Evolution of the Ultrasonic Inspection over the Past Decades on the Example of Heavy Rotor Forgings

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Abstract. Several decades ago the first ultrasonic inspections were introduced to assure component integrity. Those were, in the beginning, manual, straight beam, contact probe inspections with simple, non-descript reporting requirements. The development of ultrasonic inspection capabilities, the change in design engineer requirements, improvements of fracture mechanics calculations, experience with operation, experience with the inspection technology, and probability of detection (PoD) drove the changes that have resulted in the current day inspections. This process is described on the example of heavy rotor forgings for land-based power generation turbines and generators and shows how sizing technologies were implemented, detection limits lowered, angle and pitch/catch (dual crystal) probes introduced, and automated systems required for the inspection. Due to all these changes, model based sizing techniques and modern ultrasonic techniques, like phased array, are being introduced globally.

This paper describes the evolution of the ultrasonic inspection over the last decades and presents an outlook for tomorrow.

1. Introduction

Siemens produces various products for power production and energy distribution. Parts of this product portfolio are steam and gas turbines as well as the appropriate generators (see Fig. 1). This paper is about the evolution of the ultrasonic inspection on the example of heavy rotor forgings (Fig. 1) built into these Siemens OEM products. This Siemens viewpoint includes the history of Siemens KWU and Westinghouse Power Generation.

This paper summarizes on the basis of [1] the ultrasonic inspection and its requirements for heavy rotor forgings. Zimmer et al [2] puts the focus on the description of the implementation of the ultrasonic inspection.
2. Early History of Ultrasonics

Ultrasonics started in the second half of the 19th century with the discovery of the magnetostrictive effect by J.P. Joule (1847) and the piezoelectric effect by J. & P. Curie (1880). In the same period of time the first theoretical works on acoustics were published, such as “The Theory of Sound” by J.W. Strut (Lord Rayleigh) in 1877.

However, only due to disaster a first application came up: On April 15th 1912 the Titanic collided with an iceberg, resulting in the death of 1517 people. The magnitude and public reaction to this accident resulted in huge efforts to prevent it from happening ever again. Therefore, an ultrasonic echo ranging system was invented by L.F. Richardson in 1912 and J. Fessenden built the first iceberg detection system based on ultrasonics in 1914.

In the same year World War I began and drove the development of submarine detection systems. Therefore, the application and development of ultrasonic echo ranging systems shifted, and in 1916 P. Langevin developed the so-called hydrophone for this purpose. However, before SONAR (Sound NAivation and Ranging) systems were ready for use World War I ended and development slowed.
In 1928, the Soviet physicist S.Y. Sokolov proposed using ultrasonics for non-destructive evaluation (NDE) of materials or to be more precise, for flaw detection in metals. In the following decades, the technology was further developed all over the world, especially during World War II.

With the development of electronics and with the change from a continuous wave to a pulse echo approach, ultrasonics became one of the most important tools for NDE. F. Firestone and D. Sproule independently developed pulse echo systems during World War II. Firestone used a single crystal probe and Sproule a dual crystal pitch catch probe.

This development of pulse echo systems and the availability of first commercial systems from Sperry (in Fig. 2 an early model of a Sperry Reflectoscope, developed by F. Firestone, can be seen) and Hughes after World War II were the start of industrial UT. Based on this, several other companies started producing ultrasonic pulse echo instruments. For example, Krautkrämer, Karl Deutsch and Siemens started even before 1950. Fig. 2 shows on the right side a Siemens Reflectoscope from approximately 1950 with a creative screenshot camera [3]. Siemens is not producing any more ultrasonic instruments for NDE but this was more or less the start for the Siemens Medical Business.

