Piezoelectric single- and multi-element ultrasonic transducers for medical applications

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Meggitt Sensing Systems, Denmark
1 Company introduction
Meggitt overview

» Meggitt PLC is an international global engineering group
  - Extreme environment components and sub-systems for aerospace, defence and energy markets

» Strong expertise in extreme environment engineering
  - High technology products and systems
  - Content on virtually every aircraft – 63,000 installed base

» Well-balanced portfolio
  - Commercial/military/other (48%/34%/18%)
  - Original equipment/aftermarket (41%/59%)

» Global footprint

» Annual sales of £1.554 billion in 2014

» FTSE100 company
Piezoelectric single- and multi-element ultrasonic transducers for medical applications


Global presence

- **North America**
  - Employees: ~ 5600
  - Locations: 32
  - USA, Canada and Mexico

- **UK**
  - Employees: ~ 2800
  - Locations: 15

- **Mainland Europe**
  - Employees: ~ 1600
  - Locations: 13
  - Denmark, France, Germany, Spain and Switzerland

- **Asia and RoW**
  - Employees: ~ 800
  - Locations: 10
  - Australia, Brazil, China, India, Singapore, UAE and Vietnam

~10 800 employees worldwide
Meggitt Sensing Systems Denmark

- Meggitt A/S is a manufacturer of piezoelectric materials, components, devices of Ferroperm™ Piezoceramics and InSensor™ brands
- 3-4 million units produced annually

- Major markets
  - Medical ultrasound
  - Underwater acoustics
  - Acceleration sensors
  - Flow meters
  - NDT
  - Energy Harvesting
2 Medical ultrasonic imaging
Global imaging modalities 2011 vs. 2000

After: T. L. Szabo (2014):
Diagnostic ultrasound imaging: Inside out
Amsterdam, The Netherlands, Elsevier.
# Medical imaging and enabling technologies

<table>
<thead>
<tr>
<th>Enabling technology</th>
<th>Ultrasonic imaging</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Pre WWII</strong></td>
<td></td>
</tr>
<tr>
<td>Piezoelectricity, vacuum tube amp., radar, sonar</td>
<td>Echo ranging, First image of brain, therapy</td>
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<tr>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>1950s</strong></td>
<td></td>
</tr>
<tr>
<td>Integrated circuits, Phased array antennas</td>
<td>A-mode, Doppler ultrasound, M-mode</td>
</tr>
<tr>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>1960s</strong></td>
<td></td>
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<tr>
<td>Microprocessors, VLSI</td>
<td>B-mode, Real-time scanner</td>
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<tr>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>1970s</strong></td>
<td></td>
</tr>
<tr>
<td>RAM, EPROM, ASIC, microcontrollers</td>
<td>Real-time imaging, Gray-scale, arrays</td>
</tr>
<tr>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>1980s</strong></td>
<td></td>
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<tr>
<td>PC, DSP, CAD of VLSI, SMD</td>
<td>Commercial arrays, Doppler flow imaging, wideband transducers</td>
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<td></td>
<td></td>
</tr>
<tr>
<td><strong>1990s</strong></td>
<td></td>
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<tr>
<td>Low cost A/D, 3D image processing</td>
<td>Digital US, matrix arrays, commercial 3D systems</td>
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<tr>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>2000s</strong></td>
<td></td>
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<tr>
<td>High speed electronics, miniaturization, advanced DSP</td>
<td>Handheld 2D and 3D imaging, elastography, shear wave imaging</td>
</tr>
</tbody>
</table>
Ultrasonic imaging – basic idea

» Ultrasonic imaging is highly detailed and geometrically correct (average speed of sound in a soft tissue is 1540 m/s and varies only 3%)

» The imaging is enabled by differences of acoustic impedance defined as a product of density and speed of sound \( Z = \rho c \)

» The amplitude reflection factor acoustic plane wave incident at the interface of two tissues \( (Z_1 \text{ and } Z_2) \) is then given by \( RF = (Z_1 - Z_2)/(Z_1 + Z_2) \)

\[
t = \frac{2d}{c}
\]
Physical processes in an ultrasonic system

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Ultrasonic imaging – basic properties

Resolution of ultrasound imaging depends on:
- Aperture size
- Center frequency
- Bandwidth
- Focal depth

Typical frequencies range from 1-15 MHz, corresponding to lateral resolution of 3 mm to 0.2 mm

Typically, the best resolution is obtained at the focal depth (due to diffraction)

Resolution is also affected by attenuation in media, which also depends on frequency (the higher the frequency, the higher the attenuation)
Single element transducers
Typical structure

Modelling of a transducer – KLM model

Matching – optimizing energy transfer

- The transducer has maximum broadband sensitivity only when properly matched to the driving circuit (electrical matching) and the patient (acoustical matching)
- Typically a passive circuit network is used for electrical matching (targeting 50 Ohm matching)
- Acoustic matching is typically obtained by using additional matching layers on the front of the transducer
- Typically λ/4 layers are used with acoustic impedance between the $Z_t = 34$ MRayls (typical PZT) and 1.5 MRayls (human body)
Focusing

- Focusing is used to increase the spatial resolution in a selected region.
- There are similarities between optics and acoustics, e.g. focal region, focal length.
- However, apertures do not have to be circularly symmetric, lenses can be made out of materials having equivalent refraction index less than one.
- Acoustic focusing can also be achieved by electronic means.

A pulse-echo transducer uses the same element to send out the signal and monitor the returning sound echoes.

The transducer rests on a platform with adjustable angle with respect to the target surface (in order to make the face of the transducer parallel to the face of the steel target).

