NDT&E Methods: UT
Ultrasound Generation

PANAMETRICS-NDT™

Michael Kröning
Nondestructive Testing & Evaluation
TPU Lecture Course 2015/16
## NDT&E Methods: UT

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NDT&E Methods: Ultrasound Generation
General Considerations and Requirements on potential stress wave sources:

1. frequency content control;
2. pulse length control (damped pulses)
3. magnitude of loading force control
4. wave mode generation
5. Intensity profile control
6. Control of propagation direction
Mechanical Impacts

with solids generate Ultrasound through a linear momentum transfer from the imparting body to the mechanical waves.
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Mechanical Impact

Impact → Transducer → Data Acquisition System and Computer → Waveform, Spectrum → Voltage, Amplitude → Time, Frequency
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Mechanical Impact

CONCRETE Inspection with frequencies up to 80 kHz
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Mechanical Impact

Hand-held transducer.
Courtesy of Impact-Echo Instruments, LLC.
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Mechanical Impact

Impact-Echo pistol grip transducer

Courtesy of Impact-Echo Instruments, LLC.
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Laser Impact

Thermoelastic Regime

Ablative Regime

Laser Generation of Ultrasound
NDT&E Methods: Laser based Ultrasound

Surface Wave Generation
By a Laser Line Source
In thermo-elastic Regime
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Ultrasonic measurement Scheme using a pulsed laser and a Michelson-type interferometer for ultrasound detection
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Ultrasonic Measurement Scheme
(Pulsed Laser for Ultrasound Generation, a Michelson-Type Interferometer for Detection)
### NDT&E Methods: Laser based Ultrasound

#### ADVANTAGES & DISADVANTAGES of LBU

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<td>Noncontact</td>
<td>Lower sensitivity</td>
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<tr>
<td>Remote</td>
<td>Relatively expensive</td>
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<td>Rapid scanning</td>
<td>Generation efficiency depends on optical absorption</td>
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<td>Scanning of awkward geometries</td>
<td>Requires laser safety precautions</td>
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<td>Can be a point source</td>
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<td>Both temporally and spatially</td>
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<td>Broadband (Generation &amp; Detection)</td>
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<td>Reproducible source</td>
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<td>Generation of surface &amp; bulk waves</td>
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<td>Shaping of surface wave fronts</td>
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<td>Absolute calibration by laser interferometry</td>
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NDT&E Methods: Ultrasound Generation

Piezoelectricity - the piezoelectric effect

("Pressure Electricity")
Piezoelectricity - the piezoelectric effect
(„Pressure Electricity“)

is the appearance of an electrical potential across the sides of a crystal when you subject it to mechanical stress:

\[ P = e x \]

with \( P \): Polarization; \( e \): piezoelectric stress coefficient; \( x \): strain

In the converse piezoelectric effect, a crystal becomes mechanically stressed (deformed in shape) when a voltage is applied across its opposite faces:

\[ x = d E \]

with \( x \): strain, \( d \): piezoelectric strain coefficient, \( E \): electric field

The piezoelectric effect was discovered in 1880 by the brothers Pierre and Paul-Jacques Curie, in crystals of quartz, tourmaline, and Rochelle salt (potassium sodium tartrate). They took the name from the Greek work piezein, which means "to press."
It has been discovered that in the 32 crystal classes, which conventionally separated into 7 crystal systems, only 20 classes possesses piezoelectric crystals (Nye, 1972).

Only the crystal classes that possess no center of symmetry are the ones have piezoelectricity. The dipoles form groups of atoms in the lattice are the cause of the asymmetric crystal to have the piezoelectric effects.

*Examples of piezo electric crystals:*

Quartz
the synthetic ceramic, lead zirconate, titanate.
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Unstressed Crystal

- centres of symmetry (+ and -) coincide
- centre of symmetry for positive charge
- charged ions bound in the crystal lattice
- centre of symmetry for negative charge

Compressed Crystal

- centre of symmetry for negative charge
- centre of symmetry for positive charge
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Unstressed Crystal

- centres of symmetry (+ and -) coincide
- centre of symmetry for positive charge
- charged ions bound in the crystal lattice
- centre of symmetry for negative charge

Stretched Crystal

- centre of symmetry for positive charge
- centre of symmetry for negative charge
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Piezoelectric Effect

- Converse Piezoelectric Effect
- Poling Process
- Direct Piezoelectric Effect

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Poling Process of Ferroelectrica

The vector $\mathbf{P}$ in the diagram points in the direction of the net dipole resulting from the displacement of charge.