2.1 Start of the Ultrasonic Inspection of Heavy Rotor Forgings at Siemens

In 1952 R. Schinn and U. Wolff [4] published their successful application of an ultrasonic pulse echo system on heavy rotor forgings at Siemens-Schuckertwerke in Germany. They used Siemens and Krautkrämer instruments and inspected generator forgings with straight beam longitudinal testing only in the radial direction. Westinghouse also started in approximately 1950 with UT using Sperry Reflectoscopes. Also the start of using ultrasonics for the examination of rotor forgings at Siemens or respectively at former Westinghouse Power Generation began only five years after the start of the pulse echo systems, Literature exists which goes back to 1946 identifying Gebrüder Sülzer in Switzerland [5] using a Hughes system for a supersonic flaw detector.
How successful the use of ultrasonic instruments is, is shown by the fact that starting in the year 1954, the manual ultrasonic inspection of forgings within Siemens became mandatory and is still used today (see Fig. 3).

3. Typical Discontinuities

Ultrasound inspection gave material scientists and engineers a new view into critical components in the form of electronic signals that are indications of potential defects or other discontinuities in the material. As a result, it became necessary for Material and NDE Engineers to develop methods for categorizing the indications. Moreover, it became important to determine the relative detectability of various discontinuities based on which probes and scanning parameters were used. The following is an overview of typical discontinuities that are most commonly created during the forging and heat treatment process.

A metallic inclusion can be expected as one of the most difficult discontinuities to detect in a forging because the acoustic impedance of the inclusion is close to the acoustic impedance of the surrounding material. Due to this low contrast the metallic inclusion will hardly give any ultrasonic reflection if there is no gap to cause an efficient reflection.

Nonmetallic inclusions, which normally appear as non-concentric patterns or clouds, and indigenous inclusions are normally expected to result in quite good detectability with axial and radial UT inspections. This is especially true as they are oriented usually parallel to the surfaces due to the forging process.

Hydrogen flakes tend to form at grain boundaries and they appear usually as multiple randomly oriented single indications. The random orientation could lead to the fact that individual hydrogen flakes can be missed during inspection. However, as they normally form in numbers the chance of missing all of them is considered to be quite low.

Secondary pipes, which are formed during solidification of the ingot, ruptures such as bursts caused during forging at locations with highest shear, and tears caused by too fast heating are usually centered, if the forging process is homogeneous. Therefore, they should be detectable with radial scans, but require consideration for the diffuse echoes as the surface of such flaws is normally rough compared with the wavelength of the ultrasonic pulse, making sizing difficult. However, possible reductions in detection can be overcome in particular by observing a drop in backwall reflection amplitude.

Quench cracks can be initiated during quenching, starting at the surface and growing inwards. Therefore, the best way for UT detection is using shear waves or surface waves. Other NDE methods, like magnetic particle or dye penetrant, would typically be used to detect this type of flaws, as they are open to the surface of the forging.
3.1 Angled Discontinuities

While most of the typical discontinuities can be detected with radial or axial straight beam inspections, there are occurrences when a discontinuity is not oriented perpendicular to the surface or is not located in the center of the part (see sec. 3.2). In this case, the main wave front is not reflected into the direction of the probe, the amplitude of the received signal is lower and the indication could be missed due to the limited dynamic of the inspection system.

Fig. 4 shows an example for such a situation: In the case the probe is placed directly above the indication the reflected main wave front will miss the probe and the indication is not detected. Only when the probe is moved a diminished return signal can be seen from a part of the cone of the beam spread. However, the amplitude will be (drastically) reduced compared to an ideal perpendicular reflector. This leads to two issues: first being that the location of the indication is misjudged and second due to the reduced reflectivity the size of the indication will be underestimated when using amplitude based sizing methods such as DGS.

For a typical 25 mm (1.0 inch) diameter, 2 MHz or 2.25 MHz probe the -6 dB beam spread is about 4°. Therefore, the undersizing of indications tilted by more than 4° can be substantial.

