PHASED ARRAY POUR L’INSPECTION AUTOMATISÉE DES FORGÉS

Phased array technique applied to the mechanized inspection of large forgings

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SUMMARY

intelligeNDT Systems & Services est la composante allemande de AREVA NDE-Solutions, une division qui regroupe l’ensemble des composantes CND de AREVA NP.

Depuis la fin des années 80, intelligeNDT & Services a développé de nombreuses techniques pour améliorer la qualité et l’efficacité des inspections des composants nucléaires. En particulier, nous avons développé et qualifié plusieurs techniques ultrasons (conventionnels et multi-éléments) ainsi que des manipulateurs (automatiques ou semi-automatique). Nous avons su transférer cette expérience à d’autres applications, et notamment l’inspection de grande pièces forgées, de composants en acier et de structures soudées.

Aujourd’hui, nous disposons de trois lignes de produits clés pour répondre à tous les besoins de nos clients.

Dans cette présentation, nous exposons des systèmes innovants et spécifiques dédiés à l’inspection de viroles, disques, dômes, essieux déjà installés chez nos clients de référence.

intelligeNDT systems & Services, the German component of AREVA NDE-Solutions, specializes in mechanized non-destructive testing systems and services and have succeeded in transferring our nuclear inspection technology and know-how to the large forging inspection industry.

Since the late 80’s, intelligeNDT has developed many innovative techniques for the inspection of in-service nuclear components. In particular we have developed and qualified several ultrasonic conventional and phased array techniques as well as the mechanical manipulators (automated or semi-automated) for the inspection of various forged components. We have transferred this extensive experience to other applications, and in particular the inspection of large forgings and steel components within the manufacturing process (volume inspection), as well as of welded structures.

Today we have several great references in this market and has three key product lines to address all the needs of its customer.
In this presentation we show examples of our qualified UT and manipulator techniques and how these have been transposed to industrial applications. We show specific innovative systems for the inspection of shells, discs, domes, axles that have been installed at our reference customers. We also show in some details the concepts of our rugged and reliable constructions as well as the benefit of our UT technology and know-how.

INTRODUCTION

In the nuclear, chemical, Oil&Gas and power generation (steam, gas) industries, ultrasonic inspection of large steel components, as flaws in large components frequently cannot be repaired, ultrasonic inspection, and flaw size determination are vital factors. This inspection is performed primarily on machined surfaces, but in an early state in the manufacturing process to avoid unnecessary costs.

Today all these components must be inspected and manual inspection is still predominant world wide although the percentage of automation in rising fast. The method of inspection is classically described in the relevant codes (ASME, RCCM, API etc.) and end customer procedures (Shell, GE or Siemens to name a few.). The mechanization (or automation) of these inspection process aims at offering several key advantages. The most straightforward advantage is of course an increased productivity achieved through a faster inspection and a large part of the evaluation being done in masked time (while the inspection is performed). However other advantages are inherent to an automatic process such as repeatability and reliability of the inspection, traceability and record keeping. These factors are nowadays essential to a good quality assurance and safety process, and help reduce significantly the exposure of the manufacturer as well as of the end customers to industrial accidents.

inetlligeNDT ultrasonic inspection machines are designed specifically to bring to the user the full extent of all these advantages, focusing particularly on the industrialization aspects of the complete systems. They are not only NDT testing systems, they are German quality machine tools, fully integrated in their environment and which can be managed and utilized as all other rugged machine tools in the plant.

In the recent years we have supplied many of these machines to some of the most renowned forges in the world, such as Saarschmiede (2 disc inspection units and 1 shaft unit), Buderus (shaft). These units are utilized for the inspection of forgings according to the procedure of end customers. Our systems are qualified according to GE, Siemens, MAN Diesel & Turbo, Alstom and MTA. One key advantage of our systems come form the possibility for the end customers to own SAPHIR evaluation stations for remote data over-check. Siemens in Muelheim and Berlin have several licenses of our evaluation software.
FROM NUCLEAR IN-SERVICE APPLICATIONS TO AUTOMATIC SYSTEMS FOR MANUFACTURING QUALITY INSPECTION.

InetlligeNDT as well as the two other components of AREVA NDE-Solutions (Intercontrole and AREVA NDE-Solutions USA.) have gathered extended experiences through more than 35 years of in-service inspection of steel components (RPV, Steam generators, pressurizers) installed in nuclear plant in Germany and many other countries, France, Spain, Sweden, China, Japan, USA, Brasil, Hungary, Ukraine, etc.

Through the years, as our inspection teams qualified more and more inspection methods, our manipulators, control units, instruments, software and end effectors have progressed in performance, ergonomics and ability to adapt to many different applications. We now use the same electronic unit as well as a slightly adapted version of the nuclear inspection software for all the automatic systems used for manufacturing quality inspections.