**Lattice of $\text{Pb}(\text{TiO}_2)$**
The dipoles in macroscopic sample can have random orientations in which case the material has no net moment.

Applying a strong electric field aligns the dipoles. The oriented dipolar domains can lose their structure at high temperature, with wear etc.

**Poled ferroelectric materials form materials which are** *piezoelectric*
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Mathematical Description

Linear piezoelectricity is the combined effect of the linear electric behavior of the material and Hook’s law for linear elastic materials:

\[ D = \varepsilon E \text{ with } \nabla D = 0 \text{ and } \nabla \times E = 0 \]
\[ S = sT \text{ with } \nabla T = 0 \text{ and } S = (\nabla u + u \nabla) \]

D: Electric Charge Density Displacement, \( \varepsilon \): Permittivity, E: Electric Field Strength
S: Strain, s: Compliance, T: Stress

Combined STRAIN CHARGE FORM:

\[ S = sT + d^t E \] (\( d^t \): Matrix for the converse effect)
\[ D = dT + \varepsilon E \] (d: Matrix for the direct effect)
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Ultrasound is generated with a transducer.

A piezoelectric element in the transducer converts electrical energy into mechanical vibrations (sound), and vice versa.

The transducer is capable of both transmitting and receiving sound energy.
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- Case
- Epoxy Potting
- Backing Material
- Electrodes
- Piezoelectric Element
- Coaxial Cable Connector
- Signal Wire
- Ground Wire
- Wear Plate
What is an Ultrasonic Transducer?

A transducer is any device that converts one form of energy to another.

An ultrasonic transducer converts electrical energy to mechanical energy, in the form of sound, and vice versa (Olympus).

The main components of a piezo-transducer are:

- The active element
- The backing
- The wear plate
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The **active element**
is commonly a polarized ceramics.
It can be cut in a variety of manners
to produce different wave modes.

The **backing**
Is usually a highly attenuative, high density material.
It is used to control the vibration of the transducer
by absorbing the energy radiation
from the back face of the active element.
When the acoustic impedance matches
the impedance of the active element,
the transducer is highly damped.

The **wear plate**
protects the transducer active element. It serves as an acoustic transformer
between the active element and the media (water, Perspex, etc) of lower acoustic impedance.
This is accomplished by selecting a matching layer of ¼ wavelength thickness.
The waves generated by the active element of ½ wavelength thickness are in phase with the
wave reverberating in the matching layer.
When signals are in phase, their amplitudes are additive.
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Lorentz Force

\[ F = q \left( E + (v \times B) \right) \]

A combination of electric and magnetic force on a point charge due to electromagnetic fields

OLYMPUS EMAT Transducer
NDT&E Methods: EMAT

\[ F(z) = \frac{(j(z) \times B_0)}{n_0} \]

\(\delta: \) skin depth

Speed, density
NDT&E Methods: EMAT

\[ F(z) = \frac{(j(z) \times B_0)}{n_0} \]

\[
\frac{\partial^2 \xi}{\partial t^2} - s^2 \frac{\partial^2 \xi}{\partial z^2} = \frac{|j \times B_0|}{d}
\]

s: Sound velocity

d: Density
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Piezoelectric UT
- Crystal
- Couplant

EMAT UT
- Magnet
- EMAT Coil Circuit

Lorentz Force
- Magnetic Field
- Eddy Currents

Ultrasonic Wave

Ultrasonic Wave
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Basic Components in EMAT Transducer
There are two basic components in an EMAT transducer.
• a magnet
• an electric coil.

The magnet can be a permanent magnet or an electromagnet, which produces a static or a quasi-static magnetic field. In EMAT terminology, this field is called bias magnetic field.

The electric coil is driven with an AC electric signal at frequency, typically in the range from 20 kHz to 10 MHz.

