Introduction

The international activities in developing new flaw characterization methods with special emphasis on acoustic imaging have been increased. To reduce the dependency upon amplitude information and due to the fact that flaw information is buried in the shape and fine structure of wave fronts, considerable attention has been given to the development of methods using time-of-flight information from different probe positions. For this reason, with mechanical scanners and specially build data acquisition and evaluation systems, a variety of ways to produce images has been developed. These include echotomography, linear or two dimensional mono- or multi-frequency holography, tip echo interference methods, ALOK (amplitude-, time-of-flight-locus curves), Phased Array, SAFT or Rayleigh-Sommerfeld Holography. These methods use mathematical algorithms which seem to be independent or which have been derived heuristically. Based upon the concept of elastodynamic diffraction theory together with that of tomography a concept can be derived which reveals the inner connection of these algorithms. Differences in the reconstructions arise due to limitations like limited aperture, limited bandwidth, use of mode converted signals or due to complex surface shapes. An attempt is made to cover the theoretical background, to give an overview on existing data acquisition systems and to describe the strength, weaknesses, and difficulties in producing acoustic images.

International Approach to Practical NDE-Problems

Flaw characterization requires a knowledge of flaw position, size, orientation, shape of cracks, crackfields, metallic or nonmetallic inclusions. Besides the many approaches for evaluating amplitudes, the imaging-technique becomes more and more important. This is not only based upon practical experience but on mathematical modelling techniques, too. For instance, as stated in [1], modelling Y-shaped intergranular stress corrosion cracks (IGSCC), the dB-drop technique measured primarily the ultrasonic beam profile rather than the crack depth. Generally the pulse-arrival-time method gave more accurate sizing results.

The most problematic defects and locations seem to be:
- surface connected cracks near the root of a weld
- underclad cracks
- cracks near the nozzle/shell weld
- multiple branched cracks
- IGSCC or thermal fatigue cracks in CCSS.

Many teams claim to have found by far the best technique in using either

- a multi-angle viewing inspections in contact technique 0°, ± 15°, ± 42°,
  ± 45°, ± 55°, ± 65°, ± 70° SEL (Fig. 1),
- a multi-angle viewing inspection including tandem technique (KWU-
  Germany) or
- an immersion technique were focal probes up to 150 mm diameter and 120
  mm height have been used with insonification angles of 0°, 45°, 60°,
  70° and where the total system was rotated in 90 steps around 360
  (Fig. 2).

Fig. 1. Multi-angle viewing inspection (CEGB/UK).

Fig. 2. Immersion technique with focal probes (CEA, Framatome).
Fig. 3. Transit time methods with normal or angled beam by tip diffraction methods (CEGB, UK).

Fig. 4. Transient time methods with and without mode conversion by tracking pulses via different routes (Harwell, Nippon Steel, RTD).

- transit time method with or without mode conversion by tip diffraction techniques with angled or normal beam (Fig. 3).
- transit time method with or without mode conversion by tracking pulses via different routes (Fig. 4).
- by using a two-probe technique and geometrical reflection diffraction or different signal processing techniques (Fig. 5).
- by using tandem-techniques (Fig. 6).

In addition more sophisticated signal processing techniques like
- deconvolution
- inverse filtering
- ALOK
- Holography
- SAFT
- Phased Arrays
Fig. 5. Two probe techniques (CEGB Harwell).

Fig. 6. Probe system for automatic ultrasonic inspection (KWU, Germany).

have been used by many institutes, part of them are listed below (Fig. 7).

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<tr>
<th>Method</th>
<th>Institute</th>
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<tr>
<td>Linear Holography</td>
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<td>Germany</td>
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<tr>
<td>&quot;Real-time&quot; linear Holography</td>
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<tr>
<td>Quasi 2D-Holography</td>
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<td>2D-Holography</td>
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<td>ALOK</td>
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<td>Phased Array-Sector Scan</td>
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<td>Battelle NW</td>
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Fig. 7. Signal processing techniques.
The following theoretical discussion tries within the scope of the K-space to give a common theoretical background to all the existing imaging methods. No discussed here are time constraints for data acquisition or image reconstruction, costs, size and weight for the hardware and minimum personal qualification for the operation of the systems.

THEORETICAL BACKGROUND

The NDE imaging of flaws with ultrasound is actually an inverse scattering of wavefields. There exist two possible approaches:

- the first one is an engineering and therefore heuristic solution of the inverse scattering problem based upon backpropagation ideas. The mathematical procedures are generally matched to the hardware components available to the engineer and to the actually recorded data fields obtained with this hardware. Examples are ALOK, mono- or multiple frequency holography, and SAFT.