Typically a signal amplitude of 100 V was used, and the period of the pulse was varied to maximise the return signal (~ pulse period corresponding to one half the period of the transducer’s resonance frequency).
Characteristics of a pulse-echo signal (example)

- The pulse is a high-voltage drive; amplification of the actual signal is turned on after the pulse event is completed.
- The main-bang ringdown (MBRD) is a period where high acoustic energy reverberates in the piezo-element.
- The signal has a backing echo starting at about 20 µs and a secondary one at about 85 µs.
- The actual target echo arrives at about 60 µs.
Frequency domain pulse echo properties

- Center freq. \( f_c = \frac{f_{\text{high}} + f_{\text{low}}}{2} \)
- Bandwidth \( BW = f_{\text{high}} - f_{\text{low}} \)
- Fractional bandwidth \( f_{\text{FBW}} = \frac{BW}{f_c} \)
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PZT thick films – InSensor™

» Technology of piezoelectric thick films – enabling deposition and integration of piezoelectric layers (10 µm to 100 µm in thickness) with high lateral resolution (100 µm x 100 µm)

» Key features of InSensor™ technology
  - Capable of manufacturing miniaturized devices
  - Low prototyping costs
  - High volume production
  - High lateral resolution
  - High frequency
  - High response
  - Piezoelectric material can be deposited on a number of different substrates (compatible with MEMS)
PZT thick film compatibility

SUBSTRATES

Ceramics

Stainless steel

Silicon

LTCC


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Thick-film ultrasonic transducers - concept

» The characteristics of the printed thick film make it a perfect candidate for medical imaging due to the following:
  - More than 20% porosity
  - Low acoustic impedance
  - Low permittivity
  - High frequency (more than 20 MHz) easily obtained without machining

» When the thick film is combined with the optimised substrate, a fractional bandwidth above 100% is measured
Fabrication method – pad printing
High frequency imaging transducer


High frequency transducer manufacturing

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Curved piezoelectric thick films for high-resolution medical imaging.
High-frequency ultrasonic transducers – acoustic field

Acoustic field of thick film transducers measured by means of Schlieren setup, a) flat transducer, b) focused transducer (in collab. with A. Nowicki, IPPT).
High-frequency ultrasonic transducers – medical imaging

Real-time image of soft tissue during the treatment

Source: Ulthera video http://www.youtube.com/watch?v=XhafnO0uB_k
Multi-element transducers
Why arrays?

» No moving parts, no mechanical scanning

» Arrays:
  - Enable electronically controlled beam steering
  - Enable dynamic focusing on receive
  - Improve lateral resolution by adjustment of the length as well as apodization (compensation for finite size of an element)

» Enable flow imaging

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1D array orientation

30 MHz 1D array - an example

Beam steering

Beam focusing

Thick film arrays for medical imaging
Deposition – screen printing

Paste: PZT powder dispersed in an organic vehicle
Concept of thick film based array

- Fabrication be means of screen printing
- Special characteristics of PZT thick films open for
  - High frequency > 10 MHz
  - An integrated backing layer
  - Large bandwidth
- Fully printed design
  - Huge implication for cost reduction
  - Arbitrary patterning possible
32 element kerfless thick film ultrasonic array – fully printed

TF2100, PZT thick film

11 mm

Ground electrode, gold

Ceramic integrated backing layer

Array connected to a PCB

Top electrode, silver
Very good distribution of capacitance over the elements
Pulse-echo measurements continued

Thick film ultrasonic arrays offer a unique combination of high frequency, good sensitivity and a bandwidth comparable to conventional bulk transducers.

32-element transducers generally show acceptable uniformity.
Crosstalk is measured at time zero by comparing the voltage amplitude for the four elements closest to the excited element. The average crosstalk is found to be approx. -38 dB. An acceptable level for an ultrasonic transducer.
5

3D ultrasonic imaging
3D ultrasonic imaging

Fetus 34 weeks old with bilateral cleft lip visualized using (a) conventional 2-D US imaging and (b) 3-D US volume rendering

3D ultrasonic imaging – scanning strategies

Row-column concept

Acoustic field at transmission and reception

Conclusions

Piezoelectric single- and multi-element ultrasonic transducers for medical applications
Conclusions

- Ultrasonic imaging is a versatile, non-invasive and low cost alternative to other diagnostic methods
- Ultrasound is used mostly for imaging of soft tissue
- Image quality (resolution, contrast, etc.) strongly depends on properties of the ultrasonic transducers
- Historically, mechanically scanned single element transducers have been used, but these are now being replaced by multi-element array systems
- The current development of ultrasonic transducers is aiming at:
  - Higher quality imaging at lower cost
  - High frequency imaging with deeper penetration
  - Integrated probes reducing the impact of expensive and heavy cabling
  - New modalities, e.g. elastography (measurement of elastic properties of tissue)
  - New technologies, e.g. cMUT (capacitive micromachined ultrasonic transducer)
- The thick film process allows for cost-effective manufacturing of linear arrays, and the performance of each element is comparable to the single-element thick films
Acknowledgements

» Danish National Advanced Technology Foundation, contract no. 82-2012-4, FutureSonic platform

» Dr. Frans Lautzenhiser, Meggitt Sensing Systems, Indiana, USA

» Rasmus Lou-Møller, Meggitt Sensing Systems, Denmark

» Dr. Franck Levassort and Prof. Marc Lethiecq, GREMAN, Univ. François-Rabelais de Tours, France

» Prof. Andrzej Nowicki, IPPT, Warsaw, Poland
Thank you