Of course differences exist between in-service mechanized inspections and automatic system used in manufacturing, but the principles and the key components are identical. Most inspections performed on nuclear plants in-service can find applications in manufacturing. The shell ID and OD inspections, the weld and nozzle inspections are directly transposable to manufacturing. The inspection of large forgings such as shells and discs are not dissimilar to other volume inspections of large components.

InetlligeNDT offers three type of automated machines for the inspection of large axi-symmetrical large components.

- Machines for discs and shells,
- Machines for long cylindrical components such as axles and rotors,
- Bespoke systems for specific components or to meet specific loading-unloading requirements and extra large components (120 tons or more, large diameters).
AXLES, SHAFTS AND ROTORS MACHINES

The automated inspection of turbine/generator axles, shafts, and rotors is based on a horizontal lathe type of mechanics, the shaft lying on rollers with anti-drift devices and the probes being motioned by a tower sliding along the axis of the shaft.

*Typical horizontal lathe type machine*

*Diagram showing the probe arrangements with Phased Array probes*
All our systems can be fitted with specific phased array electronics, software and probes. The use of phased array probe is double: a) to reduce the number of probes and b) to optimize the detection and sizing of defects at all angles. One phased array probe generates all the needed radial incidence angles (e.g. 0°, ±6°, ±12°, ±18°, ±24°. And conventional probes are also used: radial/tangential ±45° and axial ±45°. The alternative to the phased array probe is, in this example to use 9 conventional probes with a 9-fold adaptation to diameter. If more angles are also demanded for the axial inspection what is the case for larger diameters, two phased array probes can be used to generate the beams at 45°, 60°, and 70° by two phased array probes.

**DICS, DOMES AND SHELLS MACHINES**

The discs, domes and shells inspection systems are based on a rotation device (either rollers or a rotation table) and a vertical to tower or gantry to mechanize the motion of the probes, and can also be used for rotors under the conditions these can be positioned vertically, meaning that they must not be higher than large (height/diameter below 2). The forgings are rotated, so the motion of the probe is simply along 2 axis (for the OD): vertical and horizontal. This is achieved with a fixed vertical tower and a horizontal arm: the horizontal arm can be fitted with special end effectors to ensure not only inspection from the OD, but also from accessible surfaces (sides and ID).

For these components as well, Phased array probes have been developed to reduce the number of angle beam probes. In addition due to the fact that most discs have an inner bore and that cracks tend to develop at the ID, a specific transducer has been designed to detect radial defects at the ID. This phased array probes has the capabilities to send the sound with the required intensity on either sides of the ID without generating a 0degree central beam, the reflection of which would hide the reflection from the potential cracks along the ID.
Diagram showing the probe arrangements with Phased Array probes

Inspection from underneath is also possible but imposes to use rollers instead of a turntable.

**Bespoke systems and systems for extra large components**

For very large shells (e.g. 6m diameter, 5-6m high, 120tons), extremely large and heavy axle (e.g. 300 tons, 3m diameter) or light & thin alloy large shells or boosters, specific mechanics based on turn tables are used.
MANIPULATORS

A key component of the automatic inspection systems is the manipulator, a generic term that depicts just as well robots, linear type mechanics or peculiar mechanical assemblies and the numeric controls that enable to animate and control them. In this field as well the experience acquired doing mechanized in-service inspections in nuclear has been paramount to our development, and later successful implementation, of large fully automated machines for various industrial applications, machines whose role is to displace the probes along uniquely programmed path along components to be inspected.

Automatic inspection is inherently different from manual or semi-manual inspections. A high degree of attention needs to be paid to the mechanical set up, in particular the positioning of the probes relatively to the component and also relatively to the other probes and to the scan path. Both of these parameters depend upon the characteristics of the probes (e.g. frequency, diameter, shape of the ultrasonic beams) and the geometry of the components, and it is only the fine tuning of these set ups that ensures all defects can be found even in they are not located directly under the probe.

Example of a manipulator used in Service for a BWR RPV shell OD inspection.

One of the key requirements of an automatic system is its productivity which is obtained simply by the optimization of two characteristics of the machine:

a) the up time of the machine must be has high as possible and as a general rule and objective INDT mechanical systems are designed to ensure ad minima a 93% up time, value which in cases can reach up to 97%

b) the time needed to inspect a given component.

c) The first parameter is linked to the quality of the machine, i.e. the soundness of its design, the quality of each and every component of the machine, and the attention to details in the assembly.
The second parameter is depending upon experience of automated UT inspection and is discussed in the subsequent section. However it is only our extensive experience with mechanized volume and weld inspection of vessels in nuclear stations, with its tough constraints n reliability, precision, repeatability and efficiency as to minimize time of exposure that has been enabled us to reach the level of quality and of performance that our machine can today deliver day after day.

Example of the rollers (adjustable in X and Y) mounted on our shaft machines, with anti-drift correction.