- the second one is the mathematical formulation of inverse scattering and derivation of appropriate algorithms [9, 10], which are either matched to the existing data fields or which require appropriate data recording with proper sample intervals or amplitude resolution. The methods addressed in this paper are derived under the assumption that multiple scattering between flaws and between single scattering centers on one flaw play no significant role.

The advantages of the second method can be summarized as:

- due to a unified theory the algorithms can be compared
- formulas for the resolution capabilities can be derived
- signal processing methods can be justified theoretically
- the utilization of mode conversion and an extension to full elastodynamic problems seems possible.

Data Fields and Engineering Solutions to the Inverse Scattering Problem: SAFT and LSAFT

The following situation describes the situation which we encounter if we apply the Synthetic Aperture Focusing Technique [2] or its line-version LSAFT [3].

Let us assume that we have a planar aperture. In LSAFT the high-frequency data from each probe position are digitized by a transient recorder. The data are real and lie in the time domain. The probe is moved along one line in x-direction like indicated in Figure 8. In the

Fig. 8. Engineering approach to SAFT.
reconstruction space the image lies in the x-z-plane, that is, the plane given by the scanned line and the insonification direction. The engineering approach to the backprojection in the time domain goes as follows: every RF-data point which is relevant to scattering events in a selected pixel is summed up. Going through all possible pixels in the reconstruction space forms the image. In the 2D-SAFT algorithm, the probe is moved in x- and in y-direction and we get a real 3D-data field in the time domain. The pixel in the reconstruction space is now a cube and gain RF data point are summed up into this pixel.

Single and Multifrequency Holography

If we use time harmonic amplitude and phase information only, we arrive at the holographic reconstruction of defects (Fig. 9). Today there exist different equipments in the world like the portable, real-time holographic system for flaw imaging [4], the line-holography [5], the two-dimensional holography [6], and the multifrequency holography [7, 8].

Again let us assume that we have a planar aperture and discuss first the single frequency holography. The data are taken in a one dimensional (y=constant) aperture (line holography) or in a two-dimensional aperture (x-y-plane). Therefore we have a one-dimensional or two dimensional data field at a single frequency \( \omega \), and because of the phase comparison with reference signals we have a complex data field in the frequency domain. Applying the Rayleigh-Sommerfeld algorithm to this complex data field we can image from a plane at \( z = 0 \) to a plane at \( z > 0 \) and so on, because of the two-dimensional Fourier transform relationship between parallel plane wave-fields. With the knowledge of the distance "hologram plane to flaw plane" we get a one- or two-dimensional reconstruction formula which can be justified mathematically within the context of a generalized tomography. From the mathematical point of view the reconstruction is only valid for planar scatterers in the imaging plane. In the case of nonplanar scatterers an engineering solution would be to use multiple frequencies. This means we have a three dimensional data field and a three dimensional reconstruction.

Let us compare LSAFT and the two-dimensional RS-Holography. LSAFT yields a two-dimensional image in the B-scan plane, 2D-Holography a two-dimensional image in the C-scan plane. These are slices or "tomograms". Therefore it suggests itself to combine the idea of tomography with scattering theory to arrive at a non-engineering solution for flaw imaging.

![Diagram](Fig. 9. Holographic imaging of planar flaws parallel to the surface.)
Computer Aided Tomography (X-Ray-Tomography)

Let us assume we have an object extended in x- and in z-direction like pointed out schematically in Fig. 10a. A two-dimensional Fourier transform yields the K-space of the object (Fig. 10b). The actual situation is that in performing an experiment we have to transform our recorded data field into the K-space. If we would have all these transformed data look like Fig. 10b by applying the inverse two-dimensional Fourier transform we would produce exactly the object of Fig. 10a.

The question is, how can we produce these data?

One way is a data production by projections. In X-ray tomography an object lying in the x-z-plane (Fig. 11b) is illuminated under an angle \( \theta \). The signal picked up along the coordinate \( \xi \) is the X-ray projection \( P(\xi) \) under the angle \( \theta \). Now we can fill up our data space by a one-dimensional Fourier transform of \( P(\xi) \) with respect to \( \xi \) and arrange it along a line under the \( \theta \) in K-space (Fig. 12). According to the Fourier Slice Theorem we have now to vary \( \theta \) to fill up the K-space line by line (Fig. 12). A top view of K-space is illustrated in Fig. 13a, and the inverse 2D-Fourier transform reconstructs then the object (Fig. 13b). The results depend on sampling rate and number of views.

