Imaging in Non-Destructive Testing

W. Arnold, M. Kröning, and F. Walte
Fraunhofer-Institute for Non-Destructive Testing
Bldg. E 3.1, University
D-66123 Saarbrücken, Germany
1929: Sokolov (Russia) notices that with ultrasound defect can be detected in metals. He calls this signal on the scope a reflectogram.

1945: Delano (Sperry Inc. USA) names this reflectogram an A-scan → A-Scan.

Reflectogram of a defect in a steel shaft

Source: L. Bergmann, Ultraschall 1954
1935: Sokolov (Russia) and Pohlmann (Germany) develop the first ultrasonic imaging system.

Source: L. Bergmann, Ultraschall 1954
Imaging in Non-Destructive Testing

Ultrasonic imaging system after Sokolov/Pohlmann

Source: L. Bergmann, Ultraschall 1954
Imaging in Non-Destructive Testing

Ultrasonic imaging system after Sokolov/Pohlmann

Two with screws joined metallic blocs

Frequency = 7 MHz

Source: L. Bergmann, Ultraschall 1954
1945: Delano (Sperry Inc., USA) calls the reflectogram A-scan as an abbreviation for amplitude-scan.
1954: Leksell (USA)  
1. Ultrasonic B-scans in medical imaging. A-scans are added in analog fashion and defect-echoes are depicted as amplitude modulated images.

**B-scans stands for Brightness Image.**

Source: Geschichte der Ultraschall- Diagnostik. Ultraschall Museum im Deutschen Röntgen-Museum
Brightness-scan = B-scan in NDT

Amplitude Scan: A-Scan

The amplitude is color coded in a typical B-Scan in a modern NDT imaging system.
1957: Michalskie (Germany/Röchling, Saarland) carries out one the first B-scans tests in NDT.

Images of inclusions in a steel shaft

Source: Chronik der zfP. U. Richter, DVS- Verlag 1999
Acoustic Holography

1954: Greguss, Hungary develops in analogy to optical holography acoustical holography.
1976: Holosonics (USA) constructs the first commercially available holographic system with analog recording and optical reconstruction.

1979: Schmitz (IZFP) and Kutzner (BAM) develop holographic systems with digital recording and numerical reconstruction.
Imaging in Non-Destructive Testing

Acoustical holography with optical reconstruction
Imaging in Non-Destructive Testing

Acoustical holography with numerical reconstruction

Digitally stored signal

PC

Holography algorithm (Back-propagation)

\[ u_2 = \iiint \frac{Z}{i\lambda r^2} e^{ikr} d\rho d\eta \]

Display
Imaging in Non-Destructive Testing

Holography

Result: ultrasound amplitude distribution in y-x plane

Rekonstruktion using backpropagation

Measurement: Real- and imaginary part of ultrasound in x-y plane at $z_0$

Result: ultrasound amplitude distribution in y-x plane

$x$ – $y$ plane at $z_1$
Holography in tandem – and pulse-echo mode

Specimen with flat-bottom holes with different orientation

Optical reconstruction

Quelle: V. Schmitz and M Wosnitza, Erfahrungen der Ultraschallholographie mit numerischer und optischer Rekonstruktion
Holography in pulse-echo and pitch-catch mode

Specimen with a side-drilled hole

Numerical reconstruction

Source: J. Kutzner, H. Wüstenberg BAM- Berlin
1979: Holography system (IZFP) based on the unit from Holosonics Inc. USA
Application of acoustical holoography in the inspection of welds

Specimen with slag inclusions

Optical reconstruction

Numerical reconstruction for line A-A

Source: V. Schmitz, M. Wosnitza. Erfahrungen der Ultraschallholographie mit numerischer und optischer Rekonstruktion

Fraunhofer Institut Zerstörungsfrei Prüfverfahren
1955: Projection of the ultrasonic amplitude as projection on the area scanned: C-Scan.
1973: Based on C-scans Lund & Jensen (Denmark) develop the P-Scan technique (projection-scan)
1985: C-scan technique (IZFP/CPSN) for austenitic welds seams. The double indications originate from the direct P-wave and the mode converted signal SPP.

