High precision & accurate sensing at lowest flow rate for metering applications
There are challenges in achieving **high precision** and **accurate sensing** at low to high flow rates in metering applications such as flow meters as well as distance measurement and level detection applications.

Ultrasonic sensing technology is outstanding at measuring flow velocity and using an integrated analog-to-digital converter (ADC) provides the ability to accurately measure flow even at the lowest rates.

This webinar will review ultrasonic sensing technology, the ADC implementation and examples using Texas Instruments MSP430 microcontrollers, tools and software.
Abstract

What you’ll learn:

• Challenges in the target applications e.g. flow meters
• Why Ultrasonic technology is used for addressing this
• How? Understanding ADC-based technique & its advantages
• What? Understand how the Ultrasonic Sensing Solution (USS) module works & its value
• Understand the tools and software for the USS module
• Demo / Results with EVM430-FR6047
Why Ultrasonic Sensing Technology?

Read the whitepaper
Why Ultrasonic for a Flow Meter?

Mechanical Meter:
- Short life time < 7 years
- Dirt accumulated on impeller
- High minimum flow rate $Q_{\text{min}} > 20 \text{ L/hr}$
- Cannot detect small flow leakage
- Low accuracy
- Need re-calibration within 6 to 7 years
- Tempering issue

Ultrasonic Meter:
- Long life time 20 years
- No moving parts
- Low minimum flow rate $Q_{\text{min}}$ at 5 - 10 L/hr
- Can detect small flow leakage (~1L/hr)
- High accuracy
- Re-calibration >20 years
- No tampering issue
- Electronic device to enable AMR
### Flow Measurement Technology Comparison

#### Ultrasonic (TOF)
- **Pros:**
  - No moving parts
  - Good accuracy $< \pm 1\%$
  - Long operation life
  - Detect variety of materials
  - Resistant to vibration infrared radiation, EMI

- **Cons:**
  - Need clear path (proper mechanical construction for transducers)

#### Doppler
- **Pros:**
  - Can be installed outside the pipes
  - Corrosion resistant
  - Low power since takes 2-3 seconds to measure

- **Cons:**
  - Less accurate $\pm3-5\%$
  - Requires particulates or bubbles in the flow (good for wastewater or dirty liquid)

#### Magnetic
- **Pros:**
  - No moving parts
  - Medium cost
  - Immune to impurities and flow profile
  - Low flow detection

- **Cons:**
  - Only conductive liquids
  - Sensitive to sediments & chemical process
  - Electrodes may wear out
  - Medium power

#### Mechanical
- **Pros:**
  - Low cost to implement
  - Accurate zero flow detection
  - Works with all clean liquids

- **Cons:**
  - Inertia and Friction
  - Low flow detection
  - Wears out
  - Sensitive to impurities, sediments, flow profile
Standards and requirements (driven by Europe)

- ISO 4064-1/EEC directive 75/33

<table>
<thead>
<tr>
<th>The flow rate</th>
<th>MPE Requirement</th>
</tr>
</thead>
<tbody>
<tr>
<td>$Q_1$</td>
<td>&lt; 5%</td>
</tr>
<tr>
<td>$Q_2, Q_3, Q_4$</td>
<td>&lt; 2% for water temperature &lt; 30°</td>
</tr>
<tr>
<td></td>
<td>&lt; 3% for water temperature &gt; 30°</td>
</tr>
</tbody>
</table>

- Accuracy requirement for leak detection, with 1 l/h water flow, 20% accuracy, 10 cm separation, is 45 ps resolution
Ultrasonic Flow Meter Working Principle

Diagonal

Reflective

Non-Invasive
Ultrasonic: Differential Time of Flight & Volume

- Ultrasound is described as the frequency range above human audible sound (> 20 kHz)
- Flow meters use in the range of 30 kHz to few MHz

\[ v = \text{Flow velocity of the medium} \]
\[ L = \text{Length of the acoustic path} \]
\[ c = \text{Velocity of sound in the medium} \]
\[ D = \text{Diameter of Pipe} \]
\[ Q = \text{Flow rate} \]

\[ \text{Transit time (t)} = \frac{\text{Distance}}{\text{Velocity}} \]

\[ T_{12} = \frac{L}{c + v \cos \phi} \rightarrow v \cos \phi = \frac{L}{T_{12}} - c \]

\[ T_{21} = \frac{L}{c - v \cos \phi} \rightarrow v \cos \phi = c - \frac{L}{T_{21}} \]
Differential Time of Flight & Volume

