pipeline environment, which is a quite challenging task for complex devices consisting of stacked components, adhesives and casting materials.
- The arrays were qualified by long-term exposition to aggressive pipeline products including solvents at high pressures and high temperatures.

Special Applications for Pitting Inspection: For the detection of small pits the technical parameters of the measurement set-up need to be adapted with the following effects:
- Slimmer lobe of the sound beam;
  this is achieved by building-up smaller virtual sensors with suitable focus.
- Shorter circumferential scanning distance;
  this is achieved by a high number of virtual sensors with sufficient overlaps.
- Shorter axial scanning distance;
  this is achieved by increasing the ratio between "pulse repetition frequency" and "tool travel speed".

Without changing the hardware, the UltraScan DUO™ system provides a special pitting inspection mode for detecting pits of half the size than the standard metal loss inspection just by optimizing these three parameters.
Any doubt in case of very small but deep pits can be clarified during the data analysis process by interpreting the full wall thickness information contained in the related A-Scans of the whole pit area.

Summary: The following Figure summarizes the main defect types detectable with UltraScan DUO™:



Phased Arrays of composite sensor elements allow to built-up virtual sensors of different sizes and shooting in different directions. Metal losses and laminations are detected with perpendicular sound beams, cracks with angular sound beams.

A prototype UltraScan DUO™ was run successfully in the GE Energy test loop in Stutensee, Germany. For commercial inspection projects the UltraScan DUO™ system is available in Q4/2004.