UT- Probe: 2 MHz, 70 ° P-wave
1968: First proposal of a phased array testing system in the USA
Control Unit

Time delay

Time delay

Time delay

TT TRR R

α

D
d

α

Time delay $D = d \sin \alpha$

Variable insonification angle

Block model of phased-array system

Imaging in Non-Destructive Testing
1979: Gebhardt (IZFP) carries out the first measurements in NDT using a Phased-Array in Germany

Imaging in Non-Destructive Testing

Transmitter device
- 32 channels
- Max. time delay = 8 μs
- Bandwidth 0.5-8 MHz

Receiver device
- 32 channel analog multiplexer
- 100 MHz digitizer
- Computer At-386 / 33 MHz
1980: IZFP phased array-system “ARGUSS”
**Imaging in Non-Destructive Testing**

**COMPOUND-Scan with Phased Arrays**

Measurement: Sector-Scans $(A, z, a)$

Reconstruction by superposition of video-signals in $x$-$z$ plane at $y_1$

Result: Amplitude distribution in the $x$-$z$ plane at $y_1$

1980: Gebhardt (IZFP) develops the COMPOUND-Scan in NDT

Fraunhofer Institut Zerstörungsfrei Prüfverfahren
Application of a COMPOUND-Scans

Source: W. Gebhardt, F. Bonitz, H. Woll, V. Schmitz. Beam Forming and Defect Characterization by Phased Array Systems. 9. World Conf. on NDT.
1978: Barbian (IZFP) develops ALOK
Amplitude and time-of-flight LOCUS Curve

Measurement: of time of flight \((t)\) for each \((A_{\text{max}})\) of all RF-signals in \(x\)-\(z\) plane at \(y_1\)

Result: Reflection points in \(x\)-\(z\) plane at \(y_1\)

Reconstruction by points of intersection in \(x\)-\(z\) plane at \(y_1\)

Imaging in Non-Destructive Testing
ALOK - reconstruction
of notches (saw cuts) in the nozzle corner

Inspection of RPV - Nozzle

notch
1987: ALOK-3 unit (IZFP)
For ndt of components of the primary circuit of nuclear power plants
Ultrasonic Inspection for 40 – 56’’ Pipelines

Insertion into a 40’’ pipeline

Transducer made of piezoelectric material
1972: Based on radar technology Prine (USA) develops the “Synthetic Aperture Focus Technique” (SAFT).

By scanning a small transducer on the component to be tested, a synthetic aperture is built. All rf-signals are stored and their origin is numerically calculated and the source displayed as defect.
Imaging in Non-Destructive Testing

SAFT
Synthetic Aperture Focusing Technique

Measurement of all RF wave-forms on the line \( y_1 \)

Reconstruction by circles with time depending summation of all RF amplitudes

Result: SAFT- B- Scan for x-z plane at \( y_1 \)
SAFT- reconstruction of a crack in a circumferential weld, wall thickness 30 mm

70° insonification of a transverse wave
Test of austenitic weld using SAFT

Austenitic weld

Hot crack 50 mm

Crack tip; Direct echo

Back wall

Angle mirror effect (Sv- P- Sv)

UT- probe 2.25 MHz, 60°, P-Wave

Test of austenitic weld using SAFT

Imaging in Non-Destructive Testing
1975: Silk (GB)
Time-of-Flight
Diffraction Technique
TOFDT

Two transducers in pitch-catch mode

Measurement of all RF-waveforms

Reconstruction: B-Scan
in x-z plane at $y_1$
Time-of-Flight Diffraction Technique TOFDT

TOFDT- B- Scan

Side drill holes

2005: Using the powerful computers available now, Andrei Boulavinov (IZFP) develops the sampling phased array (SPA) whose basic principle has been formulated by various groups previously P. Wilcox et al, Bristol, Chiao and Thomas, GE Schenectady, Ozaki et al, Mitsubishi.

Conventional Phased Array: With N elements one obtains only a sub-number of the matrix based on n signals.

The functions:
- Ultrasonic beam sweeping
- Focusing
- Sectors-can
- SAFT- reconstruction
- COMPOUND- scan

must be carried out consecutively by acquiring new data.
Imaging in Non-Destructive Testing

Sampling Phased Array (SPA)

- First element transmits, all elements receive
- Second element transmits, all elements receive

Filling up the complete matrix with N elements, one obtains $N^2$ data, allowing one to:

- Beam sweeping
- Focusing
- Sector-scan
- SAFT reconstruction
- COMPOUND-scan

All functions can be realized in one test.
Imaging in Non-Destructive Testing

Sampling Phased Array (IZFP)

Specifications:

- Synthetic transmitting channels: 16 - 1024
- No. of channels: 16 - 64
- Dynamic range: 110 dB
- Signal depth ADC: 14 Bit
- Maximal digitization rate: 80 MHz
- Maximal IFF: q0 kHz

Phased array transducer with 16 elements

Electronics
Application: Sampling Phased Array

Stationary SAFT- Inspection (manual)

- Phased Array Probe
  - 16 Elements
- 50 mm
- 25 mm
- P-wave
- Isotropic material
- Natural crack