Formula for average flow velocity:

\[ v = \frac{L}{2 \cos \phi} \left( \frac{1}{T_{12}} - \frac{1}{T_{21}} \right) \]

\[ v = \frac{L}{2 \cos \phi} \left( \frac{T_{21} - T_{12}}{T_{21}T_{12}} \right) \]

\[ v \propto T_{21} - T_{12} \rightarrow \Delta T \]

Calculating the Volume:

\[ Q = \frac{\pi D^2}{4} \frac{L}{2 \cos \phi} \left( \frac{\Delta T}{T_{21}T_{12}} \right) \]

\[ = \frac{\pi D^3}{4 \sin(2\phi)} \left( \frac{\Delta T}{T_{21}T_{12}} \right) \]

Measure difference in upstream vs. downstream TOF to calculate flow rate

In addition to dTOF, we also measure the AbsTOF (T21, T12) for UPS (upstream) and DNS (downstream)

Final volume is based on the area of the flow tube (meter constant)

- Temperature and Pressure are constant within few ms of measurements
- Medium density, velocity of sound do not impact measurement
ADC-Based Technique

www.ti.com/product/MSP430FR6047
Techniques for differential TOF estimation

1) Zero crossing detection: detect arrivals of upstream $r_1(t)$ and downstream $r_2(t)$ signals & estimate $\Delta T$ (Time of flight difference) based on averaging of zero crossings.

$$r_1(i) = s_1(i) + n_1(i)$$

$$r_2(i) = s_2(i) + n_2(i)$$

$$s_2(i) = a s_1(i - \Delta T)$$

$a$ is the amplitude difference up/downstream - Ideally $a \approx 1$

2) ADC based Algorithm: Cross-correlation Method for $\Delta T$ estimation:

a) Fold $r_1(t)$ & $r_2(t)$

$corr(k) = \sum_{i=1}^{N-k} r_1(i+k)r_2(i)$

$Z_n = corr(\hat{k} - n) \quad n = (-1,0,1)$

b) Interpolate time offset for maximized correlation at 3 points
Features of ADC based processing

- **Fundamental Difference:** Signal processing
  - Performance
    - Best in class Zero flow drift across temperature and enables low flow detection (<1L/h)
    - The correlation acts as digital filter to suppress noise
      - Benefit of ~3-4X noise lower standard deviation. Can also suppress other interference like line noise etc.
    - Allows use of lower voltage driving (0-3V only) for gas applications
  - Robustness
    - Robust to signal amplitude variations
      - The algorithm is insensitive to the received signal amplitude as in high flow rates, transducer to transducer variation, temperature variation, different gas compositions (air, methane)
  - Envelope of signal is obtained naturally in ADC based processing.
    - Enables tuning to the transducer frequencies
    - Slow variations in envelope across time can be used for detection of aging of transducers/meter
MSP430FR6047
Ultrasonic Sensing Analog Front End
Detailed Module Description

Read the whitepaper
USS IP Block Diagram I (Signal Path)
PPG

PPG (Programmable Pulse Generator)

- Generate Excitation Pulses
  - # of pulses:
    - In phase: 1 ~ 127
    - Stop phase: 0 ~ 15
- Frequency Range: 33KHz ~ 2.5MHz
- Test tone generation for continuous pulses (Debug/Analysis)
- Resolution is dependent on the nominal transducer frequency & HSPLL frequency

\[
\Delta F = \frac{HSPLL - Frequency}{HPER + LPER} - \frac{HSPLL - Frequency}{HPER + 1 + LPER}
\]

HPER : High period of pulse
LPER : Low period of pulse

- Examples:
  - For 1 MHz pulses with 80 MHz PLL, \( \Delta F \approx 13 \text{ kHz} \)
  - For 2 MHz pulses with 80 MHz PLL, \( \Delta F \approx 51 \text{ kHz} \)
PHY