Fig. 4 gives an idea of the severity of undersizing indications depending on the angle. Typically, such cross-sections are shown featuring multiple side beam lobes with extremely reduced amplitudes in between them as the result of monochromatic (harmonic) calculations using only the center frequency. Taking into account the limited band with character of real inspection systems for a polychromatic (transient) calculation [7] leads to a smoother cross section. Fig. 4 shows the result for a medium band pulse both using harmonic and transient calculation. Already for small off-center angles it shows a large drop in amplitude.
3.2 Off-Centered Discontinuities

The same applies to (flat) off-centered discontinuities in circular components like discs or shafts. Such discontinuities as shown in Fig. 5 may possibly not be detected directly. Only when the probe is moved around the part by almost 90° the indication will be detected due to the higher reflectivity of the flat side (however only with the beam spread). This will lead to a false estimation of the indications location because it will appear off by about 90° and the soundpath to the indication is longer than expected ($s' \geq s$). Additionally, the indication will appear too small when using amplitude based sizing methods, because it is detected off center beam. In the worst case the discontinuity will not be detected at all, if the amplitude response of the indication is smaller than the noise.

![Fig.5](image)

**Fig.5** Left: Detection of off-centered discontinuities in circular components with the soundpath $s$ or respectively $s'$ [1].

4. Sizing Methods & Fracture Mechanics

Beginning in the 1960s, design engineers adopted fracture mechanics methods into the design and evaluation of new and existing rotor forgings, requiring indication sizing steps to be added to the evaluation of indications found with ultrasonic testing.

Indication sizing in rotor forgings is done by amplitude based sizing methods. For indications larger than the beam spread, sizing by probe travel (echo dynamic sizing, e.g. -6 dB drop method) is used and for indications smaller than the beam spread area amplitude based sizing methods are used (like DAC or DGS). Both amplitude based sizing methods are found to provide sufficient consistency and reliability, and when combined with the use of safety factors give a conservative design approach.

4.1 Sizing by Probe Travel

For the sizing by probe travel the probe is moved in two (perpendicular) directions on the surface of the component, the signal on the screen is observed, and evaluated. The distance between points with defined amplitude characteristics (e.g. 6dB drop of the amplitude compared to the maximum indication amplitude) is then used to define the extent of an indication in two dimensions. The third dimension is given by the soundpath. Therefore, the extent in all three dimensions can be estimated for indications larger as the beam diameter.
Discontinuities which have to be found in forgings nowadays are pretty small. Due to the size of the components (discs can have diameters up to 3000 mm) and the resulting long soundpath and large beam spread and due to the small size of the discontinuities to be detected indication sizing by probe travel is not applicable in most cases. Therefore, other sizing methods have to be used.

For this application area amplitude based sizing is mostly used. The location of the indication in the component is given by the soundpath and the location of the probe on the surface. However, the information of the size is based on the amplitude of the reflection. Those methods compare the reflection amplitude of an indication to the reflection amplitude of reflectors with a known size, be it artificial reflectors like flat bottom holes (FBH) or side drilled holes (SDH) in the part, or simply the back wall. After a correction for different distances to the indication and the calibration reflector, the size of the indication is denoted in a unity of “equivalent reflector size” like “mm FBH”. In contrast to sizing by probe travel, different area amplitude based sizing methods are used depending on qualification of techniques on a location-by-location basis.

The most traditional methods used from the early days of ultrasonic testing employed Distance Amplitude Correction (DAC) based on calibration using multiple flat bottom holes machined into calibration blocks. Some of the specifications from Westinghouse required exactly this method. However this DAC was only based on two measured points: one at ~75 mm (3”) and one at ~280 mm (11”) and extrapolated to ~560 mm (22”) and ~840 mm (33”). This extrapolation was based on the inverse square law.

Already in 1950, five years after the start of ultrasonic testing, Kinsler and Frey published their book about the fundamentals in acoustics [8] with a theoretical calculation of the sound field of a piston source in the far field (this work is actually in general about acoustics). Seki et all [9] took this work a few steps further. Their work is the basis for all theory based sizing methods on Siemens and former Westinghouse designs.