All our machines incorporate a specific NC/PLC based part rotating platform (either rotation table or a horizontal lathe type mechanics), to allow the complete inspection of all accessible surfaces (sides, OD, ID). The key aspects of the mechanical design are:

**Mechanics**
- Precision of the positioning and repeatability of the positioning
- Reliable mechanics
- Anti-drift or centering devices
- Specific shielding of all cables
- Specific electromagnetic protection of the entire machine (patented design)

**Drives and controls**
• Drives and motors from SIEMENS
  o Siemens NC 840 D or S7 PLC with two tableaus - on the rack and handheld
• 3d-scan control e.g. for conical geometries, simultaneous movement of several axes with 840D.
• EM-safety: CE-Certification with safety concept fully compatible with regulations

End effector
• Cube system to attached the probe holder to the scanning arm, allowing easy rapid dismounting and rotations
• Multi probes probe-holders
• Good coupling of the probes to the surface
• Oil or water coupling medium
• Closed circuit couplant feeding and collection device

Example of a probe holder for a single probe with adjustable squirting water feeder.

Automated inspection versus manual inspection

A priori path definition and probe positioning depends upon logic thinking and basic mathematics accessible to everybody, but in reality it is such an obvious task. Many problems must be solved all together and it is only the fine equilibrium that ensures success. Among these parameters we can identify three which are rather important: the relative position of the probes the pulse repetition frequency (i.e. how often the
electronics can fire the same probe and the parameters of the scan path (index, step, direction). We discuss later in this article the question of suppression of phantom echoes via adjustment of the PRF and the relative position of the probes. This problem has a great incidence on the linear velocity of the scanning. Another complex issue is the scant path parameters. To illustrate let’s imagine a simple raster scan of 2 lines strictly parallel and separated by an index of 15mm. Imagine now that the defect to be found, e.g. a FBH2 is located exactly in between the two lines. This means that the probe as it moves along the scan lines will pass above the defect, and therefore that the reflection form the defect will be of lower amplitude as if the index had been smaller. There is a value of the index beyond which the defects located in between two scan lines become undetectable. However a small scan index imposes a larger number of scan lines and therefore a longer scanning time detrimental to the productivity. There is therefore an optimization of the scan path parameters in needed.

This problem is even greater when the automatic inspection must be compared to a manual inspection. During a manual inspection even if the operator follows as well a raster scan path, the operator will adjust the position of the probe to optimize every small echo that may appear on the screen. He can either move the probe slightly off the scan path or skew the probe to optimize the incidence angle, tasks which machines cannot (yet?) perform simply due to the fact that the machine does not perform the evaluation (what the eye and brains of the operator do instinctively) and also because even if it would do so, the live feedback to the scan path is not yet an available function. Therefore when performing an automatic inspection one must remember that as a general rule the signal reflected by defects is not the most optimized signal and comparison with a well done manual inspection may show difference in amplitudes. Therefore the optimization of the contributing factors is very important and iNDT recently achieved to optimize an automated system so that all defects found manually were also found with the system with a amplitude difference lesser or equal to 3dB.

PHASED ARRAY TECHNIQUE

Phased array is a term that describes a technique which, based on probes made of several small elements and multi-channel electronics (1 channel per element in the probe) allow changing the focal point of the probe and also allows steering the sound beam at various angles. This technique was primarily developed in the medical industry to perform echographs and in the industry it was developed for nuclear inspections. iNDT performed the first phased array qualification in nuclear in Oyster Creek (PWR feed water nozzle mockup, with blind detection and sizing) nuclear plant in New Jersey, USA, in January 1988. Since, iNDT has developed its own electronics, and the recent developments in computer technology make the use of Phased Array technology a highly competitive option to conventional UT.
iNDT has developed since more than 20 years a unique line of Saphir conventional and phased array instruments. The new generation that will slowly replace the well known Saphir plus is the Saphir Quantum. This new instrument has a flexible architecture with modules of 32 channels, stackable to 256 channels. A parallel architecture offers full 256/256 channels configuration capable of handling a 16x16 matrix array. In addition, up to 8 parallel firing sequences (for each module of 32 channels) can be combined with different parameters, allowing to use up to 8 different PA probes (each with up to 32 channels). This new system has been built to offer a best in class signal quality with pre-amplification, minimized electronic noise and a dynamic range of 120dB. The unit is capable of a comprehensive self-check and of calibration via an automated calibration module. A database of probe parameters and scanning setups can be called. And various dedicated software are available, including a very advanced simulation software for UT and another simulation software for trigger path generation (when using Robots).