Diffraction Tomography - Through-Transmission - Single Frequency

Unfortunately with ultrasound, projections are not available. Due to scattering effects, the data field consists of "diffractions". Let us assume through-transmission or tandem technique like in single frequency holography: an ultrasonic wave at a single frequency insonifies an object,
and along a linear (or two-dimensional) aperture the diffracted data are recorded with respect to amplitude and phase (Fig. 14). The data \( H(\xi) \) which form the transmission hologram are now Fourier transformed. The Fourier transformed diffracted signals \( \text{FT}(H(\xi)) \) in the K-space lie on a semicircle with the center point given by the polar coordinates \((k, \theta_1)\), \(k\) is the wave number of the incident wave; the circumferential length corresponds to the aperture length and only parts of the circle are filled with actual data. The K-space can now be filled partly by varying the insonification angle - just similar to X-ray tomography. In X-ray tomography the frequency goes towards infinity and the circles degenerate into straight lines. Therefore X-ray tomography is a special case of diffraction tomography.
Experimental Situation

Data Space

(Reflection Holography)

Fig. 15. Pulse Echo Diffraction Tomography.

Diffraction Tomography - Pulse Echo - Single Frequency

Again we will assume that we transmit a single frequency wave - like in ultrasonic holography (Fig. 15), but that we receive the echoes in pulse echo technique. Now the Fourier transformed data $\text{FT}(H(\xi))$ cover the outer part of the circles. To fill K-space, again the insonification angle $\theta$ has to be varied. The reconstruction is obtained by a 2D-inverse Fourier transform.

If we use only one insonification angle and transmit longitudinal or shear waves at a constant frequency and record the hologram, it is now clear that this Rayleigh Sommerfeld Holography is a special case of the "Ultrasonic Reflection Diffraction Tomography" for only one look-angle. But the general context explained above allows now to derive for instance a formula for the resolution properties of RS-Holography for cracklike- and voluminous scatterers. Let us assume that a non surface connected crack like scatterer with the length $L$ is nearly vertical oriented and a holographic experiment is performed in tandem technique (Fig. 16). Performing the reconstruction in different depths $z$ results in an image spot of the crack which is of elliptical shape. As can be seen in the formula of Fig. 16 the length of the image spot in insonification direction $\theta$ is not only a function of the insonification direction $\theta$ and the wavelength, but of the crack size $L$ too. If the crack gets very large the axial resolution gets very poor. Despite this and with the additional knowledge that the crack is nearly vertical oriented, the crack depth extension $L$ can be calculated from the measured vertical extension of the image spot $L'$ and the insonification direction $\theta$.

Fig. 16. Axial resolution of Holography for nearly vertical oriented cracks.
Diffraction Tomography - Pulse Echo - Broadband

It is obvious that not only the insonification angle $\theta$, but also the frequency could be varied to fill K-space. This can be done either in the time-domain by transmitting short pulses (SAFT) or by transmitting step by step monochromatic signals of different frequencies (Multifrequency Holography). Let's assume a constant insonification angle $\theta$ (Fig. 17). The Fourier transformed data of the pulses in the time-domain or of the set of different frequencies will now fill K-space in the shaded area of Fig. 17 where the boundary circles are given by the frequency bandwidth of the exciting signal. To fill K-space more completely one has to vary $\theta$ in addition.

For small objects and large observation distances special versions to minimize the calculation time have been developed which are called FIFFIS (Frequency Independent Far Field Inverse Scattering) [9]. Using this method the data can be put immediately into K-space without performing a Fourier transform with respect to the aperture coordinate.

In Fig. 17 the incident wave field angle $\theta$ was held constant. In contrast to that using a pulse echo technique with varying angle of incidence one sees that K-space is filled with data according to Fig. 18; obviously the area of data coverage is larger than in Fig. 17, and this means that lateral and axial resolution are both improved. A special version of this procedure, called POFFIS (Physical Optics Far-Field Inverse Scattering) [11, 14] reduces computer time too by saving the Fourier transform if the data were taken in the far-field of the scatterer.
Up to now we have described how K-space will be filled with data. Figure 18 relates to the experimental set up for an LSAFT experiment. Therefore LSAFT (or SAFT in three dimensions) is nothing else but "Pulse Echo Diffraction Tomography". Embedding SAFT into the formalism of diffraction tomography allows now to improve its performance capability by

- an alternative data processing via K-space
- comparison with other procedures
- resolution enhancement via K-space extrapolation
- a formulation which takes into account mode conversion.

In Fig. 19 with experimental data this alternative K-space data processing is compared with time domain LSAFT-processing. Flat bottom holes have been drilled from the backside of a test specimen with wall to wall distances in lateral and axial directions of 1 to 6 mm. The results are quite similar.

CONCLUSIONS

The theoretical part tried to explain that only with a completely filled data set in K-space a true reconstruction can be performed. To fill K-space as good as possible one has to increase the bandwidth of the system and simultaneously try to get a 360° aperture. This can easily be performed on turbine shaft rotors but not on pipes, nozzles or pressure vessels. For the latter cases different approaches have been developed like the multiangle viewing inspection technique, tracking pulses via different routes like half skip or pitch and catch, tandem techniques or the use of mode converted waves.

REFERENCES