Besides the DAC method (for which the extrapolation is also based on this theory), one of the theory based methods used at Westinghouse used the calibrating on only one FBH [10]. As this calibration is not done on the actual component (like normal DAC) some component dependent factors had to be taken into account. Therefore, several papers were published in the following years to compensate for surface roughness, curvature and beam attenuation.

A different approach was taken by different specifications at Westinghouse. Those specifications called for calibrating on the backwall of the component. Therefore, those component depending factors were automatically taken into account and eliminate the need for precision calibration reflectors.

In 1959 J. Krautkrämer published the Distance Gain Size (DGS or AVG) Method which is a method widely used in Europe. This method is actually based on the same theoretical basis and puts the information into a very handy diagram (in particular at a time in which it was not normal to have access to a computer). Hereby the amplitude loss (gain) of the backwall or of a particular FBH size is plotted against the soundpath. The different curves within this coordinate system start with the backwall curve on the top (low gain values) and multiple curves for different FBH sizes. Those FBH curves are parallel in the farfield and the gain increases with decreasing FBH value. With this diagram it is not only very easy to calibrate the equipment but also to size indications [11]. Up to the current day this method is used at Siemens for all new discs and shafts including former Westinghouse designs and also for the US market.
4.3 Implementation of Indication Sizing

Fracture mechanics was implemented in the 1960s and starting in 1970, the sizing of indications, using in particular area amplitude sizing, became a requirement for most large forgings for our industry. The first specifications were merely a single sentence in a 2-page forging procedure: “Intermediate echoes occurring during ultrasonic testing of an equivalent reflector size of > 5 mm Ø and all indications with a reduction of the backwall echo have to be reported”. This is in contrast to our present day 40-page specification (not counting the component specific riders).

5. Experience due to Turbine Operation

With exactly those inspection requirements an LP (low pressure) steam turbine rotor was forged in 1970 for a 330 MW steam turbine. After 16 years of operation, on New Year’s morning at approximately 6:08 a.m., one of the worst accidents in the history of power production turbines occurred (see Fig. 6). The rotor cracked, some of the parts flew through the wall of the turbine and of the power plant. Some parts were found up to 1.3 km (approx. 1 mile) from the power plant. Luckily nobody was hurt. [12, 13]

The analysis of the accident showed that the reason for this accident was a forging defect that had produced an ultrasonic indication during manufacturing inspection. It was evaluated at that time to be equivalent in size to a 5 mm FBH with a complete loss of the backwall. The indication was classified as a group indication of numerous (rather small) non-metallic inclusions and therefore accepted. However, after the accident, detailed metallurgical investigations determined the cause of the failure to originate from four secondary pipes. The largest pipe found was about the size of a hand and was off-centered. Due to this off-centering the indication size was underestimated by about 50 to 60 dBs (Fig. 4 right and Fig. 7 left). [12, 13]

This finding lead to a significant revision to the specification VGB 504 for the production of heavy rotor forgings. For the ultrasonic inspection of rotor forgings, angle scans became necessary, drastically increasing the importance and the effort for the ultrasonic inspection.

For components without a bore angle scans were introduced. The angles have to be in intervals of no more than 2 times the -6 dB beam spread so that an off-centered or angled indication would be undersized by not more than 6 dB. This means for a standard 2 MHz, 25 mm Ø probe that 7°, 14°, 21°, and 28° have to be used (Fig. 7 middle). Moreover, once an indication is found, intermediate angles are required to be used to maximize amplitude response allowing for best possible sizing of the indications.

Fig. 6 LP rotor failure from 1988 [12, 13].
Fig. 7 Left: Situation during the inspection of the rotor in 1970 [1]; Middle: Mandatory angle inspections starting from 1989 for forgings without bore [1]; Right: Mandatory angle scans for forgings with bore to cover a (highly stressed) zone around the bore [1].