Corresponds to SAFT- reconstruction based on a stationary probe position with redundant data acquisition

SynFo- reconstruction

Crack
Angle mirror
Backwall

Imaging in Non-Destructive Testing
COMPOUND- Scan with SPA

Sampling Phased Array

Complete Information Matrix

Phased Array Probe

Inspection Volume
Inspection of turbine axle using SPA-COMPOUND-scan

Side-drilled holes 3 mm φ
Imaging in Non-Destructive Testing

Application: Sampling Phased Array

Specimen with 4 side-drilled holes
2 mm φ

Reconstruction without depth compensation
Imaging in Non-Destructive Testing

SPA: First Application on anisotropic composite materials

Phased-array probe on component

SF-phased array without focusing

GT- phased-array with inverse phase-matching

Artificial defect

Back-wall signal

Artificial defect

Back-wall signal
Application: SPA sector-scan

Imaging in Non-Destructive Testing
Imaging in Non-Destructive Testing: Surface Characterization

- Acoustic Microscopy (SAM)
- Atomic Force Acoustic Microscopy (AFAM)
(a), (b): Scanning directions of the lens.
Measurement of Acoustic Impedance with the SAM

Acoustic impedance

\[ Z = \rho \times v \]

Calibration curve for acoustic impedance
Acoustic images of a sandstone with clay cement made at 1 GHz. Impedances in the AM image is coded by gray shades: black = low impedance pore space, and light gray to white = high impedance quartz grains. The gray scale in the image extends from 45 Mrayls (white) to about 3 Mrayls (black). The right image show details of the clay contact zone with significantly lower impedance that the quartz.
Rayleigh wave velocity in Al$_2$O$_3$ from V(z) measurements
High-Resolution Testing of Piezoelectric Ceramics by Atomic Force Acoustic Microscopy Techniques
Atomic-Force Microscope

Harmonic oscillator model:
\[ \omega_0 = 2 \cdot \pi f_0 = \sqrt{\frac{k_C}{m^*}} \]

Typical values:
- Resonance frequency \( f_0 \): 10 - 300 kHz
- Spring constant \( k_C \): 0.1 - 50 N/m
Imaging using AFAM

Area of higher stiffness; It appears as a bright one when imaged at (b) frequency.

Soft area: Here one is out of resonance frequency and the amplitude of cantilever vibrations is small.

Courtesy by NT-MDT, Zelenograd
Excitation of Contact Resonance Frequencies

AFAM
- Cantilever beam
- Out-of-plane surface vibrations
- Ultrasonic transducer
- Piezoelectric sample
- Waveform generator
- Frequency range: 10 kHz - 3 MHz

Piezo-mode
- Cantilever beam
- Local electric field
- Bottom electrode
- Local vibration due to inverse piezoelectric effect

Fraunhofer IZFP
AFAM and Ultrasonic Piezomode Images of PTC Samples
Annealed at Different Temperatures; Image Size 2 μm x 2 μm.

Sample:
Rf-sputtered thin films of lead calcium titanate;
University of Saarland (C. Ziebert)

Cantilever:
Coated with conductive diamond layer;
Spring constant:
k_s = 44 - 46 N/m;
First free resonance:
f_1 = 188 - 198 kHz
Transmission of Ultrasound in Macroscopic Experiments: Interface with Mesoscopic Contacts

Harmonics $f_0, f_1, f_2, f_3, \ldots$

Sample with damage
- cracks
- delaminations
- internal interfaces

Frequency $f_0$

Ultrasonic transducer
Rosetta-Mission

- Space Probe
  consisting of an orbiter & the lander PHILAE

- Target
  67P/Churyumov-Gerasimenko

- Time schedule
  Start: 2. März 2004
  Approach: August 2014
  Landing: November 2014
  End of mission: December 2014
**Philae Landing Gear**

Weight on Earth: ~ 830 N
Weight on the comet: ~120 mN

Stabilization of the lander on the comet by a harpoon and ice screws

Three-leg landing-gear each leg with two soles

On the lander there are 10 experiments designed to examine the structure and the composition of the comet nucleus.

MPAe, Katlenburg-Lindau
CASSE: Cometary Acoustic Surface Sounding Experiment

- Transmitter and receivers

  Piezoelectric transmitters
  Fraunhofer-Institute for Non-Destructive Testing;
  Piezoelectric accelerometer
  Brüel & Kjaer, Naerum, Denmark

- Operation modus

  Passive: inactive transmitter
  Active: active transmitter
Imaging in Non-Destructive Testing

1. Resolution of imaging determined by wavelength
2. Near-field imaging by antenna size

For data reconstruction there are still many things to do