Based on the application needs, the signal can be a continuous wave, a spike pulse, or a tone-burst signal. The electric coil with AC current also generates an AC magnetic field. When the test material is close to the EMAT, ultrasonic waves are generated in the test material through the interaction of the two magnetic fields.
NDT&E Methods: Ultrasound Generation

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Based on the application needs, the signal can be a continuous wave, a spike pulse, or a tone-burst signal.
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(a) 

(b)
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Effect of Air Gap (Lift-off and Tilt)
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A MASTERTHESIS

D. Rueter, T. Morgenstern. *Ultrasound generation with high power and coil only EMAT concepts*, Ultrasonics vol. 54, issue 8, Elsevier, 2014

Our intention

- *is the investigation of powerful and magnetically induced (non-contact) ultrasound at notably higher frequencies (i.e., >1 MHz instead of 300 kHz or less), suitable for NDT.*
- *Furthermore, increased lift off distances towards 1 cm instead of just 1 mm or less are approached, interesting for more or new application fields like prepackaged products.*

The approach

- *via magnetic pressure appears to be more convenient here and it still reasonably describes the actual findings from experiments.*
- *The underlying physics is viewed under the terminology magnetic pressure (more common in EMF technologies) instead of explicitly evaluating eddy currents and Lorentz forces (as typically done in EMAT considerations).*
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A simple LC-Oscillation Circuit

Characteristic Frequency:

\[ f = \frac{1}{2\pi\sqrt{LC}} \]

Electric Impedance

\[ Z_{el} = \sqrt{\frac{L}{C}} \]

\[ E = \frac{1}{2} CU^2 \]

stored Energy in the Capacitor

\[ E = \frac{1}{2} LI_{el}^2 \]

for ideal elements the stored Energy in the Capacitor is fully converted into a magnetic field of the inductor \( L \) with discharge current \( I_{el} \)
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For NDT ultrasound, L-C-frequencies in the order of $10^6$ Hz are interesting elements $L$ and $C$ with relatively small values.

MAXIMUM ELECTRIC POWER
Reference Power for Efficiency Considerations

$$P_{el,\text{max}} = \frac{1}{4} \frac{U^2}{Z_{el}} = \frac{1}{4} \frac{1}{\sqrt{LC}} CU^2 = \pi f E$$
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Magnetic Pressure $p$

equals the energy density

of an oscillating transient magnetic field

\[
p = \frac{1}{2} \frac{B^2}{\mu_0}
\]

Effective Sound Intensity

The effective sound intensity $I$ of an ultrasound wave at sound pressure $p$ (peak value) in a material is:

\[
I = \frac{p^2}{2Z_M} \quad (Z_M: \text{Acoustic Impedance})
\]
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FINAL GENERATED ULTRASOUND POWER

\[ P_{US} = \frac{1}{32} \frac{1}{Z_M A} \left( \frac{E}{g} \right)^2 \]

EFFICIENCY

\[ \eta = \frac{1}{32} \frac{1}{\pi \mu_0} \frac{B^2}{Z_M g f} \]
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MISTRAS, USA
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MAGNETOSTRICTIVE EFFECT

Ferromagnetic materials change their shape or dimensions during the process of magnetization.

The reciprocal effect, the change of the susceptibility (response to an applied field) of a material when subjected to a mechanical stress, is called the Villari effect.

Le Chatelier’s Principle

\[ \left( \frac{d\lambda}{dH} \right)_\sigma = \left( \frac{dB}{d\sigma} \right)_H \]

\( \lambda \): magnetostriction

\( H \): magnetizing field strength

\( B \): flux density

\( \sigma \): mechanical stress
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CAPACITIVE ULTRASONIC TRANSDUCER

Total Force exerted on a membrane of a capacitor

\[ F_{\text{elec}} = \frac{\varepsilon_0 A V^2}{2(d_0 - x)^2} \]

A: Area; V: applied dc voltage; x: membrane displacement; d_0: initial gap height

EQUILIBRIUM CONDITION:

Electrical force balances mechanical restoring force \( F_{\text{mech}} = kx \)

Relation between the membrane displacement and applied dc voltage

\[ V = \sqrt{\frac{2kx}{A \varepsilon_0}} (d_0 - x) \]
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CAPACITIVE ULTRASONIC TRANSDUCER

Transmit Mode

Receive Mode

Electrical Circuits to Drive CMUTs
NDT&E Methods: Ultrasound Generation

CAPACITIVE ULTRASONIC TRANSDUCER

Cross-sectional Schematic Drawing of Membrane
Optical Picture of 2D Array Element that is 400μm by 400μm in size. It Consists of 76 membranes which are 36 μm in Diameter.
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Literature

4. D. Rueter, T. Morgenstern. *Ultrasound generation with high power and coil only EMAT concepts*, Ultrasonics vol. 54, issue 8, Elsevier, 2014