For bored components the highest stressed areas are around the bore, making discontinuities in the radial orientation most critical. Therefore, a scan with the beam tangent to the bore and additional scans with higher angles to cover the highly stressed zone (determined by fracture mechanics) around the bore were introduced (Fig. 7 right).

Similar changes to the specifications in America had been made because of a different failure in 1974. This failure happened to an IP (intermediate pressure) – LP steam turbine rotor forging of a 225 MW steam turbine which was placed into service in 1957. After 17 years of operation, this rotor failure happened due to a combination of creep initiated fatigue and brittle fracture and resulted the forging splintering into multiple pieces (see Fig. 8). Detailed metallurgical investigations reported an area of MnS segregations as the crack initiator. Moreover, both temper and hydrogen embrittlement were found as contributing factors. The accident led specifically to adoption of boresonic inspections in the industry. [14]

Fig. 8 TVA Gallatin rotor failure [14].

6. Introduction of Further Scans

The manufacturers of early gas turbine rotor forgings used the ultrasonic inspection specifications for steam turbine rotor forgings. In the early 1980s gas turbines became more widely used for power generation and the specification for gas turbines rotor forgings was separated from the specification for steam turbines. Moreover, due to using stacked discs in gas turbine rotors, axial scans were introduced to improve defect detection probability.
Approximately at the same time angle scans were introduced [15]. They can be used for a more accurate inspection of critical areas like blade roots, coil notches and cooling bore areas.

7. Recent Developments of Ultrasonic Inspection

With the development of computer based ultrasonic instruments and electromechanical drives, automated ultrasonic inspection systems became practical. The advantages of the automated systems provide more precise control of key factors of the ultrasonic inspection process, especially probe positioning, scanning speed, contact pressure, probe direction and angle control. Also the detection of indications became more consistent and reliable with digital recording of the ultrasonic data. Due to recording, A, B, and C-Scan offline review and other evaluation methods became possible and allowed more consistent comparison with other examinations. The first automated inspection system used for Siemens rotor forgings was installed at Saarschmiede at 1995 [2] (see Fig. 9). Finally, with the year 2004 automated inspection became mandatory for certain critical components. Today, the automated inspection is mandatory for the majority of the large rotor parts.

Approximately at the same time the miniaturization of electronic circuits allowed the construction of first phased array systems for ultrasonic inspection. One of the first commercially available systems was the Siemens ALOK Phased Array Integrated Reliable (SAPHIR) inspection system [16] from 1996 (see Fig. 9).

Besides further automated inspection systems Saarschmiede started using phased array probes in 2002 to inspect all necessary angles with one probe and in 2009 Siemens implemented the use of phased array probes into the specifications.

To realize the demand to increase turbine generator performance over the past decades, the requirements for the integrity of forgings were raised and the detection sensitivity for small indications had to be improved. This was possible by taking advantage of better rotor forging manufacturing processes as well as improvements in ultrasonic technology. In the meantime, this resulted in the increase of the inspection sensitivity from the original equivalent of 5 mm FBH to 0,7 mm FBH.
8. Outlook

As shown by this publication although multiple developments in the history of ultrasonics were caused by war and disasters at least as many developments were caused by the technically possible or necessary. Future improvements have been identified for heavy rotor forging inspections:

- International harmonization of standards
- Better characterization of defects by improving the data analysis process to reduce risk of failures and increase manufacturing yield
- Standardized ultrasonic data files (DICONDE seems to be a good start)
- 3D Ultrasonic data fusion with other NDE data to improve sizing
- Incorporate complete NDE results into 3D CAD engineering tools for Design Engineers
- Ultimately incorporate subsequent NDE results after service exposure for the purposes of: feedback to manufacturing and design, lifing, and condition based maintenance
- Relaxation of inspection criteria by probabilistic design methods to improve design margins

References