All our systems, Saphir plus and Saphir Quantum, can operate both conventional and phased array probes. One key differentiating factor is that iNDT develops and manufactures phased array probes. It is this ability to tailor phased array probes that allowed us to obtain better results with PA than with conventional probes. We can produce PA probes with the same footprint as the conventional probe(s) to replace and the design of the probe (size of the elements, choice of piezoelectric and front and backing materials) is optimized to deliver the best possible characteristics, which depending on the application can be a high steering power, or a high capacity to focus and emit a high intensity of sound.

Conventional probes performances from a detection point of view are in most cases sufficient, and all existing codes are based on conventional probes. However, these codes also allow the use of Phased array probes. Phased array probes provide in certain conditions some sizeable advantages, namely:

- Ability to focus and steer with one probe
- Improved SNR
potentially higher inspection time
reduction of number of probes and smaller footprint

The reduction of probes is obtained by using 1 phased array probe in place of several angle probes. In many cases the inspection code requires for the OD inspection to use up to 6 different angles (0°, 6 or 7°, 12 or 14°, 18 or 21°, 24 or 28°, 45° and 60°) both in clockwise and anticlockwise directions, leading to a total of 13 probes. One phased array probe can be used for all the angles between 6 and 28° for example), reducing the number of probes to 7.

An important part of the PA probes is the cable. For each element that constitutes the probe, one copper wire is necessary. So for a 32 element probe, the main cable is made of 32 wires. In order to minimise the attenuation and signal distortions of the signal as it propagates in the cable, iNDT designs and manufactures cables. All our probes can be delivered with detachable cables allowing in case of replacement of the probe or of the cable to limit the cost and the duration of the operation.

1) conventional dual crystals probe, 2) PA probe for diameters > 24”, 3) PA probe for small diameters. Showing our concept of probe detachable from the cables.
Probe Holder

The probes are handled by the probe holder whose primary function is to ensure proper coupling and the good sliding of the probes onto the component. The probe holder must also offer a great flexibility to adapt to various diameters, various number of probes and also capable of being exchanged in maximum 5 minutes.

One key element of our probe holders is the couplant removal device. This device whose role is to remove the couplant residuals just behind the probe plays a vital role to equalise the backwall echo as required in the procedures.

Software

The software used for these applications derives directly form the software used for our automated inspection services in nuclear plants. The basic features are:

- Complete acquisition set up interface (for conventional and phased array probes)
- Saving of all A-scans
- ALOK compression of A-scans
- Display of A, B, C, D and tomographic scan views for all probes (conventional or PA)
- Specific software for tomographic views
- Interface with various type of motion controls (Step motors, PLC, NC)
- Evaluation tools
- Automating indication reporting
PERFORMANCES

Due to our high quality UT electronics SAPHIR, also used for AREVA nuclear inspections, at 4MHz we can detect of 0,8mm FBH in rotors with 1,800mm diameter.

In Saarschmiede we achieved in 205/2006
- 2,2 m diameter shaft of 1mm FBH
- 3,5m diameter disc 1mm FBH

Speed of rotation can be elevated but usually it is the practical pulse repetition rate (PRF) that limits the scanning speed. The PRF is limited due to the long sound path in the component and the possible cross talking and ringing of the sound in the component. However we have designed specific system using parallel electronics, to combine conventional and phased array probes, arranged in a very specific manner to be able to decrease the inspection time by large factors (for 2 to 10 compared to a basic configuration with one conventional probe of each type).

As an example, a 400mm diameter shaft, 10meter long can be inspected (with 0 degree probes) in less than 45minutes. Combining 3 probes (0degree and forward and backward facing 45degree), the speed of inspection is therefore of 13,5minutes per meter shaft.

Ghost Echoes (ringing in the component)

The art of productivity improvement is to optimize the position of the probes and the PRF all at once. If software features can assist to optimize the PRF for each probe only a good experience really helps when many probes are used at once. To give an idea of the order of magnitude of the problem, the theoretical PRF assuming the sound would be attenuated sufficiently not to be detected after its second reflection on the backwall is usually in the rang of 1kHz when the effective PRF is usually below 100Hz.

CONCLUSION

AREVA NDE-Solutions Germany, IntelligeNDT systems & Services specialises in automated inspection solutions, and in particular provides automated turn-key systems for the inspection of forged components and other large metal structures. The key advantages of iNDT are its abilities to develop the suitable solution and to adapt or manufacture all components of the system if needed. However for standard geometries our systems use standard and proven modules for the mechanics, probe holders, controls, software, electronics. Technology is not used for the sake of having high technology but only in the aim to reach the performances defined by the customer. The key characteristic of our systems are:

- Input of comprehensive operating experience (from references)
- Reliable mechanics and controls
- Leading edge sensors technology, instrument and software
• Ability to modify and adapt these as we manufacture them
• Minimized susceptibility to electromagnetic noise
• Proprietary electro-tech solution for interference reduction.
• Integrated user-friendly operating interface
• Fully customizable solution
• Maximized productivity and availability Guaranteed by contract
• Short delivery