Dynamic Characteristics of Flexural Ultrasonic Transducers

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18th December 2017, International Congress on Ultrasonics, Hawaii, USA
The flexural ultrasonic transducer (FUT) is a sensor used primarily in flow measurement, proximity sensing and industrial metrology.

Currently FUTs are used at ambient conditions and low ultrasonic frequencies, up to around 50 kHz.

### Overview of Research

- **Application**
  - Domestic water meters: 20 bar
  - Industrial gas meters: 300 bar
  - Industrial flow meters: 300+ bar

- **Environment**
  - Oil production: 120 °C
  - District heating: 250 °C
  - Petrochemical: 350-450 °C
  - Power plants: 560 °C

### Target Operating Conditions

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

### Ultimate Goal

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

- Close collaboration with industry.
- A major aim is to design FUTs operational towards 1 MHz.
- FUT resonance frequencies depend on cap material and dimensions.
- The physics of FUT behavior is currently not understood.
- This study demonstrates results from the characterisation of a set of 5 flexural transducers, all nominally identical.
The flexural ultrasonic transducer is a unimorph device, with a piezoelectric driver bonded to a metal cap.

The vibration of the piezoelectric element causes bending of the metal cap.

An advantage of flexural transducers is that the transducer couples efficiently to low-impedance media, operating effectively with relatively low input voltage.

Flexural transducers have been exploited for a range of applications, including for non-destructive evaluation, and as car-parking sensors.

The FUT of the type analysed in this study (Multicomp)
Operating Characteristics

(0,0) Mode

(0,1) Mode

(1,0) Mode

(1,1) Mode

Isolated response regions for an amplitude-time spectrum of a FUT

Zone 1: Build-up towards steady-state
Zone 2: Steady-state
Zone 3: Resonant ring-down
Characteisation Methods

• The experimental setup is shown opposite, and consists of a function generator and oscilloscope with a measurement instrument.

• The function generator is used to provide the input signal to the FUT, and the oscilloscope is used to measure the voltage across the electrical contacts of the FUT. The mechanical vibrations are recorded by the measurement instrument, which can be:
  - An acoustic microphone
  - A laser Doppler vibrometer (LDV)
  - A second FUT

• The response of the transducer can be monitored for different input signal frequencies, amplitudes, and number of cycles.

• All flexural transducers analysed in this study possess a nominal (0,0) mode frequency of 40 kHz.
Resonance Frequency Measurement

- Measurement of FUT resonance frequency using only an oscilloscope and function generator.
- Two drive frequencies of 40 kHz and 41 kHz are applied to the FUT, at 10 V_{p-p} and 10 cycles, as burst sine signals.
- Discontinuities in the FFTs of the amplitude-time responses indicate resonance, due to the phase difference between the driving signal and the vibration displacement of the membrane.
Comparison of Measurement Methods

- Three methods: An acoustic microphone (BK 4138-A-015), a laser Doppler vibrometer (LDV, Polytec OFV-5000), and a second FUT acting as a receiver.

- Burst sine signals at 10 V\textsubscript{p-p} are applied, at 40 kHz (the (0,0) mode) and 44 kHz (off-resonance).

- The amplitude oscillation and overshoot of the build-up to steady-state indicates proximity to resonance.

- Too few cycles in the drive signal prevents the generation of the steady-state.

Drive frequency of 40 kHz, 10 cycle burst sine signal
Cross-Correlation

- The cross-correlations were calculated to determine the signal similarity between different characterisation methods.
- The transition from Region 1 into steady-state was studied.
- 3rd order polynomials fitted to the absolute magnitude responses.
- The acoustic microphone and FUT\(_R\) show the greatest similarity. One explanation is that these methods both measure far-field, whereas LDV optically records membrane motion.

Cross-correlation of the signal spectra at 40 kHz and 110 cycles
The Mechanical Analog Model

• The FUT can be modelled as a mass supported by a spring-dashpot in parallel, and subject to a forcing function.

• Relationships governing the three response regions separately are:

  Region 1 \[ M\ddot{x} + C\dot{x} + Kx = F\sin\omega t \cdot H(t_0 - t) \] \[ H \text{ for } 0 < t \leq t_0 \] and \[ C^2 < 4MK \]

  Region 2 \[ M\ddot{x} + C\dot{x} + Kx = F\sin\omega t \]

  Region 3 \[ X(t) = Fe^{-\zeta\omega nt}\cos(\omega_dt + \theta) \]

• The equations for Region 2 and Region 3 are familiar. For Region 1:

  \[ H = 1 \text{ for } 0 < t \leq t_0 \]

• The full solution is:

  \[ x = N_P e^{-at}(\cos\alpha t + isin\alpha t) + N_N e^{-at}(\cos\alpha t - isin\alpha t) + \sqrt{G_1^2 + G_2^2} (\sin(\omega t + \theta)) \]

• Or simplified, with the real part of the equation:

  \[ x = N (e^{-\alpha t}\cos\alpha t) + R(\sin(\omega t + \theta)) \]

Correlation of Analog and Experiment

Amplitude-time spectra from LDV for drive frequencies of (a) 39.9 kHz (close to resonance), and (b) 40.5 kHz (off-resonance)

Equation: \[ x = N (e^{-\alpha t} \cos \theta t) + R \sin (\omega t + \theta) \]
Summary and Future Research

Summary

• The amplitude-time response of flexural ultrasonic transducers can be discretized into three zones.
• These zones have helped in the development of a mathematical analog model.
• Multiple characterisation methods have been outlined for the experimental analysis of FUTs.

Future Research

• Development of FUTs which operate in axisymmetric modes at multiple frequencies, above 100 kHz.
• Design FUTs suitable for hostile environments, in particular with respect to high pressure and temperature.
• Investigate the dynamics of the FUT at higher excitation amplitude levels.

Acknowledgement

• I would like to acknowledge the Engineering and Physical Sciences Research Council (EPSRC) Grant Number EP/N025393/1 for funding this research.