Analysis of Flexural Ultrasonic Transducers for High Frequency Applications

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EPSRC
Engineering and Physical Sciences Research Council

CIU Centre for Industrial Ultrasonics
www.ciu.ac.uk
Overview of Our Research

- The FUT is currently used primarily for flow measurement, proximity sensing and industrial metrology.
- Designed for ambient conditions and low ultrasonic frequencies, up to approximately 50 kHz.

How can we adapt FUTs for operation at higher frequencies, in high pressure and temperature environments?

<table>
<thead>
<tr>
<th>Application</th>
<th>Example Pressure (bar)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Domestic water meters</td>
<td>20</td>
</tr>
<tr>
<td>Industrial gas meters</td>
<td>300</td>
</tr>
<tr>
<td>Industrial flow meters</td>
<td>300+</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Environment</th>
<th>Example Temperature (°C)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Oil production</td>
<td>120</td>
</tr>
<tr>
<td>District heating</td>
<td>250</td>
</tr>
<tr>
<td>Petrochemical</td>
<td>350-450</td>
</tr>
<tr>
<td>Power plants</td>
<td>560</td>
</tr>
</tbody>
</table>

Ultimate Goal

The development of high frequency flexural ultrasonic transducers (HiFFUTs), a new class of ultrasonic transducer.

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Applications of FUTs

Robotics, Obstacle Avoidance
Proximity and Parking Sensors
NDT Inspection

Short-Range Wireless Communication
Flow Measurement and Metrology
Phased Arrays
Applications of FUTs

TARGET HIGH FREQUENCY APPLICATIONS FOR OUR HIFFUTs (> 100 kHz)

- NDT Inspection
- Robotics, Obstacle Avoidance
- Proximity and Parking Sensors
- Short-Range Wireless Communication
- Flow Measurement and Metrology
- Phased Arrays
The Flexural Ultrasonic Transducer

- Unimorph device
- Piezoelectric driver bonded to a metal cap
- Vibration of the piezoelectric causes metal cap bending
- Efficient coupling to low-impedance media

![Diagram of Flexural Ultrasonic Transducer]

- Vibrating membrane
- Epoxy resin bond layer
- Piezoelectric ceramic disc
- Air-filled cavity
- Silicone backing layer
- Cap housing
- Aluminium 40 kHz FUT
- 10 mm
Operating Characteristics

(0,0) Mode  (0,1) Mode

(1,0) Mode  (1,1) Mode

Region 1: Build-up towards steady-state
Region 2: Steady-state
Region 3: Resonant ring-down

Isolated Response Regions

Amplitude vs Time
Dynamic Characterisation

- FUTs characterised with acoustic microphone, LDV, or a receiver FUT
- Function generator and oscilloscope can be used for rapid resonance check
Dynamic Characterisation

- Resonance and off-resonance responses of the FUT measured
- Cross-correlation of responses at 40 kHz and 110 cycles computed
Mathematical Analog Model

- Relationships governing the three response regions separately are:
  
  **Region 1** \( M\ddot{x} + C\dot{x} + Kx = F\sin\omega t \cdot H(t_0 - t) \)
  
  **Region 2** \( M\ddot{x} + C\dot{x} + Kx = F\sin\omega t \)
  
  **Region 3** \( X(t) = F e^{-\zeta\omega n t} \cos(\omega_d t + \theta) \)

- The equations for Region 2 and Region 3 are familiar. For Region 1:
  
  \[ H = 1 \text{ for } 0 < t \leq t_0 \quad \text{and} \quad C^2 < 4MK \]

- The full solution is:
  
  \[ x = N_P e^{-\alpha t} (\cos \alpha t + \sin \alpha t) + N_N e^{-\alpha t} (\cos \alpha t - \sin \alpha t) + \sqrt{G_1^2 + G_2^2} (\sin(\omega t + \theta)) \]

- Or simplified, with the real part of the equation:
  
  \[ x = N (e^{-\alpha t} \cos \alpha t) + R(\sin(\omega t + \theta)) \]

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Correlation of Analog and Experiment

Effective Frequency Responses of a FUT

45kHz Drive Excitation
Dynamic Nonlinearity

- Sample of 5 aluminium FUTs analysed
- Electrical properties measured
- LDV used to assess nonlinearity
Dynamic Nonlinearity

- FUTs driven around resonance with burst sine signals
- Steady-state and resonant decay isolated
- Zero-crossings calculated for nonlinearity in Region 3
Dynamic Nonlinearity

- Dynamic properties of five FUTs summarised
- Characteristics variable between nominally identical FUTs