- 2ch. to control Input & Output of the USS Module
- Impedance Matching for best ZFD performance
  - Device specific ATE Trimmed values
  - Internal Multi-plexing feature
- Dedicated Low Impedance drivers
  - \( \leq 4 \, \Omega \) (Typ), 120 mA (Typ) \( \times 2 \)
- Operating voltage range 2.2V – 3.6V
12-bit 8MSPS ADC

**PGA**
- Input Voltage: 35mV ~ 760mV (<2.5V)
- Input Voltage: 35mV ~ 1000mV (>=2.5V)
- Gain: -6 ~ 19dB with ~1dB step

**SDHS (Sigma Delta High Speed ADC)**
- 12 bit, SNR – 63dB (typ) up to 1.5MHz BW
- Input Voltage max. 600mVpp
- Modulator Frequency: 68MHz ~ 80 MHz
- Output Data Rate: up to 8MSPS
- OSR Ratio: 10, 20, 40, 80, 160
- Stand alone mode

**HSPLL (High Speed PLL)**
- Input: 4-8MHz
- Output: 68-80MHz
PSQ (Power SeQuencer)
- Detect “Start” signal
- Control Power Up/Down Sequence
- Detect Debug Mode

ASQ (Acquisition SeQuencer)
- Control measurement sequence
- Start/Stop PPG & SDHS
- Programmable events
The USS terminals on the device are symmetric to the package axis, thus allow to easily maintain symmetry on the PCB.

TI will provide guidelines on how to connect the Transducers via cable or PCB via App Notes.
MSP430FR6047 Evaluation Module

www.ti.com/tool/EVM430-FR6047
EVM430-FR6047 Key Components

- Alphanumeric LCD
- Transducer Connectors
- External Power
- BoosterPack Connectors
- USB Interface
- eZ-FET emulation circuit
EVM430-FR6047 Features

- External/USB Power Options
- On-board eZ-FET for programming/debug
- Header available to measure current consumption
- USB HID interface to PC GUI
- Alphanumeric LCD for stand-alone operation
- Two transducers can be connected
- Booster-Pack Connectors for additional functionality such as RF
- Compatible with USS Software Library
Application Software and USS SW Library

www.ti.com/tool/MSP-USSSWLIB
Software Architecture – Ultrasonic Application

Application

- USS measurements
- HMI Design Center

USS SW Library

- APIs
  - Measurements
  - Algorithms
  - Application Debug
  - Calibration
  - Configuration Update
  - Interrupts

HAL

PC GUI

Driverlib

Rest of MSP430 Modules

USS Timer LEA
Ultrasonic Software Library

USS SW Library

APIs
- Measurements
- Calibration
- Algorithms
- Configuration
- Update
- Application
- Debug
- Interrupts
Ultrasonic Software Library - Implementation

**USS_userConfig.c**

- USS_SW_Library_configuration
  - .systemConfig
  - .meterConfig
  - .measurementConfig
  - .pllConfiguration
  - .captureConfig
  - .triggerConfig
  - .algorithmsConfig
  - .interruptConfig

**Application**

- USS_configureUltrasonicMeasurement
- USS_initAlgorithms

**Application**

- USS_startUltrasonicMeasurement

**Application**

- USS_runAlgorithms

- AbsTOF
- dTOF
- Flow Rate
USS Software Library offering

<table>
<thead>
<tr>
<th>Feature</th>
<th>TI – MSP430FR6047 with USS</th>
</tr>
</thead>
<tbody>
<tr>
<td>dToF</td>
<td>✔</td>
</tr>
<tr>
<td>AbsTOF</td>
<td>✔</td>
</tr>
<tr>
<td>Flow Rate</td>
<td>✔</td>
</tr>
<tr>
<td>Filtering / Post processing</td>
<td>✔</td>
</tr>
<tr>
<td>Averaging</td>
<td>✔</td>
</tr>
<tr>
<td>Waveform capture</td>
<td>✔</td>
</tr>
<tr>
<td>Automatic Gain Control</td>
<td>✔</td>
</tr>
</tbody>
</table>
Ultrasonic Design Center

www.ti.com/tool/msp-ultrasonic-design-center
Ultrasonic Design Center GUI

The Design Center (DC) GUI provides an easy and quick solution to get started with the MSP430FR4067 Ultrasonic Sensing Library and begin experimental water flow measurements.