<table>
<thead>
<tr>
<th>FUT</th>
<th>Coupling Coefficient $k^2$</th>
<th>Quality Factor $Q_M$</th>
<th>Resonance Frequency $f_r$ (kHz)</th>
<th>$f_n$, nom. 4 V$_{p-p}$ (kHz)</th>
<th>$f_N - f_S$ (Hz) nom. 4 to 20 V$_{p-p}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>0.33</td>
<td>71.01</td>
<td>39.51</td>
<td>40.00</td>
<td>300</td>
</tr>
<tr>
<td>2</td>
<td>0.32</td>
<td>56.13</td>
<td>40.64</td>
<td>41.00</td>
<td>200</td>
</tr>
<tr>
<td>3</td>
<td>0.33</td>
<td>56.71</td>
<td>39.97</td>
<td>40.40</td>
<td>200</td>
</tr>
<tr>
<td>4</td>
<td>0.31</td>
<td>54.17</td>
<td>38.23</td>
<td>37.90</td>
<td>200</td>
</tr>
<tr>
<td>5</td>
<td>0.32</td>
<td>49.75</td>
<td>39.72</td>
<td>40.10</td>
<td>200</td>
</tr>
<tr>
<td>Mean</td>
<td>0.322</td>
<td>57.55</td>
<td>39.59</td>
<td>39.66</td>
<td>220</td>
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<tr>
<td></td>
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</tr>
<tr>
<td>Standard Deviation</td>
<td>0.007</td>
<td>7.16</td>
<td>0.88</td>
<td>0.90</td>
<td>40</td>
</tr>
</tbody>
</table>
High Frequency Operation

- Propagation of ultrasound in air
- Efficient driving mechanism required
- Bespoke amplifier adopted
- Two FUTs, one as a transmitter, one as a receiver, both with a (0,0) mode of 40 kHz

Burst sine signal, 150 cycles, 10 V_{P-P}

Measurement distance: 500 mm
High Frequency Operation

(0,0) Mode at 41 kHz

(1,0) Mode at 177 kHz

(2,0) Mode at 319 kHz

\[ SNR = 20 \log_{10} \left( \frac{V_{RMS, SIGNAL}}{V_{RMS, NOISE}} \right) \]
HiFFUT Design: Operating Modes

• FUT membrane equivalent to an edge-clamped thin plate
• Differential equations used to approximate the normal mode frequencies

\[ D \nabla^4 w(r, t) + \rho \frac{\partial^2 w(r, t)}{\partial t^2} = 0 \]

\[ D = \frac{E h^3}{12(1 - \nu^2)} \]

\[ \omega = \left(\frac{\lambda}{a}\right)^2 \sqrt{\frac{D}{\rho}} \]

Transverse Displacement \hspace{1cm} Rigidity \hspace{1cm} Angular Modal Frequency

• Mode frequencies dependent on plate geometry and material
• Online design tool designed, available on project website
• Estimated mode frequencies instantly generated for different materials, including custom

[Online Design Tool]

https://warwick.ac.uk/fac/sci/physics/research/ultra/research/hiffut/
HiFFUT Design: Finite Element Analysis

We use PZFlex® finite element analysis software for simulating performance.

(0,0) Mode at 69.35 kHz
(1,0) Mode at 246.57 kHz
High Temperature Piezoelectric HiFFUTs

- Custom pressure rig used to bond components
- High temperature epoxy resin: EPO-TEK® 353ND
- Titanium (Grade 2 ASTM) cap
- PZ46 bismuth titanate (BiT) ceramic (Meggitt)

Disc, cut from Ti sheet, with BiT ceramic bonded on top, forming the membrane

Rig Components for Laser Welding

Titanium tubing for side-wall

Prior to laser welding

Recess cut into tubing

Assembled Configuration

Side-wall

Laser-cut membrane

Rig
High Temperature Piezoelectric HiFFUTs

**Phase 1**
- Measurement Oscilloscope
- Function Generator
- TRIGGER

**Phase 2**
- HiFFUT
- Laboratory Furnace
- HiFFUT

**Experimental Process**
- Acoustic Microphone, Brüel & Kjaer BK 4138-A-015
- Laser Doppler Vibrometer, Polytec OFV-5000

**Titanium HiFFUT**

**(0,0) Mode, FEA**

**Burst Signal of 400 cycles at 20 V_{p-p}**

**Resonance frequency at ambience:** 73 kHz

**Resonance frequency at 150°C:** 68 kHz
Summary

- FUTs are efficient and low cost
- Prototypes show potential for operation at high temperature and frequency
- HiFFUTs for hostile environments, including high pressure, are in development
- Industrial collaboration is ongoing for assessment of prototypes

Acknowledgement

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