The GUI equips the user with the ability to easily modify key USS Library members with a variety of input parameters.

Some of the modifiable Parameters and Advance Parameters include:

- The excitation frequency of the ultrasonic pulse (F1)
- Number of excitation pulses
- Gap between pulses (UPS0 – UPS1 Gap)
- ADC Sampling Frequency
- USS crystal settling time
- … Much more
In addition to the ability to modify major USS Library Members, the DC GUI also provides visual data results in real time through the graphs in the “Waveforms” panel.

Each of these graphs provide editable options, giving an expanded control of the data that is visualized through the GUI. These options are editable though a ‘Waveforms Options’ pop-up window.

http://www.ti.com/tool/msp-ultrasonic-design-center
Ultrasonic Design Center GUI

The DC GUI further has the capacity to perform three crucial actions:

1. **ADC Capture**
   - Capture a single ADC waveform from an excitation pulse and display it the ADC Capture graph.

2. **Continuous Capture**
   - Continuously capture the ADC waveform from consecutive excitation pulses, display and log the data in a .csv file.

3. **Frequency Sweep**
   - Sweep through a selectable range of frequencies for the excitation pulse allowing the user to obtain an optimal excitation frequency for best performance.
EVM430-FR6047 Test Results

www.ti.com/tool/EVM430-FR6047
ADC Waveform & TOF captures

- Transducer excitation frequency = 1.03 MHz
- Sampling rate: 3.6 MHz
- Capture duration: 40 us

- Measurements at room temperature over 15 ½ hours
  - TOF Single shot standard deviation = 26 ps
  - TOF Mean = 36 ps
Zero Flow Drift: Room Temp (Overnight)

- Overnight Room Temp ZFD Test
  - Measurement Rate: 1 Hz

- Zero Flow Drift (ZFD): **8 ps** (15 1/2 hours run) (32ps : 40ps)

- Single shot standard deviation (STD): 26 ps
Low Flow Detection

- Setup allows for testing very low flow rates:
  - < 1 drop/sec
  - Equivalent to < 0.2 lph
- Test results for <1L/h

![Low Flow Measurements](image)
## Results from EVM430-FR6047

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Std. Deviation for single shot measurement</td>
<td>&lt;32 ps</td>
</tr>
<tr>
<td>Zero Flow Drift Over Temp. (5°C – 85°C)</td>
<td>&lt;25 ps¹</td>
</tr>
<tr>
<td>Min. Timing Resolution</td>
<td>5 ps</td>
</tr>
<tr>
<td>Average current consumption @ 1Hz</td>
<td>4.29 µA²</td>
</tr>
</tbody>
</table>

1. has transducer / pipe dependency  
2. Current Silicon performance – will be improved to ~3uA with the final silicon
MSP430FR6047
The next level of performance for Ultrasonic Sensing Solutions

Features/Benefits

• First Single Chip solution with the best performance
  ~ 25ps Zero Flow Drift
  ~ 32ps Standard Deviation
  ~ 3uA measurement current

• Ultrasonic Sub-system (Integrated High Performance SD-ADC, Pulse Position Generator & Integrated PHY) with Software Library Support

• LEA (Low Energy Accelerator) for optimizing power

• MTIF (Metering Test Interface Module) running in Sleep Mode

Tools

Flow Meter EVM 100-pin Target Socket Board USS S/W & GUI

Software

• Code Composer Studio™ IDE
• EnergyTrace++™ Technology
• DSPLib
• USS Software Library
• ULP Advisor

Target Applications

• Ultrasonic Flow Meter
• Liquid Level Sensing
• Occupancy Monitoring System
• Security Sensing
• Distance Measurement System
Summary

- Industry’s first integrated SOC for Ultrasonic Sensing
  - High Accuracy, High Precision measurements
  - Low power (~ 3uA) for 1 meas/sec
  - Low flow rate detection (<1 L/h)
- Ultrasonic Design Center with Software Library, GUI for ease of development
- FR6047 EVM for hardware evaluation
- Documentation – App Notes and User Guides with Links
- Training Videos - Coming Shortly......

www.ti.com/product/msp430fr6047
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